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Study of FCC-ee Sensitivity to the Production of Axion-Like Particles

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Study of FCC-ee Sensitivity to Potential Production of Axion-Like Particles

by

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Contents

1 Abstract

In this paper we will be focusing on simulating events for a beyond standard model process $e^+e^- \to H(a \to \mu\mu)$ and comparing it to other decay processes at the same center of mass energy $\sqrt{s}$. We also show that by making selections on several variables such as the acoplanarity, leptonic recoil, and missing energy we can cut down on background processes in order to see how sensitive to the FCCee would be to the detection of a light pseudoscalar.

2 Introduction

The standard model is one of the most successful and widely predictive models in all of physics. The standard model is an organized model of the varying types of elementary particles that can exist in the known universe, including both bosons (the force-carrying particles for the various types of interactions) and fermions (the leptons and quarks). For the most part, the standard model is organized based on particle spin, with the half-integer spin indicating fermions and whole integer spin indicating bosons. The interactions between particles and their decays are explained through the interactions of gauge bosons. $W^\pm$ and Z^0 particles mediate weak interactions, gluons are the force particles for strong interactions, and photons mediate electromagnetic interactions. More massive particles have larger rest energy and will decay into less massive particles if able. Today the standard model can be displayed by tables such as that of Figure 1, with the Higgs as a recent addition that is the first 'scalar' particle to be included to date. This is a relatively compact summary of a nuanced model of relativistic quantum fields, but it serves as a straightforward organizational tool.

Despite the standard model being a succinct and predictive tool to describe the subatomic model of particle physics, it is important to note that this picture is incomplete.

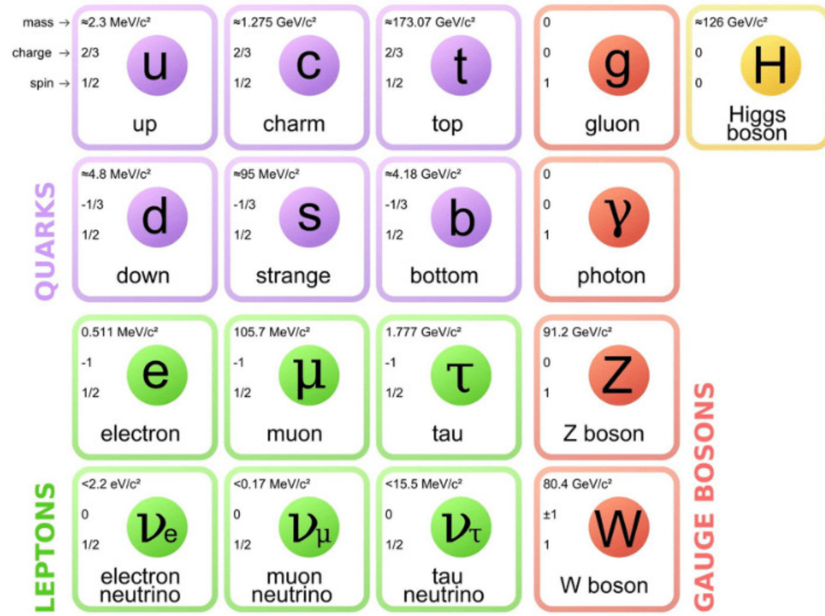


Figure 1: Standard model of particle physics as known today [1]

The discovery of the scalar Higgs boson with a spin of 0 has provided a new route for inquiry in the past decade [2]. The Higgs, the only elementary scalar particle, and its interaction through the Higgs mechanism is still not entirely understood and invites questions about the nature of dark matter or the existence of other such scalar particles. Electroweak symmetry breaking with a single Higgs doublet is understood, but the Higgs mass is much lighter than theory predicts [3] if quantum corrections are taken into account. Supersymmetry [4] addresses this, and requires an extension to 2 Higgs doublets. In some models, one of the extra physical scalar particles can be much less massive than the discovered standard model-like Higgs, making for an interesting search channel. These decays are rarer and are at the forefront of collider research since the discovery of the particle in 2012.

3 Literature Review

Currently, research in the field aims to further elaborate upon and complete the standard model. Supersymmetry theories and the predictions conveyed by it are a major source of solutions to the problems of the standard model that current research hopes to corroborate or approach. The idea behind supersymmetry (SUSY) theory is the idea that there is space-time symmetry between bosons and fermions. The next-to-minimal extension to SUSY (NMSSM) is a variant that has been extensively studied as a potential solution to the dark matter problem in the universe. The NMSSM model includes two Higgs doublets and an extra gauge singlet, which naturally leads to a low-mass pseudoscalar particle. In a paper published in 2009 ([5]), researchers proposed that the light pseudoscalar could be a candidate for dark matter, but despite many searches, no evidence has yet been found to support this hypothesis. The lack of evidence for the light pseudoscalar remains an open question in the field of particle physics and motivates further exploration of the NMSSM model.

The lack of evidence for the light pseudoscalar in the NMSSM model has led researchers to explore other theoretical frameworks. One such framework is the 2HDM+S Type 2 model, which has the same Higgs sector phenomenology as the NMSSM, but is more general. This model was tested at the Large Hadron Collider (LHC) using the CMS detector, which is designed to detect the various particles produced in high-energy proton-proton collisions. Figure 2 shows the results of the CMS search for the 2HDM+S Type 2 model using data collected during the LHC's Run 2. The figure demonstrates that the experimental data is consistent with the predicted background, and no evidence of the 2HDM+S Type 2 model was observed. Nevertheless, the similarity between the 2HDM+S Type 2 and the NMSSM models suggests that further studies of the latter model could provide important insights into the nature of dark matter and the Higgs sector of particle physics.

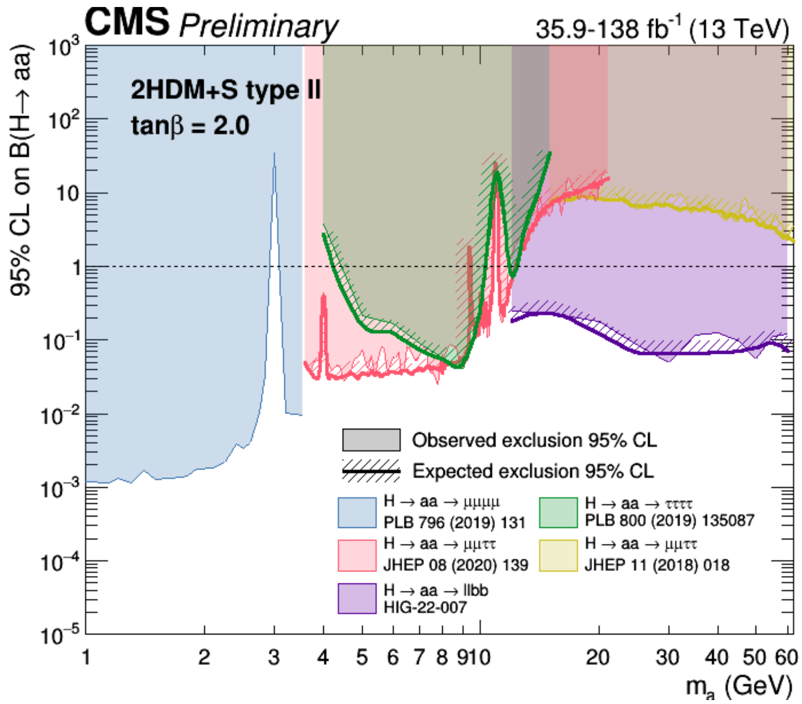


Figure 2: 95% CL on $\frac{\sigma_h}{\sigma_{SM}}B(h \to aa)$ in the 2HDM+S type-2 $tan\beta = 2$ scenario for exotic h decay searches performed with data collected at 13 TeV center-of-mass energy [6]

In Figure 2, the peaks that dip below the dotted line indicate models excluded or rejected by CMS searches for a light pseudoscalar a in $h \to aa$ decays. It is clear that a massive amount of the light pseudoscalar SUSY models are missed by the CMS, and there is a limit on the capabilities of current collider technology as a result of how messy the data from proton collisions is. In order to properly observe these events, a higher luminosity collider that collides charged leptons is much more ideal. With shortcomings in some of these specific searches, it is clear that not only is progressing the field with colliders an imperative for some range of analysis, it is also a collaborative, massive undertaking that requires a lot of care and attention to evolve.

In recent years, decadal meetings such as ‘Snowmass’ or likewise the European Strategy for Particle Physics have seen minds from across the world come together to discuss the direction of future research in the field. As new technology and discovery is necessary for consistent progress, these events allow discussion and planning to be undertaken in the aims of advancing a broad range of research. In these kinds of meetings, proposals of new collider technology, experimentation, and the sharing of existing data allows for more direct plans to be made in relation to future large-scale experimentation. Among other ideas, a major proposal of the field has been in making an electron-positron collider, which would be capable of operating at 240 GeV center-of-mass energy with much higher precision than a proton-proton collider would be able to. This precision is due to the colliding beams consisting of electrons, which allows for the kinematics of each collision to be tracked with ease, allowing for better reconstruction of particle data from the detector elements. This would be a massive step up from a hadron collider for such analyses and allow for a more specific type of search into new physics.

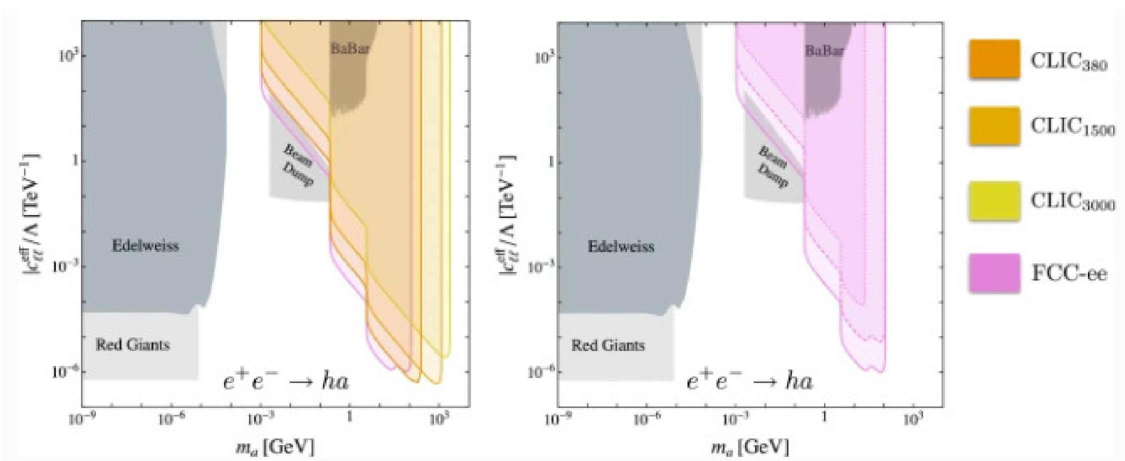


Figure 3:

C_{eff}/Λ is the coupling coefficient divided by the new physics scale where m_a in the x-box is the ALP mass

The gray regions shown in the figure represent excluded models while the colored regions represent sensitivity regions in which 4 reconstructed signal events have been found [7]

Left: Projected sensitivity regions for $e^+e^- \to ha \to bb^- l^+ l^-$

Right: Sensitivity regions for the example of the FCC-ee with $|C_{eff}ZH| = 0.72\Lambda/TeV$ (solid contour), $0.1\Lambda/TeV$ (dashed contour), and $0.015\Lambda/TeV$ (dotted contour) which corresponds to $Br(h \to Za) = 34\%$, 1%, and 0.02% respectively [7], (i.e, varying branching ratios)

As previously stated, the electron-positron collider, called FCC-ee [8], that has been proposed can probe final states with precision not available at the LHC. Also true of the CLIC [9] machine which has been proposed to collide electrons and positrons as well, the idea of colliding leptons makes more intuitive sense kinematically, since the 4-momenta of the colliding electron and positron are precisely known, allowing for the full event kinematics to be quite simple to reconstruct.The plan for FCC-ee is to run at a center-of-mass energy of 240 GeV, which maximizes Higgs production via $e^+e^- \to Zh$ for precision studies of the Higgs. Additionally, if the pseudoscalar exists, it can also be produced at this center-of-mass energy via $e^+e^- \to ha$. FCC-ee is capable of analyzing similar pseudoscalar mass ranges as CLIC ([7], shown in Figure 3 of this document), but can reach lower effective coupling for masses of a few to tens of GeV as the luminosity is much larger. When compared generally to beam dumps and the capabilities of current technology, the range that the FCC-ee can analyze is untouched territory that probes what the current CMS is unable to do easily.

As of now, the FCC-ee is not a physically existing collider, but the software and framework simulating potential FCC-ee events is available for public use courtesy of collaborators at CERN [10]. The existing framework on the software side simulates the 'Innovative Detector for Electron-positron Accelerator' or 'IDEA' detector [11] response to both standard and non-standard model processes generated using PYTHIA [12]. PYTHIA is an event generation software for high-energy particle physics that is entirely written in the C++ coding language. This spectacular event-generator runs Monte Carlo simulations for each and every collision event, giving an extremely comprehensive interpretation of a broad range of particle physics decays and processes. Simulating these collisions is helpful for various reasons, as it allows users to manipulate previously produced large-sample standard model background collision data as well as generate and analyze their own chosen new physics processes to view how such data would look with the capabilities of the future collider. The ability to compare and overlay such signal and background decays allows for the investigation of how generally accurate and sensitive

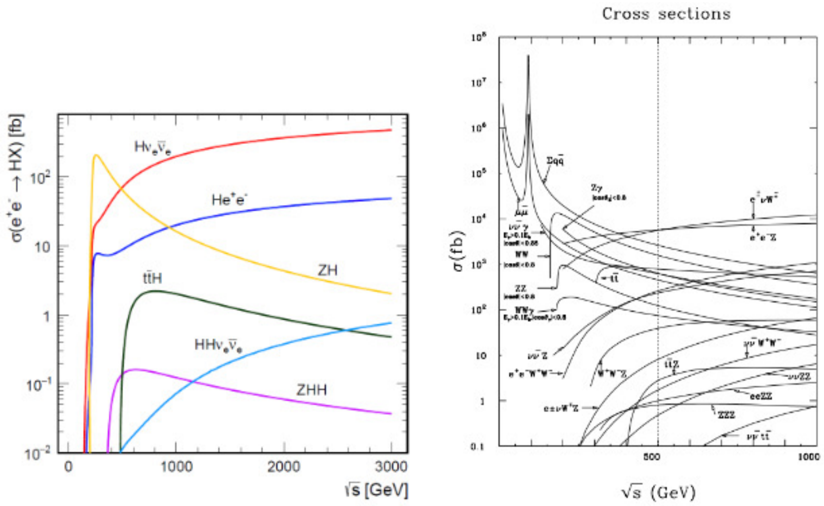


Figure 4: Both figures show center-of-mass energy on x-axis and cross section on y-axis
Here we see the maximization of ZH production at around 240 GeV center-of-mass energy [13] and also shows the ZZ and WW production is prominent in similar $\sqrt{s}$

the IDEA detector framework is for varying searches. As for our research, the main goal is to look at the FCC-ee IDEA detector's sensitivity with Higgs and pseudoscalar production, namely in this case $ee \rightarrow H(a \rightarrow \mu\mu)$ using a repository that allows for the analysis of varying processes. The idea is that by looking at center-of-mass events of 240 GeV where the produced sample is the signal $ee \rightarrow H(a \rightarrow \mu\mu)$, it is possible to then compare this signal with the other prominent background processes and start to create cuts or selections on the properties of particle data and therefore allow for a more proper analysis of the properties of the signal.

There are a few major background event decays that are extremely prominent alongside the $H(a \rightarrow \mu\mu)$ decays (Figure 4). Most prominently, the production of ZZ or WW pairs are extremely large background samples in comparison to the signal of interest which is a much rarer decay to a pseudoscalar and an H. To observe the smaller signal, the large sample background decays must be suppressed in order to allow us to discriminate the signal in the reconstructed data. For the individual signal of a pseudoscalar to two muons, we have begun by setting the cross-section for the process to be around 1 fb as a benchmark, with the signal pseudoscalar particle mass being set to 5 GeV, and thus have to begin selecting on the other data. Knowing that the pseudo-Higgs decays into two muons, we can further select on our data by making cuts such that our events are required to have opposite charge decay muons. Furthermore, checking the invariant mass of the signal allows us to see the signal being created at the expected 5 GeV resonance. While implementing such cuts the leptonic recoil mass is also monitored, which approximates the mass of the particle that is recoiling against our detected muons, in our case a Higgs at around 125 GeV. By making further cuts and ensuring the generated data indicates our signal is at expected values for invariant mass and leptonic recoil mass, we can begin to test the sensitivity of the detector compared to that of the existing CMS.

The decay of focus for this paper, referred to in the Analysis as our “source”, is $H(a \to \mu\mu)$. In this case, the decay process results in both a Higgs as well as a low mass pseudoscalar particle. In addition to the NMSSM pseudoscalar, these particles can also play the role of ‘Axion-Like Particles’ or ALPs [7], which appear in a variety of extensions to the Standard Model. These particles are light, gauge-singlet particles with derivative couplings to the Standard Model. In theory these particles are created from spontaneous symmetry breaking and are massless. In this sense, ‘pseudo’ carries with it the caveat that our a particle is not massless, but is parameterized as low mass (≈ 5 GeV). The main interest in ALPs as they relate to the FCC-ee and related BSM probing processes is that they could be one of many potentially non-thermal candidates for dark matter. Further exploration of this decay as well as others deriving from symmetry breaking can probe new physics at a high energy scale Λ.

High-energy colliders are sensitive to a large and previously inaccessible region in parameter space, which is possible by requiring the ALP to decay within the detector(s). Different ALP production mechanisms at the collider offers a rich phenomenology to probe a large range of ALP masses and couplings. The production of ALPs can be achieved in decays of heavy SM particles or in our case, in association with Higgs bosons [7]. This probes the hZa coupling, as indicated in Figure 5.

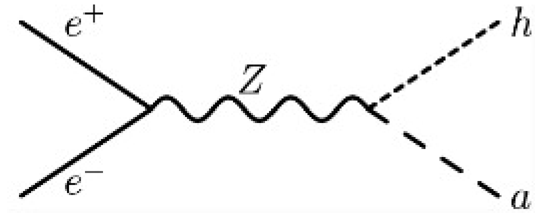


Figure 5: Tree-level Feynman diagrams for the process $e^+e^- \rightarrow ha$ [7]

4 Methodology

The international Future Circular Collider (FCC) study aims at the design of p-p, e^+e^-, and e-p colliders to be built in a new 100 km tunnel in the Geneva region. The FCC-ee specifically offers unprecedented possibilities for the measurement of the four heaviest SM particles (the Higgs, Z, and W bosons, and the top quark), but also those of the b and c quarks and of the τ lepton. Additionally, circular colliders have the advantage of delivering collisions to multiple interaction regions, allowing for various detector designs to be studied to optimize the setup. The actual collider layout could fit within the footprint of a potential hadron collider to increase the overarching goals of the FCC project. Luminosity figures very high at $2 \times 10^{36}\text{cm}^{-2}\text{s}^{-1}$ per IP at the Z pole decreasing with the fourth power of energy at top energies. The number of Z bosons alone to be produced by the FCC-ee would be five orders of magnitude larger than the number of Z bosons collected at the Large Electron-Positron (LEP) collider and three orders of magnitude larger than that of envisioned linear colliders.

The main design components for the FCC-ee [14] are a double ring collider with e^+ and e^- circulating in separate vacuum chambers allowing large and variable bunch numbers to be stored as well as a beam intensity that can be increased in inverse proportion to the synchrotron radiation per particle per turn. The device would use common low emittance lattice for all energies, with optics optimized at each energy by changing magnet strength. The length of free area around the interaction points and strength of detector solenoid are constant at 2.2 m and 2 T for all energies. Alongside this design is a top-up injection scheme that maintains the stored beam current and the luminosity at the highest level throughout the experimental run using a booster synchrotron situated within the collider tunnel.

The FCC-ee would feature a yearly integrated luminosity of more than five orders of magnitude larger than that of LEP [15], with natural buildup of transverse beam polarization that allows for ideal conditions for a precise beam energy calibration up to above W-pair energies. This potential operation range is a result of the expected longevity of the project, which would begin as an electroweak, Higgs, and top factory by spanning energy ranges from the Z pole and WW threshold and potentially being a hadron collider in future iterations of the design.

This future collider design also offers unparalleled control of center-of-mass energy and distribution. At the Z pole specifically, center-of-mass energy scale would be known to 1 ppm or better with a point-to-point residual backward asymmetry of the produced muon pairs. The FCC-ee would boast a minimized synchrotron radiation background due to the asymmetrical rings surrounding the interaction region. Having a large number of bunches and low level of bremsstrahlung radiation also allows for a lower pile-up rate for events and the small beam transverse dimensions would allow for the beam pipe to have as small a radius as 15 mm or less.

The detector response in this paper is simulated with the DELPHES [16] software package. DELPHES is a C++ framework that allows for fast, multipurpose response simulation. This simulation includes a tracking system embedded into a magnetic field, calorimeters, and a muon system. The framework interface is standard file formats and outputs observables such as reconstructed charged tracks which can be used for specific analyses. The detector response simulation takes into account the effect of the magnetic field, the granularity of the calorimeters, and the sub-detector resolutions. Also, DELPHES provides parameterized track information with the full covariance matrix using the FastTrackCovariance software.

For the detector configuration we are utilizing the Innovative Detector for Electron-positron Accelerators (IDEA) concept [11]. This is generally comprised of a silicon pixel vertex detector, a large-volume extremely-light short-drift wire chamber surrounded by a layer of silicon micro-strip detectors, a thin, low-mass superconducting solenoid coil, a pre-shower detector, a dual-readout calorimeter, and muon chambers within the magnet return yoke [17]. The DELPHES configuration card used for this analysis is accessible in the repository given in Ref. [18]. Also, the k4SimDelphes [19] project converts the DELPHES objects to EDM4HEP [20], and the subsequent Monte Carlo (MC) production is performed in the common EDM4HEP data format.

Event samples are used to simulate detector response to signal and background processes. These signal and background events are generated with PYTHIA [12] in conjunction with the leading order cross-section from the generator with no K-factor. Several important parameters are configured to be the same for all samples in the PYTHIA steering cards. At FCC-ee [17], the energy of the beams is distributed according to a typical Gaussian function.

An advanced analysis framework has been developed for all FCC analyses using the common EDM4HEP data format [21]. It is based on RDataFrames [22], where C++ code is conveniently compiled in a ROOT [23] dictionary as “analysers” which are subsequently called in Python. The analysis code is distributed via the CERN virtual machine file system cvmfs, and can be run locally or on batch systems. The complete software stack used to produce the results in this paper can be accessed and results reproduced [18].

5 Analysis

Generally, we know that the ALPs we are looking for have different event features from the other background decays that occur at the same center-of-mass energy. From Figure 4 we see that there are several background signals that dominate similarly at a beam center-of-mass energy of 240 GeV. The signal we generate consists of 100k events prior to the application of any cuts or selections, and this will remain the case as we lead into the rest of the analysis. In the interest of comparison, we choose several backgrounds, in the case of this analysis the chosen background processes along with the sample size for each decay are as follows:

Process	Events
WW	10,000,000
ZZ	59,800,000
ZH	10,000,000
Zll	9,900,000
Zqq	10,000,000
eeH	900,000
$\mu\mu H$	1,000,000
$\mu\mu$	78,300,000
$\nu\nu Z$	1,000,000
$\nu\nu H$	3,000,000
qqH	9,900,000
$\tau\tau$	49,600,000

Table 1: Background decays relevant for 240 GeV center-of-mass energy, used in comparison with our signal which consists of 100k events

When first looking over the processes, we are able to conveniently look at the reconstructed recoil mass of the decay particles (Figure 6). The recoil mass in this case is the mass of the system that recoils against the detected particles. By measuring the energy and momentum of the collision, we are able to calculate the mass of the recoiling system and indirectly prove the properties of the system, even if the constituents themselves are not detected directly.

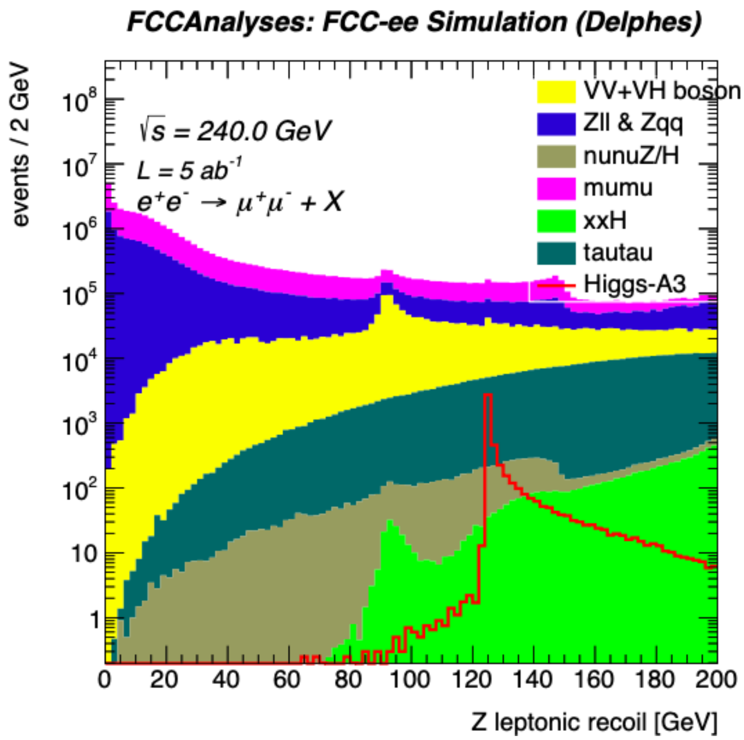


Figure 6: Recoil mass distribution

Note that there are distinguishable resonance peaks in the background decays at 91 GeV as well as 125 GeV, corresponding to the Z and Higgs respectively. For the signal specifically, we see only a peak at the Higgs mass, which logically follows from the expectation that this process involved only the production of a Higgs recoiling against the ALP. Otherwise, the background decays have a rather broad distribution in this histogram indicating that while a preferential amount of decays occurred from expected bosons, a large amount of the muon producing decays were from other particles or virtual particles mediating the decays.

We run our analysis in consecutive steps, each of which will makes additional cuts as well as save different information regarding each event that will be of interest for the sake of comparison. Utilizing the specified software framework from the 'Methodology' section, we can make several immediate selections on the parameters of our signal. We set in the first stage of the selection that we are interested in the pseudoscalar at a light mass, in this case we set the ALP mass to 5 GeV. This makes it such that in our $H(a \to \mu\mu)$ decay, our a particle has a mass of 5 GeV. This can be seen quite easily if we simply plot the mass for each decay:

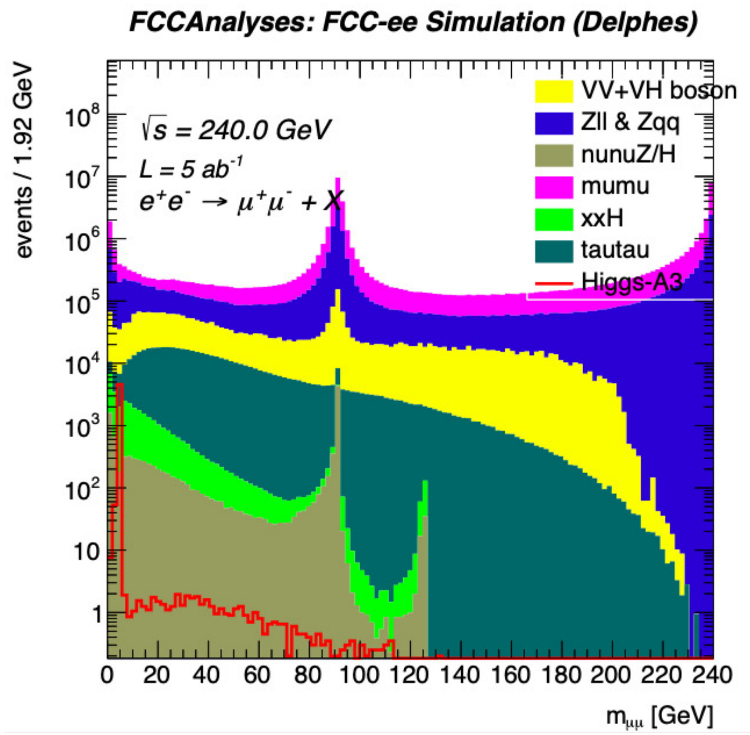


Figure 7: Histogram of the invariant mass of decay particles; it is important to note here that the signal is clearly seen with a resonance peak at 5 GeV.

When looking at the mass of the decays, it is clearly obvious that there is a peak for many of the background processes at around 91 GeV which is indicative of the Z boson mass, while for the few background processes in which e^+e^- produces a Higgs, we see a resonance peak at 125 GeV which is the characteristic mass of the Higgs as we would expect. In addition, we see that at the end of the plot the number of events steeply falls off for most processes as the center-of-mass energy of 240 GeV is met.

With this being said, at the lowest bounds of the histogram, nearing the resonance peak of our particle of interest, we see an amalgamation of background data spiking all the way to somewhere between 10^5 and 10^6 events per 2 GeV. This is where it becomes clear that we must make further cuts on the data in order to get a more pronounced signal in comparison to the chunks of background data. To do so we must think about the process of interest itself. While most of the background decays have varying decay products, we know that for our process we expect quite restrictively a decay of "a" into $\mu^+\mu^-$ where we have two oppositely charged muons as the products of our ALP. By simply applying a filter on the charge where the sum of charge for our product muons is equal to zero and zooming in to the zero to 20 GeV range, it is clear that our picture is immediately improved, with much less background at the lower mass range. This can be seen in Figure 8.

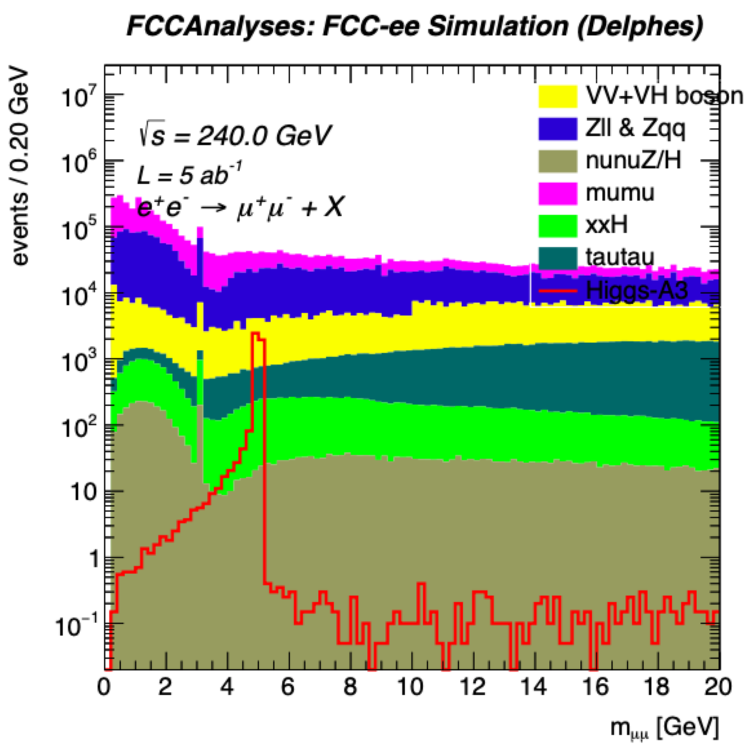


Figure 8: Histogram of the invariant mass of decay particles; it is important to note here that, compared to Figure 7, below 5 GeV we have a reduction of background and our resonance peak becomes more prominent.

With this we see that it is necessary to make cuts and selections on our data in order to determine what exactly allows our signal of interest to be analyzed with as little background overlap as possible. It is also worth noting that the background processes were cut by roughly two orders of magnitude with the addition of the charge selection, while the magnitude of our signal peak did not change. This immediately makes the process of interest more prominent in comparison to the other information at the same collision energy.

In the context of particle physics, ΔR is a quantity that is roughly defined as the angular distance between two particles in the $\eta - \phi$ space, where η is defined as the pseudorapidity, and ϕ is the azimuthal angle with respect to the beam line. In this sense, pseudorapidity is defined as $-ln[tan(\theta/2]$ where θ is the polar angle with respect to the beam axis [24].

We can use this value in order to further select on the detected muons from our simulated detector. Running analysis selections as specified above with charge and resonance mass, we can produce figures for both the ΔR of the simulated decay muons before reconstruction and after:

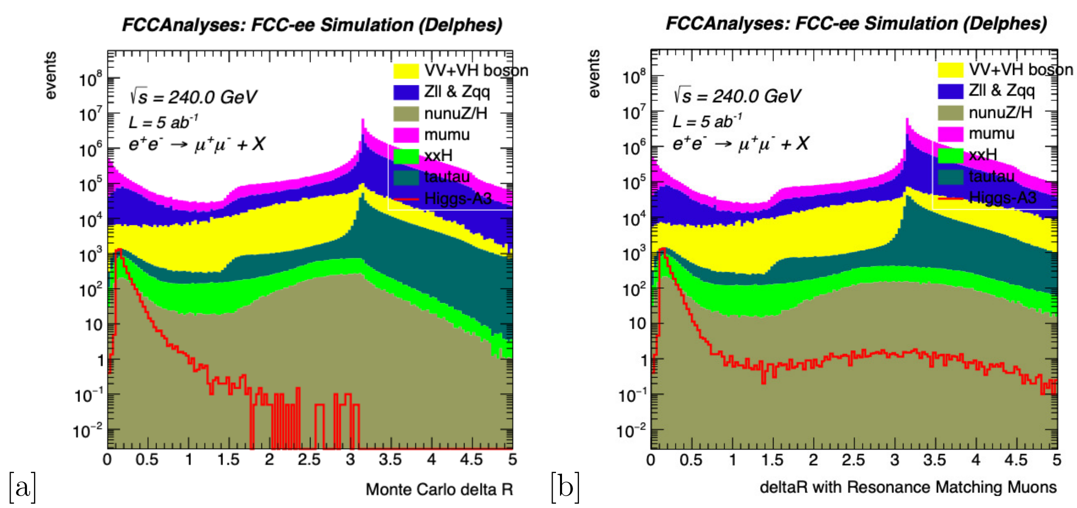


Figure 9: (a) Generator-level muon ΔR (b) Reconstructed muon ΔR

Here we have two cases of calculating ΔR, one taken from the Monte-Carlo generated 4-vectors directly and the other from a reconstruction of the detected muons. Here we have filtered in the case of the reconstruction for muons that specifically fit the resonance mass requirement that the two detected muons sum as close as possible to the 5 GeV of their ALP parent particle. With this reconstructed ΔR, we see as we did in Figure 8 a peaking distribution. In this case, our process peaks at a low ΔR of roughly 0.2 radians. This resonance peak is visible over $\nu\nu H/Z$, qqH, $\mu\mu H$, eeH, and ZH decays.

This is extremely useful, for this implies that by selecting for processes based on their ΔR, this framework allows us to see our signal over about half of the relevant background decays for a 240 GeV center-of-mass energy collision.

As we see, we still need to make further cuts to show our signal over some of the other background processes. The next thing we will look at is the acoplanarity of the particles. The acoplanarity of the two muons that reconstruct our ALP is the angle between the two planes defined by the two particles and the beam axis [25]. Implementing in our analysis a selection that allows us to graphically view the acoplanarity of our chosen processes, we can see the following:

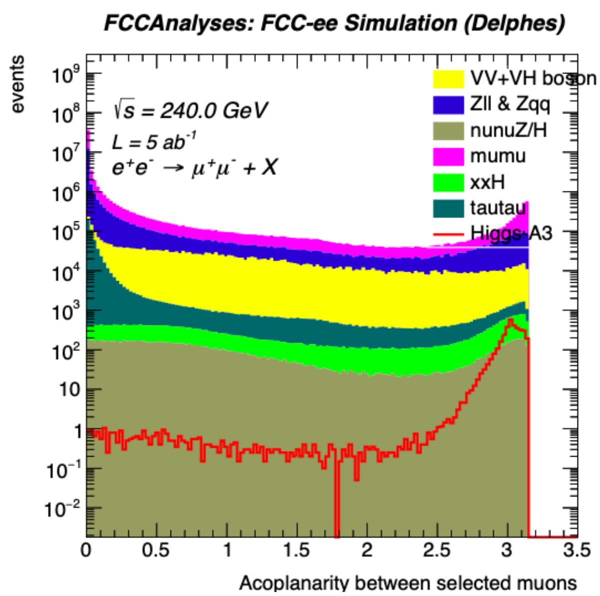


Figure 10: Here we see that our background processes have a relatively broad distribution for their acoplanarity angle, while our process has distinct peak

By analyzing this trend in our reconstructed data, we can further implement a filter on the overall processes we are interested in, here we choose that we are only interested in the processes where their reconstruction provides us an acoplanarity of between 2.7 to 3.2 radians. By then looking at the mass of our reconstructed particle data in Figure 11, we see that there is a reduction in ZZ, WW, and ZH processes, denoted as 'VV' bosons in the legend of Figure 11.

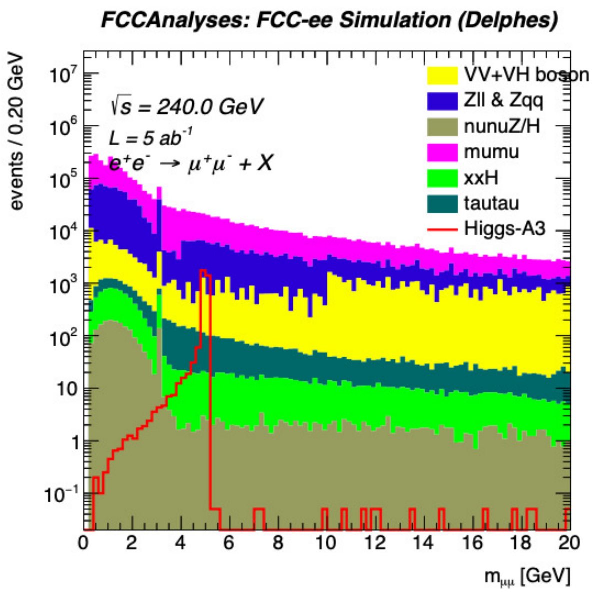
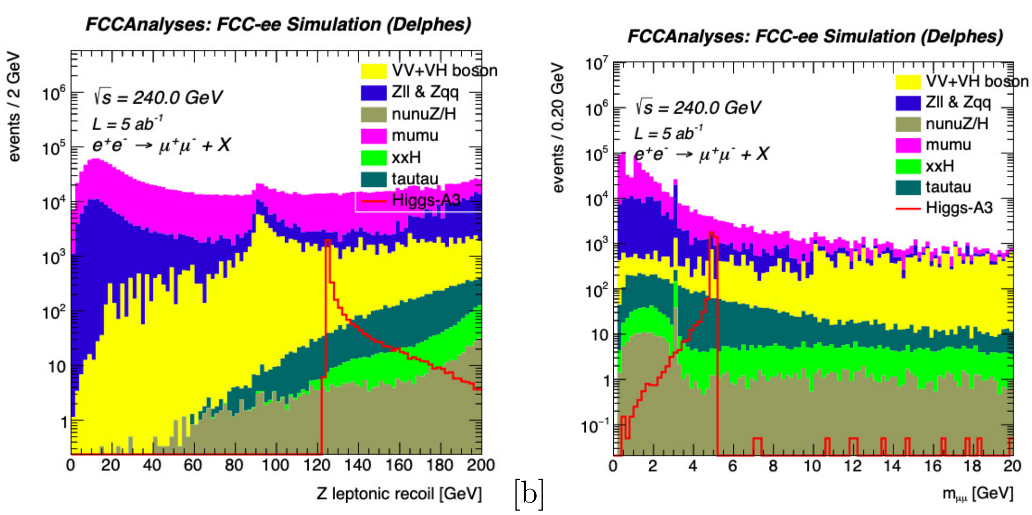


Figure 11: It is clear here that our signal peak has stayed relatively level to what we saw in Figure 8, but the background, specifically what we define as 'VV+VH' bosons have a clear decrease.

It makes sense to use acoplanarity for our process in comparison to heavy boson processes, since the angle between our signal legs is much smaller than if the two muons decayed from a heavy boson. It also is pretty clear that by selecting for two oppositely charged muons for the reconstruction we can cut out muons from different decaying particles since our process ALP decays quite clearly to those exact products.

Now, we have the issue of the $\mu\mu$ decay processes as well as the Zll and Zqq decays. Both of these have still not been cut on much, and our resonance peak at 5 GeV is relatively buried underneath the reconstructed data for those processes. Another major cut we can make on the data is motivated by the strong resonance peak at 125 GeV of our leptonic recoil mass as seen in Figure (12.a). Leptonic recoil mass in this sense is the detector reconstructing the parent particles of the detected muons by combining the energy and momentum vectors of the products into their parent invariant masses. This is why in Figure (12.a) our signal has a resonance at 125 GeV, where the Higgs mass is expected, and nothing below that, and all other included processes have a broad range of reconstruction at lower masses than the signal. Most notably, we can see slight peaks at Z and W boson masses and a lot of low-mass background reconstruction, which drastically differs from our signal.

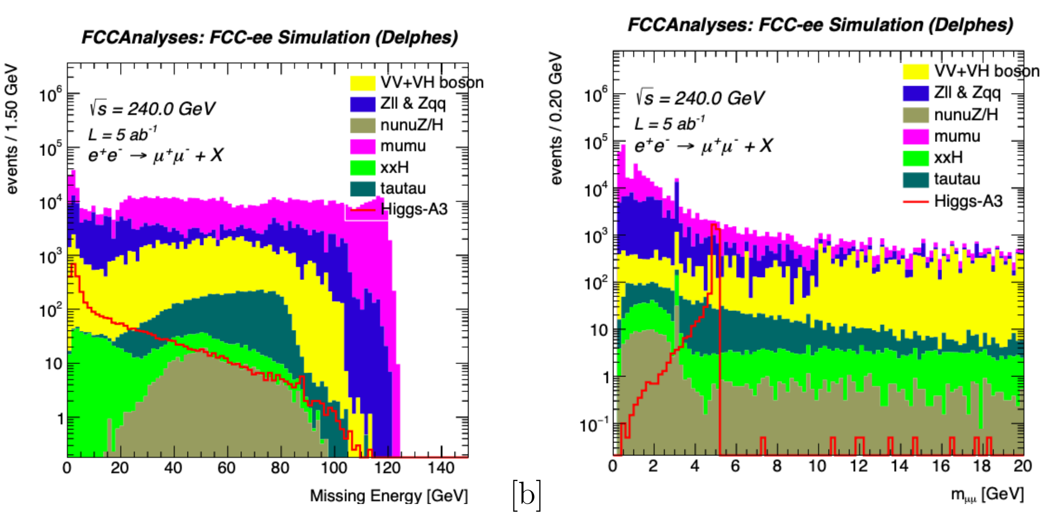


[a] [b]

Figure 12: (a) Post-acoplanarity filter leptonic recoil mass (b) Reconstructed particle mass in events following a cut on the leptonic recoil mass

At this point we have managed to filter out both the *Zll/qq* decay processes using the requirement on the leptonic recoil [26]. Our resonance peak at 5 GeV is still quite prominent and actually rises above the data from all other processes at its respective mass resonance except for that of the di-muon decay process.

Similarly, missing energy can be defined as the amount of energy that is not accounted for by the detected particles in a collision event [27]. Since we have a clear understanding of the products of our decay process, we would not anticipate a significant amount of missing energy. However, in the case of background events, bosons can decay in various ways, leading to the loss of more energy during the decay process. Thus, we are motivated to introduce an additional filter on the reconstruction process that limits the missing energy to less than 60 GeV. Figure (13.a) illustrates that our signal exhibits a resonance peak well below this threshold, whereas other decay modes such as $\tau\tau$, ZZ, WW, ZH, $\nu\nu Z/H$, and qqH display broad distributions of missing energy between 40-100 GeV. By imposing a cut above 60 GeV, we further reduce the backgrounds, enabling our signal to almost surpass that of the largest background, namely $\mu\mu$.



[a] [b]

Figure 13: (a) Post-recoil mass filtered missing energy (b) Reconstructed particle mass in events following adding a cut on the missing energy

To reiterate, in order to cut on the chosen backgrounds in this paper, we have made general selective cuts based off of the properties of only our signal as well as further filtering cuts to target high statistic background processes. These cuts can be summarized by the Table 14 below. As a result of each of these cuts, we systematically are able to improve the statistical significance of our signal process at 5 GeV compared to the defined background processes.

	Cuts	Explanation For Filter
General Selections	Number of muons ≥ 2	Follows from signal decay
	$\mu_1 + \mu_2$ charge $= 0$	Signal decay specifies $\pm$ pair
Background Filters	Acoplanarity ≥ 2.7	180° production in center-of-mass frame
	Recoil Mass ≥ 100 GeV	Known signal decay; Higgs and high-energy muons
	Missing Energy ≤ 60 GeV	Little to no missing energy for signal

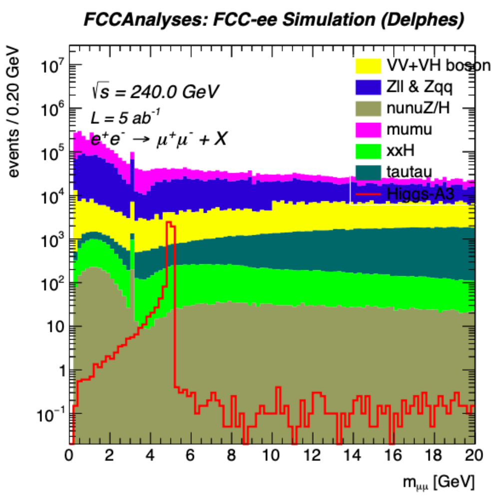
Figure 14: Cuts used in our decay reconstruction, including both the general purpose cuts as well as the background focused filtering

6 Conclusion

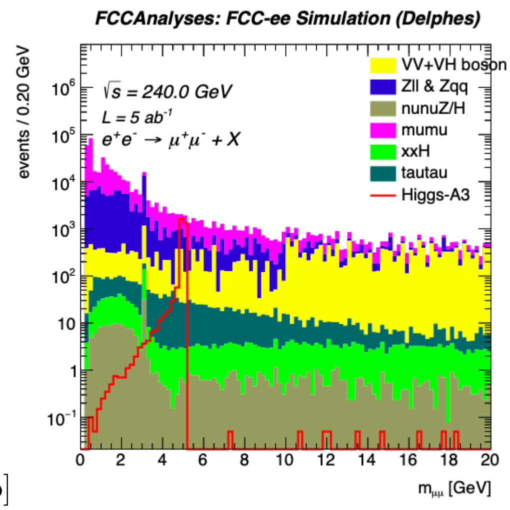
In the interest of analyzing beyond standard model processes, the software framework for FCCAnalyses [8] working in conjunction with DELPHES [16] for simulation as well as PYTHIA [12] for Monte Carlo event generation can be used to compare and analyze chosen event decays.

Through our analysis of $e^+e^- \to H(a \to \mu\mu)$ at 240 GeV center of mass energy, we find that the other backgrounds around 240 GeV can be placed through several selections that when combined, allow for detection of a proposed low mass ALP. For our analysis specifically, we chose to select on a few major things, prefacing by cutting on the sum of charge for the two muons used for reconstruction.

Then, by filtering our data based off of the acoplanarity, leptonic recoil, and missing energy of the reconstructed particles, we were able to cut down all background processes by at least two orders of magnitude, while keeping the signal relatively untouched by the chosen selections.



[a]



[b]

Figure 15: (a) Reconstructed particle mass prior to selections (b) Reconstructed particle mass after all selections and filters are instantiated

From Figure 15 we see that our selections made a massive improvement on the signal's resonance peak in relation to large background sample information. All of our background processes ran with a sample size of at least 10^7 while our signal was generated with 10^5 events, and by the time all of the selections ahve been applied, the signal peak at 5 GeV is almost visible above even the $\mu\mu$ decays. As of now, simulation analysis is still focusing on different parameters to use in order to cut WW and $\mu\mu$ decays, yet the results of our applied filters shows promise in the way of searching for highly boosted pseudoscalar particles.

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