Measurement of the H $\rightarrow \gamma\gamma$ and H $\rightarrow \mu^+\mu^-$ decay processes at the Future Circular Collider

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Abstract

The project examines the measurement of the H$\rightarrow \gamma\gamma$ and $H \rightarrow \mu\mu$ decay process at the Future Circular Collider, with the outlook of determining the precision of the data expected. The selection cuts described in the LEP3 simulation are implemented; the efficiencies for signal and background are accurately reproduced for H$\rightarrow \mu\mu$ but the selection efficiency for the H$\rightarrow \gamma\gamma$ channel could not be accurately reproduced. The source of the background photons and effectiveness of the individual cuts is investigated.

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1 Introduction

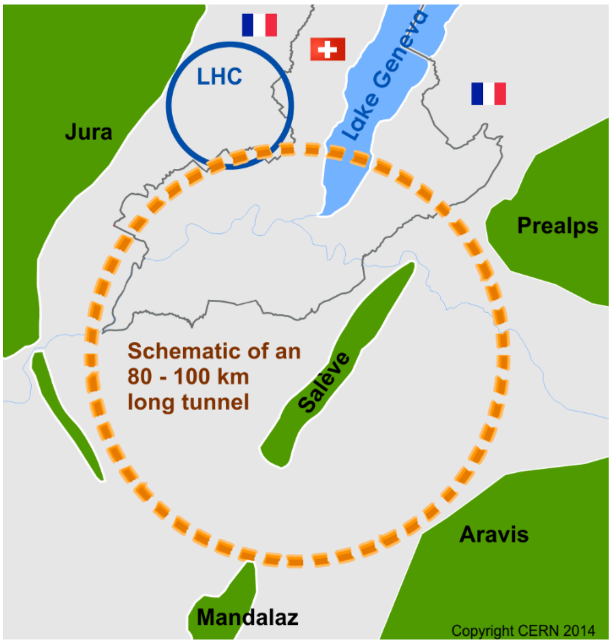

Figure 1: A schematic map of the proposed location of the Future Circular Collider (image:CERN).

The Future Circular Collider study [1][2] aims to develop plans for a particle accelerator which will continue the research done at the LHC after 2035, following the high luminosity upgrade. The conceptual design report, to be submitted before the end of 2018, will contain plans for a high-luminosity circular collider to be contained in a 80-100 km tunnel in the Geneva area. The focus will be mainly on the hadron collider (FCC-hh), which will determine the infrastructure, but there will also be an electron-positron collider (FCC-ee). This will run for a total of 14 years, including 3 years at 240 GeV, with the earliest possible Physics starting date in 2039.

The FCC-ee is intended as a Higgs factory, providing a clean experimental environment to measure Higgs properties with greater precision, in particular couplings to gauge bosons and fermions, and it will look for any deviation in expected production and decay rates in the Higgs resonance as a guide for searches for new Physics at a higher energy scale. The global fit of Higgs couplings - tested using decay processes including the ones in this study - will be an important test of the Standard Model, with small variations predicted by many Beyond Standard Model theories. High precision measurements can be made using a lepton-antilepton collider as, unlike in a hadron collider, these have a well-defined initial state.

This project studies the results produced in the LEP3 simulation [3], an old idea for an electron-positron collider in the LHC tunnel, with the aim of recreating the efficiencies produced by the LEP3 simulation and then adjusting to simulate measurements made at the FCC-ee.

2 Theory

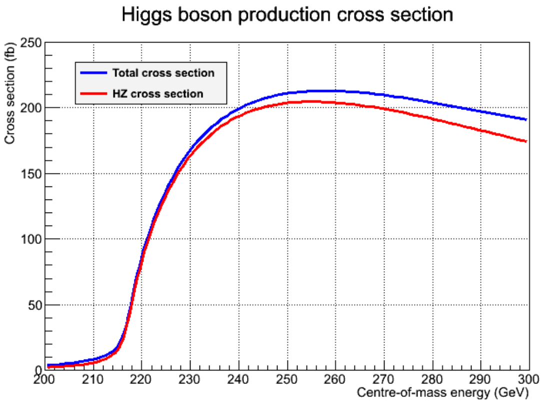

Figure 2: Higgs boson production cross section as a function of centre-of-mass energy. Image from the LEP3 note.

Figure 2 shows the Higgs production cross sections at differing centre-of-mass energies. The centre-of-mass energy is chosen as 240 GeV to maximise the Higgs boson production (an increase to 260 GeV corresponds to an increase in cross section of 6% but an increase in power consumption of 40% so is not economically viable), with a cross section of approximately 200 fb.

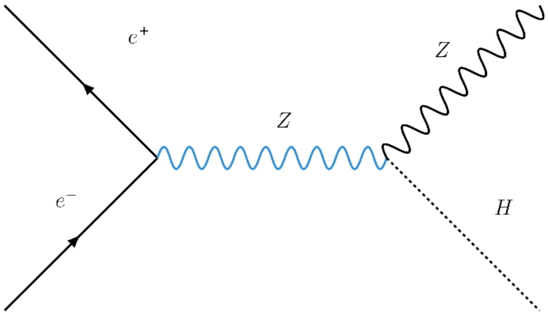

Figure 3: Higgs production through the Higgsstrahlung process.

The Higgs boson can be produced resonantly in particle collisions, such as W boson fusion, or through the decay of an energetic photon or Z boson (the ‘Higgstrahlung’ process, shown in Figure 3), which is the dominant production channel in the simulation at this energy and is the process used in the study. This project focuses in particular on the decay of the Higgs into a pair of photons (via a top quark or W boson loop, as the Higgs does not couple directly to massless photons) or into a muon-antimuon pair, as shown in Figure 4. The diphoton decay channel was a historically important channel in the 2012 discovery of the Higgs, and the muon decay channel is particularly interesting - it has a very low branching ratio of 0.02%, and is a rare Higgs process being examined by the ATLAS collaboration. It has not yet been observed at the LHC, as this would require significantly more data than is currently available (although the H$\to \tau\tau$ process has been recorded), so is of particular interest in the work to be done by the FCC and ILC. The Higgs decay into leptons, and in particular coupling to the second generation, is a promising area in the search for new Physics.

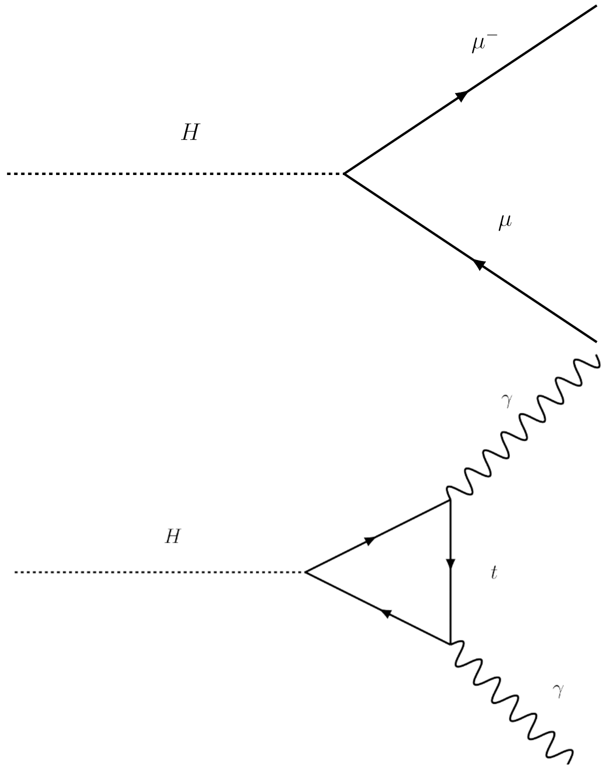

Figure 4: Higgs decay into a pair of muons or into a pair of photons via a top quark loop.

The LEP3 study is an old idea for an electron positron collider to be run in the LHC tunnel, at $\sqrt{s} = 240$ GeV, for 5 years, with an integrated luminosity of 500 fb^{-1}. Although the aims and underlying Physics are the same as for the FCC, the LEP3 study has several differences, including a lower integrated luminosity, and that it uses the CMS detector, whereas the FCC is planned to use a specialised detector for e$^+$e$^-$ collisions (largely based on studies for the ILC).

3 Method

3.1 Simulation

For the H→ $\gamma\gamma$ channel, 10 000 signal events (the Higgsstrahlung process e^+e^- →ZH, with the Higgs decay restricted to the production of 2 photons and no restriction on the Z decay) and 5 000 000 events with the Higgs decay via any channel to simulate the main photon background, were generated using PYTHIA 8, a Monte Carlo event generator for high energy particle collisions [4] (in comparison to an expected 266 signal and over 30 000 000 background events described in the LEP3 note). After the selection process this led to 5 679 remaining signal and 6213 remaining background events.

For the muon decay channel, 10 000 signal events were produced of e^+e^- →ZH with the Higgs decay restricted to the muon pair, alongside the 5 000 000 background events, which consisted of e^+e^- →ZZ (shown in Figure 5). The LEP3 simulation runs with only 22 and 650 000 of these events respectively. After the selection process this led to 5 404 remaining signal and 166 632 remaining background events.

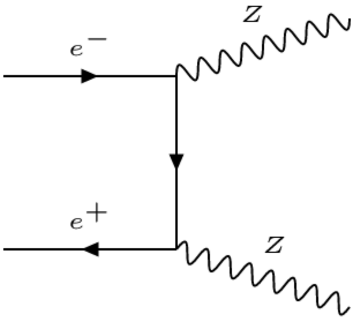

Figure 5: The muon background mostly originates from ZZ production.

The rest of the analysis was carried out using Heppy [5], a modular Python framework created by Colin Bernet to analyse collision events. This reconstructs the events using Papas, a parametrised particle simulator, that produces a realistic simulation of the measurements taken by the CMS detector, carries out the selection, and reconstructs the Higgs particle from the chosen pair of photons or muons.

It is worth noting that PYTHIA was developed in particular for hadron colliders and for the ILC, and therefore there may be some discrepancies between the events generated using this method and the expected collision events.

3.2 Selection for the H $\rightarrow \gamma\gamma$ decay channel

The main photon background came from initial and final state radiation. The selection requirements to distinguish legitimate Higgs decay events from photons produced by background events were implemented as described in Section 3.7 of the LEP3 note. Each event was required to produce at least 2 photons, and as these were expected to have an invariant mass (given by $m_H = \sqrt{2E_1E_2(1-\cos(\theta))}$, where E_1 and E_2 are the photon energies and θ is the angular separation) close to the Higgs mass of 125 GeV, only photons of energy greater than 40 GeV were selected. Photons with a high angular separation could have a high invariant mass, but signal photons tend to be emitted centrally, and this cut has an efficiency of 94% on the signal, but only 3% on the background, discarding the majority of background events with double radiative return to the Z mass.

Pseudorapidity, given by $\eta = -\ln(\frac{\theta}{2})$ (in which θ is the angle between the particle's three-momentum and the beam axis), is a measurement of the angle of the particle relative to the beam, with higher values closer to the beam axis and $\eta = 0$ for particles emitted centrally. Due to the detector acceptance, the pseudorapidity of the photons is required to be less than 2.5. This is a limitation associated with the CMS detector and so this cut may not be valid in the case of a specialised FCC detector.

From the remaining photons, the "Higgs candidates" were chosen as the pair with the recoil mass closest to the nominal Z mass, ie by minimizing the quantity $|m_Z - m_{recoil}|$, with the recoil mass defined as:

$$m_{recoil} = \sqrt{(240 - E_1 - E_2)^2 - \mathbf{p_1} \cdot \mathbf{p_2}}.$$

An important cut to identify photons that are produced from the decay of the Higgs boson, particularly in distinguishing coloured and colourless photon production, is the relative isolation. A cone of radius 0.4 is constructed around each photon in (η, ϕ) space and relative isolation is defined as the sum of the energy of the particles in this area (excluding the photon in question) divided by the energy of the photon. Photons produced in jets of hadrons created by the Z boson decaying to a pair of quarks (for example by the decay of π^0 mesons within the jets) would have a high relative isolation. The Higgs candidate photons were therefore required to have relative isolations that sum to less than 0.4.

As mentioned previously, a greater invariant mass can be produced by the photon pair if they are emitted with a large angular separation, so the photons are required to have a pseudorapidity difference of less than 1.8 (pseudorapidity is used instead of the angular separation as it is a Lorentz invariant quantity in boosts along the z-axis). Finally, the direction of the Higgs candidate momentum is required to be at an angle greater than 25° with respect to the Z-axis. This ensures there is the best resolution on the reconstructed Higgs, due to the distinction between the barrel region and forward region of the CMS detector.

Table 1: Selection efficiencies on the signal events

Selection cut	Individual efficiency	Cumulative efficiency	Notes
More than 2 photons	99%	98.92%	
Energy>40 GeV and η <2.5	93%	91.63%	
Sum of isolations <0.4	96%	87.83%	LEP3 simulation gives 85% after this cut
Difference in η <1.8	73%	63.98%	
Higgs candidate $\theta > 25°$	90%	57.84%	LEP3 simulation describes final efficiency as 'almost 60%'

Table 2: Selection efficiencies on the background events

Selection cut	Individual efficiency	Cumulative efficiency
More than 2 photons	70%	70.20%
Energy>40 GeV and η <2.5	3%	1.96%
Sum of isolations <0.4	23%	0.40%
Difference in η <1.8	43%	0.17%
Higgs candidate $\theta > 25°$	75%	0.13%

The selection efficiency of each of these cuts on both the signal and background events are shown in Table 1 and Table 2 respectively. It can be seen that the cut which dismisses the most signal events is the pseudorapidity difference, the most effective cut in dismissing individual photons is the photon energy, and the most effective cut in dismissing photon pairs is the isolation sum. Furthermore it can be seen that the selection applied to the signal matches the efficiencies expected from the LEP3 simulation.

The results of the diphoton invariant mass after this selection is applied is shown in Figure 6, with the statistical error bars produced by ROOT. The background is fit to a third-order polynomial, and the signal to a Gaussian. The final number of events is scaled to reflect the actual number events expected by the LEP3 simulation. It can be seen that the aim of recreating the selection efficiencies of the LEP3 simulation (shown on the left of Fig. 12 in the LEP3 note) was therefore unsuccessful, due to the presence of too many background events surviving the selection cuts. In order to identify the source of the background photons that were not being dismissed, the background events with Z decaying into leptons, neutrinos, or quarks were analysed separately. The results

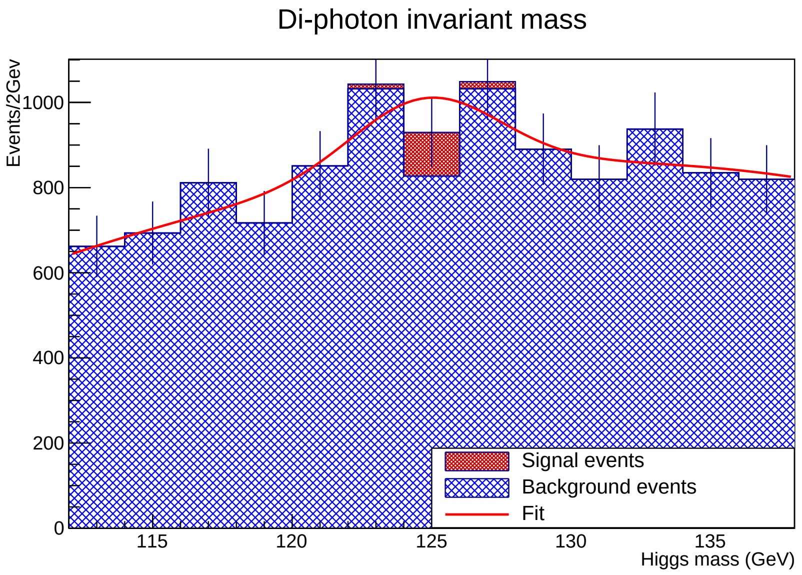

Figure 6: The diphoton invariant mass after the selection is applied to both the signal and background events.

are in Figure 7, with further information given in the Appendix. It can be seen that the primary sources of misindentified photons come from the channel with Z decaying to quarks or leptons.

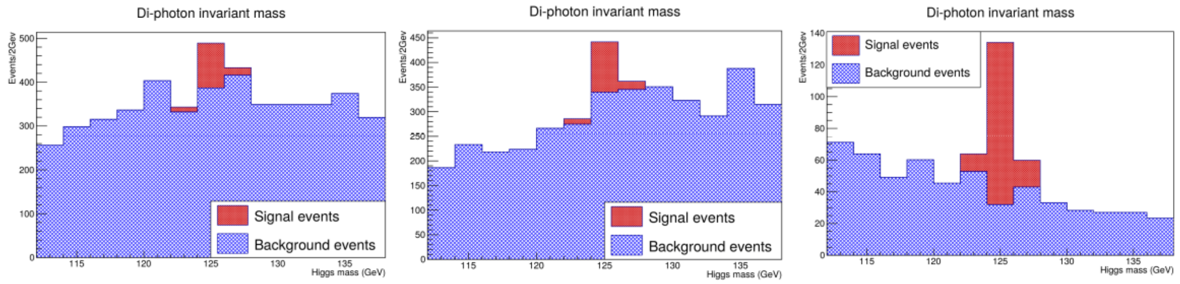

Figure 7: The diphoton invariant mass in cases where the background events are generated with restrictions on the Z decay modes. From left to right this is Z decaying into a pair of quarks, leptons, and neutrinos.

It therefore seems likely that the misread photons come from the decay of tauons or pions, which should be dismissed by the isolation cut. The authors of the LEP3 simulation have been contacted to find out if it has been incorrectly applied - this may be, for example, if the radius of the cone has been chosen incorrectly, or if the isolation cut needs to be adjusted within the framework used.

3.3 Selection for the H $\rightarrow \mu^+\mu^-$ decay channel

Unlike the H$\rightarrow \gamma\gamma$ analysis, the LEP3 simulation uses an integrated luminosity of 2 ab^{-1} for the H$\rightarrow \mu^+\mu^-$ channel, as otherwise there are too few events for meaningful statistics. Two oppositely charged muons are required, with a relative isolation (defined above) of less than 0.2.

The system formed of the muon pair and bremsstrahlung photons is required to have a recoil mass compatible with the Z mass (between 80 and 110 GeV). The appropriate bremsstrahlung photons could theoretically be found by testing this requirement against all possible combinations of recovered photons and an oppositely charged pair of muons, however this could not be implemented as testing the various combinations of photons greatly increased the processing time for each event. Therefore the bremsstrahlung photons were defined as the photons within a cone of radius 0.5 around either muon, which still had an appropriate efficiency for the signal events - however this would be a possible improvement of the analysis given greater computing power. This system of photons and muons was used to reconstruct the possible Higgs candidates.

The Higgs candidate is required to be accompanied by two visible 'jets' (although these were not defined as hadronisation jets but any non-neutrino particles), in order to reject the WW background where each W boson decays into $\mu\nu$ (this would produce an oppositely charged pair of muons). However, this rejects signal events where the Z boson decays into a pair of neutrinos, which is 20% of the signal. Finally, the electromagnetic fraction - defined as the proportion of the energy in each jet from photons or electrons - of at least one of the jets is required to be less than 0.8. This rejects 3.4% of the signal, with Z decaying into a pair of electrons.

The selection efficiences from these cuts are shown in Table 3 and Table 4. It can

Table 3: Selection efficiencies on the signal events

Selection cut	Individual efficiency	Cumulative efficiency	Notes
Pair of muons	87%	86.68%	
Relative isolation < 0.2	89%	77.34%	LEP3 simulation gives 90% for this cut
Appropriate recoil mass	94%	72.55%	
Two visible jets	77%	55.59%	This should reject 20% of the signal
Electromagnetic fraction < 0.8	97%	54.04%	This should reject 3.4% of the signal

Table 4: Selection efficiencies on the background events

Selection cut	Individual efficiency	Cumulative efficiency
Pair of muons	7%	6.92%
Relative isolation < 0.2	89%	6.17%
Appropriate recoil mass	74%	4.60%
Two visible jets	78%	3.56%
Electromagnetic fraction < 0.8	97%	3.47%

be seen that the most effective cut on the background is the presence of two visible jets (although this similarly has a low selection efficiency on the signal), and that the selection efficiences on the signal match those expected from the LEP3 note.

The invariant mass of the surviving events is shown in Figure 8, which has the right shape for the expected plot.

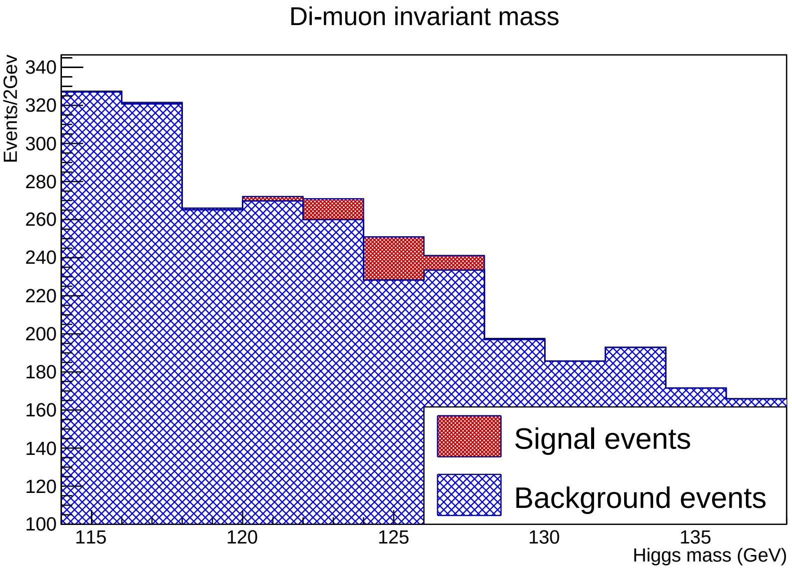

Figure 8: The dimuon invariant mass for both signal and background events.

4 Conclusion

The selection cuts for the H→ $\mu\mu$ could be correctly reproduced using the Heppy framework. However, it became clear that the selection cuts described in the LEP3 simulation were not being implemeted correctly, as the cuts were not effective enough in dismissing background photons. It currently seems that these photons originate in jets or tauon decay, following the Z boson decay, which suggests that the isolation cut is not effective enough.

5 Outlook

This project would be continued by adjusting the simulation for a more accurate representation of the results expected from the FCC. The biggest difference would be to use the specialised FCC-ee detector rather than the CMS detector, and updating the integrated luminosity to the planned 5 ab^{-1}.

Several of the selection cuts could be changed to reflect the differences between the CMS detector and the specialised detector to be used at the FCC. For the diphoton decay channel, this includes the cut on the pseudorapidity of the photons and the momentum angle of the reconstructed Higgs boson. The muon selection could also be refined, as discussed, by changing the method used to select the appropriate bremsstrahlung photons, although this would have little effect on the muon signal selection efficiency.

It would also be possible to vary certain elements of the detector to see what aspects have the biggest effect on the results for these chosen Higgs decay channels, such as the cluster size, ECAL resolution, and HCAL resolution. It would also be useful to investigate differences to the results if a different program than Pythia were used to generate the events.

6 Acknowledgements

I am incredibly grateful to my supervisors Katharine Behr and Krisztian Peters, for their invaluable guidance in carrying out the project (particularly when the results did not turn out according to plan), and Janik von Ahnen for his inexhaustible patience. I would also like to thank Claire David and Ingrid Gregor, as well the rest of the ATLAS group, for such a warm welcome, and the summer school organisers - particularly Olaf Behnke - for a very rewarding experience.

7 Appendix

7.1 Accessing the code

The Heppy framework, with all adjustments made by this project, is available at: //github.com/nrsolomons/heppy, and can be run according to the Heppy instructions. The adjusted files are:

- analyzers.examples.zh_had.Selection.py: This now runs the selection cuts for the photon decay channel. In the current form the final 3 cuts are not applied but are variables in the root tree and cuts can be applied from there.
- analyzers.examples.zh_had.Selection_mu_1 and Selection_mu_2.py: These run the selection cuts for the muon decay channel (therefore note that the cut flow output for the second selection file is not representative of the full selection).
- analyzers.examples.zh_had.TreeProducer.py: Produces the root tree for selected photons, including various variables used in the photon selection.
- analyzers.examples.zh_had.TreeProducer_mu.py: Produces the root tree for selected muons.
- analyzers.PhotonHistory.py: Used to trace the photon history.
- test.analysis_ee_ZH_gamgam_cfg.py: Photon analysis file - the address of the generated root files needs to be changed.
- test.analysis_ee_ZH_mumu_cfg.py: Muon analysis file.
- test.background.txt (and similar): Files for creating separate events in Pythia.
- test.generate.py: File to generate events in Pythia.

Further codes used to create important histograms in this report are gammacombined.C and mucombined.C, in the test folder.

7.2 Notes on photon selection

The isolation sum and pseudorapidity difference (without any of the final 3 cuts applied) are shown for both the signal and background in Figure 9. This shows how effective the isolation cut is in distinguishing the signal and background, whereas the difference in pseudorapidity has a lower efficiency on the signal.
The photon invariant mass for the case where the Z boson is required to decay into an electron-positron pair is shown in Figure 10. This has a relatively low background in comparison to the case of leptonic Z decay, which suggests that many of the photons are being produced by tauon decay.
The PDG ID of the mothers of photons (given by Pythia) which remain after the selection process is shown in Figure 11. ID 111 corresponds to neutral pions. The majority of the mothers are registered as ID 22, which corresponds to photons - therefore further study is needed to trace the photon ancestors back further.

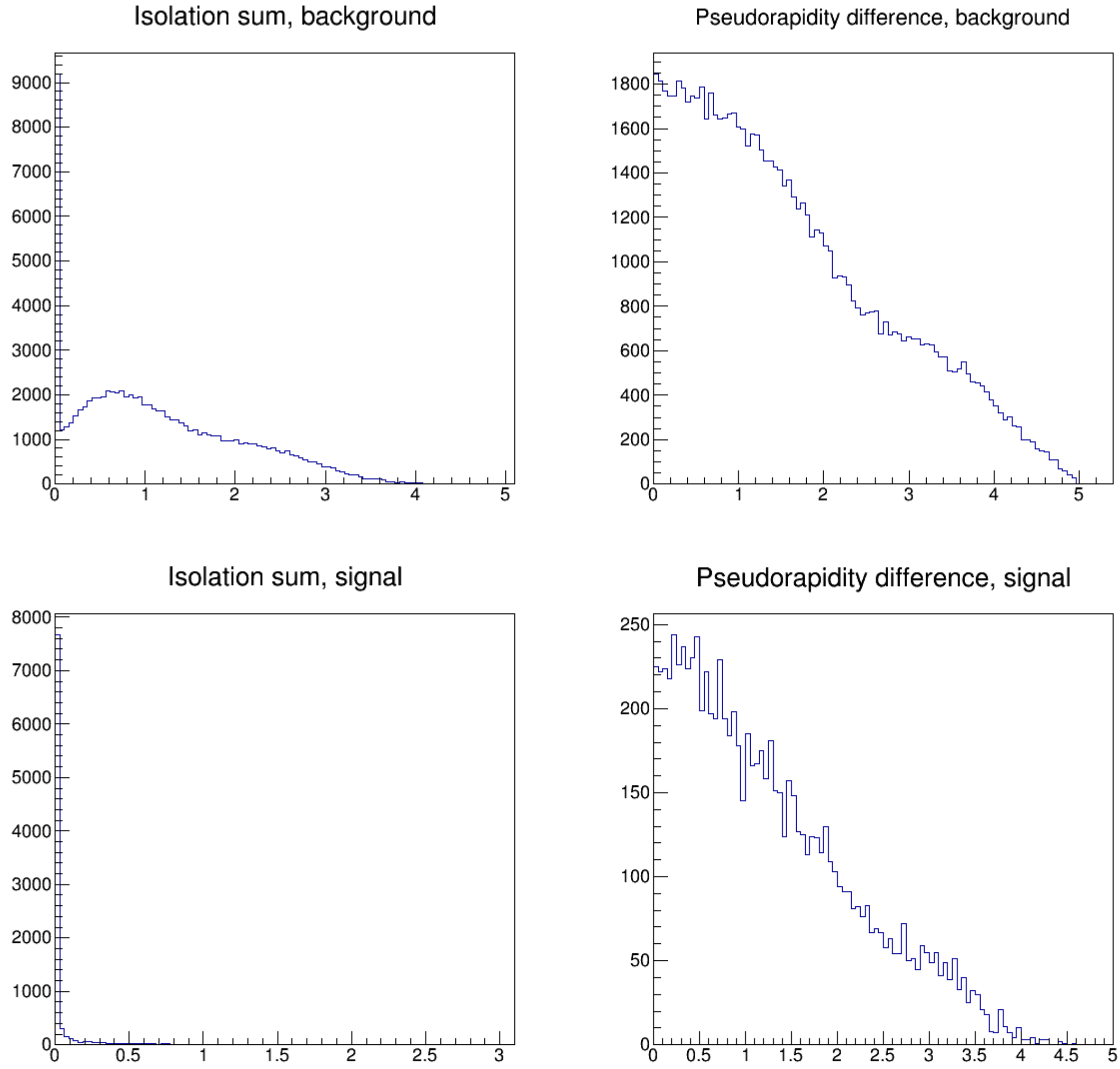

Figure 9: The isolation sum and pseudorapidity difference for both signal and background events.

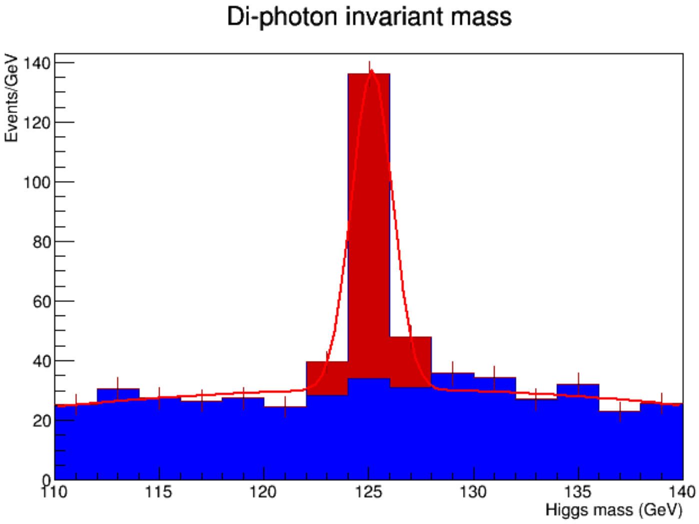

Figure 10: The di-photon invariant mass for the case where the Z boson is required to decay to an electron positron pair.

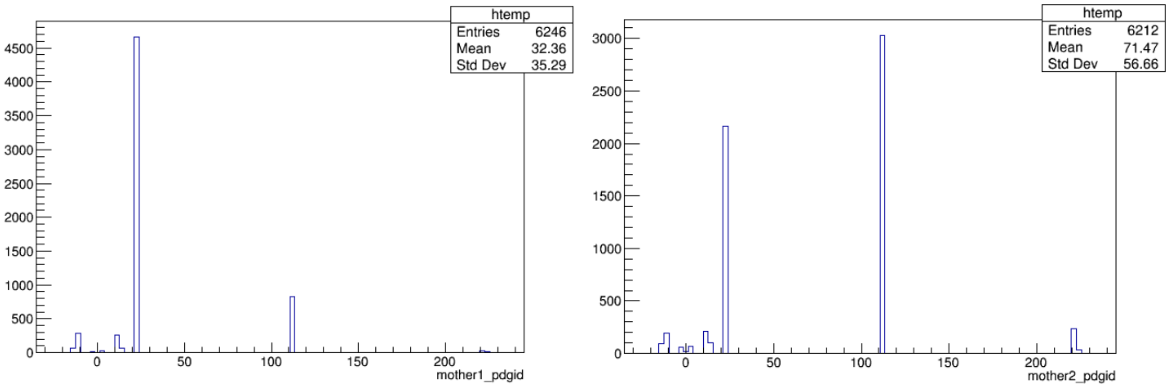

Figure 11: The PDG ID of the mothers of remaining photons after all cuts have been applied.

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