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Report

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Title

Search for a photophilic scalar mediator between standard model and dark sector particles in di-photon final states

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Table of Contents

Table of Figures and Table

I. Introduction

The strong CP violation and Dark matter are two important and theoretically compelling issues in modern particle physics and cosmology and the concept of axion-like particle (ALPs) is an elegant solution to both. To solve the CP violation problem we introduce a scalar field. The quanta associated to this field is the ALP.

By proving the existence of these quanta we open the door to the dark matter sector and solve CP problem.

The Large Hadron Collider (LHC) is an energy frontier proton-proton collider, but also collides heavy ions (Pb-Pb ; Pb-p).

The large charge of heavy ions $Z = 82$, gives a huge Z^4 enhancement for the photon-photon luminosity, which can be exploited to search for new physics that couples to photons.

The project is about searching for these quanta (ALP) in di-photon final stats, using Light-by-Light scattering in heavy-ion (^{82}Pb) collision with the ATLAS detector at the LHC.

Light-by-light scattering can be studied in $Pb - Pb$ ultra-peripheral collisions (UPCs), with impact parameters larger than two times the radius of Pb. At high energies the Pb can generate an Electro-Magnetic field up to $10^{25} Vm^{-1}$. In this case the EM fields produced by the colliding Pb nuclei can be treated as an elastic beam of photons (figure 1).

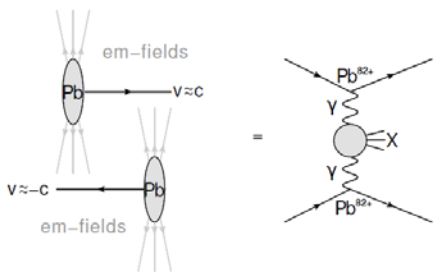


Figure 1: Light by light scattering

The Integrated luminosity used in our analysis is 480 μb^{-1}.

The scalar ALP can couple to the electromagnetic field (photon), by the following Lagrangian density [1]:

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}M_{ALP}^2\phi^2 - \frac{1}{4\Lambda}\phi F^{\mu\nu}F_{\mu\nu}$$

where ϕ is the ALP field, M_{ALP} is the mass of ALP in the range of 5 to 20 GeV. This range is fixed by looking at the exclusion limits from pervious experiments [1], $\Lambda = 1$ TeV is the inverse coupling constant and finally $F^{\mu\nu}$ is the electromagnetic field strength tensor.

The decay width of the ALP into photons is [1]:

$$\Gamma(ALP \to \gamma\gamma) = \frac{\frac{1}{64\pi}M_{ALP}^3}{\Lambda^2}.$$

And we have verified this quantity using Mathematica.

II. ANALYSIS

1. Backgrounds

In this section I discuss the background process considered in this analysis. As our research is based on di-photon final states. All SM processes that give di-photons in the final state are considered background processes.

The principle backgrounds are the Standard Model (SM) processes:

$$\gamma\gamma \to \gamma\gamma \ (irreductible)$$

$$gg \to \gamma\gamma$$

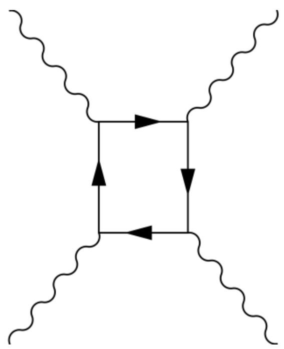


Figure 2 : standard model light-by-light scattering, possible with any charged particle in the loop

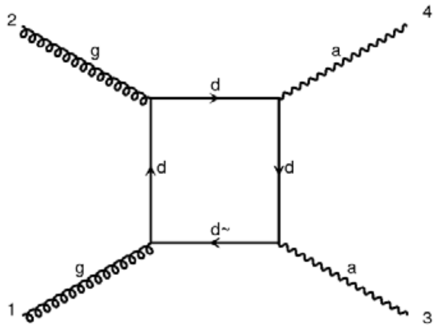


Figure 3 : $gg \to \gamma\gamma$, *this can be done with all quarks*

The second background is the miss identification of electrons as photons in the EM calorimeter (experimental background). For high photon energies the efficiency to detect electrons as photons is about 0.03%, with 40% to detect photons as photons.

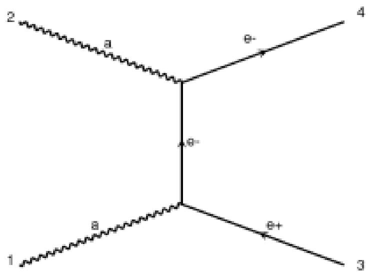


Figure 4 : $\gamma\gamma \to e^+e^-$

2. Signal Simulation

The coupling of ALP is described by the previous Lagrangian; we are using this Lagrangian to simulate the light-by-light scattering via ALP exchange using the MadGraph Monte Carlo (MC) [9], generator with different masses $M_{ALP} = \{5{,}10{,}15\}\ GeV$, and $\Lambda = 1\ TeV$ and with center of mass energy $\sqrt{s} = 13TeV$. To construct the ALP model Feynrules is used [3].

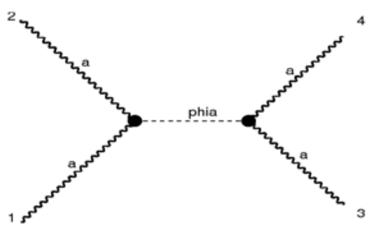


Figure 5 : Ligh-by-light scattering via ALP simulated with MadGraph

The simulation was done without any parton shower because we are interested in events where the initial state stays intact. Only then is it possible to identify the photon initial state. ExRootAnalysis is used to convert the LHE output from MadGraph to Root files to use it with RootCore which is the framework used in this analysis [4]. To obtain fully simulated and reconstructed events we looked for a method to convert LHE files to EVNT file without using Pythia8 as parton shower, for use with the Athena framework for reconstruction. This proofed to be difficult; therefore we have used a simple idea to get the reconstructed information in our analysis. This idea will be described in the next section.

3. Event Selection

In this part we discuss the strategy used to reduce the background.

First, the selected events are required to have exactly two photons. In the case of more than two photons we studied the case of tree photons, doing all the possible combinations to calculate the invariant mass of the di-photon system. In thess events two photons can be very close together ($\Delta R\ very\ small$). These two photons seem to originate from one primary photon and their energies should be combined.

To reduce the experimental background we do a veto on charged track particles with P_T larger than $100\ MeV$. This requirement reduces significantly the experimental background. To reduce the background from $gg \to \gamma\gamma$ and SM $\gamma\gamma \to \gamma\gamma$ reactions, an additional cut on di-photon Acoplanarity is applied. The Acoplanarity is defined as [2]:

$$Aco = 1 - \frac{|\Delta\phi_{\gamma\gamma}|}{\pi} < 0.01.$$

This requirement is optimized to obtain a high signal efficiency and to reduce the principal background; this cut is powerful to discriminate between the SM signal and ALP signal.

We show bellow the table of cut efficiencies:

	$\gamma\gamma \rightarrow \gamma\gamma$ (SM)	$gg \rightarrow \gamma\gamma$	$\gamma\gamma \rightarrow e^-e^+$	$MC\ ALP\ Signal$
$Charged\ Track$	79%	78.8%	6%	100%
$Aco < 0.01$	97.20%	12.1%	2.5%	100%
$Total$	76.95%	9.5%	0.15%	100%

Table 1 : cuts efficiency

As for the MC signal the reconstructed information is not available our analysis is based on truth information for all samples, once for all ALP masses the cut efficiency is still 100%. For the reconstructed information just the Acoplanarity cut's efficiency will be changed to a higher value (more than 0.01).

4. Background + Signal

In this part we show some plots for the background and signal distributions after each cut for different ALP masses. We show the number of signal events divided by the square root of the sum of background events and signal events $\alpha = \frac{S}{\sqrt{\{S+B\}}}$ [5];

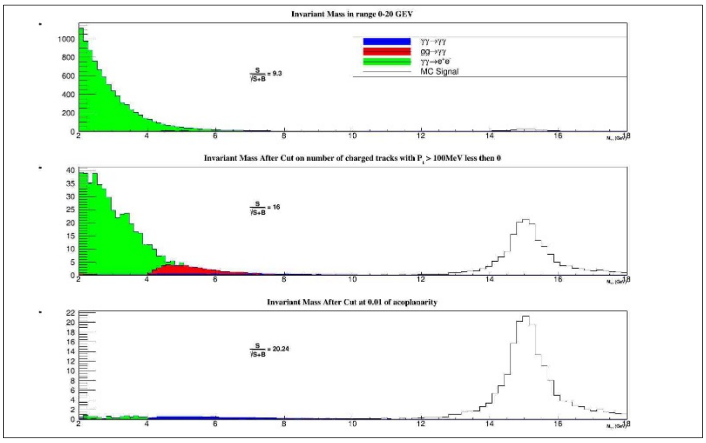


Figure 6 : Background + MC signal with $M_{ALP} = 15\ GeV$

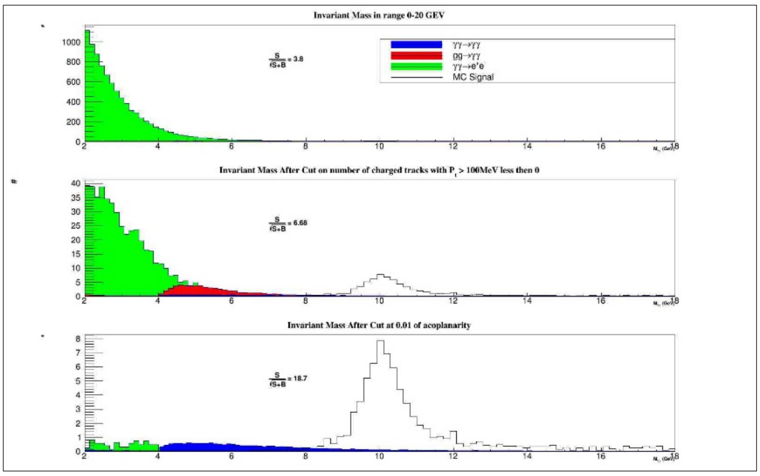


Figure 7 : Background + MC signal with $M_{ALP} = 10GeV$

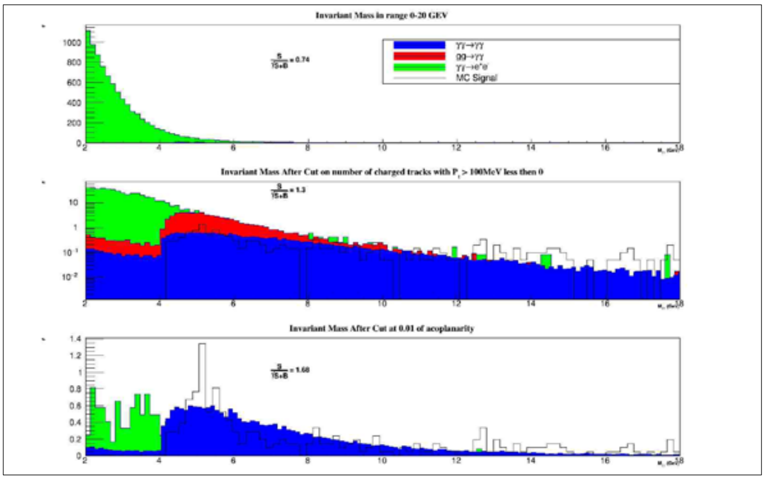


Figure 8 : Background + MC signal with $M_{ALP} = 5GeV$

To see clearly these plots go to appendix A.

In these plots we show the invariant mass for the di-photon system $M_{\gamma\gamma}$ (GeV) on the x-axis and the number of event on the y-axis. All the samples are normalized to the luminosity of $Pb - Pb$ collision for 480 μb^{-1}. For the experimental background the cross section is 171 μb for 1M events, the SM signal has 147nb as cross section and 95k events and for $gg \rightarrow \gamma\gamma$ the cross section is 440nb and 50k events, for the MC signal we have used 5nb for the cross section and 50k events [8].

III. Reconstruction

For the reconstruction information the idea used is to get the detector resolution for each parameter used in the cuts, which correspond to the standard deviation of the difference between the truth and reconstructed information from the MC signal ($\gamma\gamma \rightarrow \gamma\gamma$) plots. Then all points in the parameters histograms are replaced with a number drawn from a Gaussian distribution where the mean is the truth value and the standard deviation is the detector resolution on this parameter.

For the di-photon invariant mass we find that the resolution is 1.12 GeV, and for the Acoplanarity the resolution is 0.009.

This method is not very adequate for the full analysis, but it's give an overview about the reconstructed distribution.

Bellow we show the distribution before and after smearing.

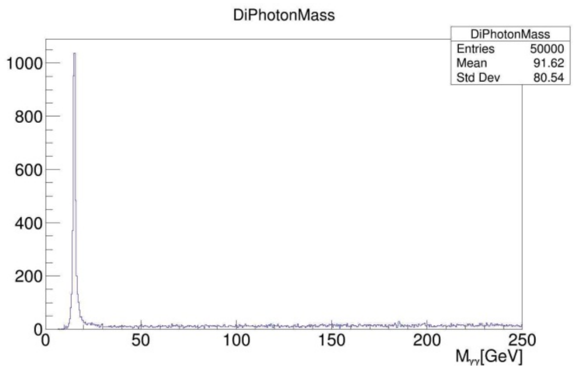


Figure 9 : Truth di-photon invariant mass $M_{\gamma\gamma}$

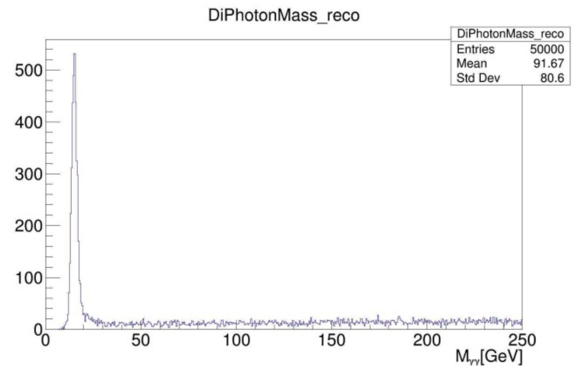


Figure 10 : Reconstruction di-photon invariant mass $M_{\gamma\gamma}$

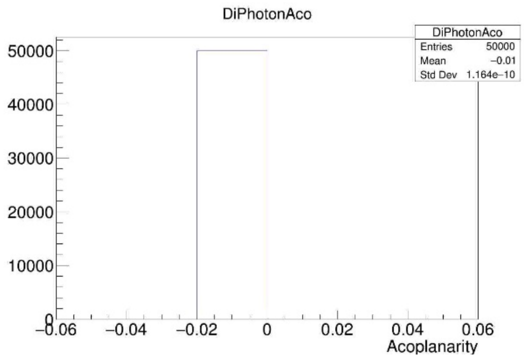


Figure 11 : Truth Acoplanarity

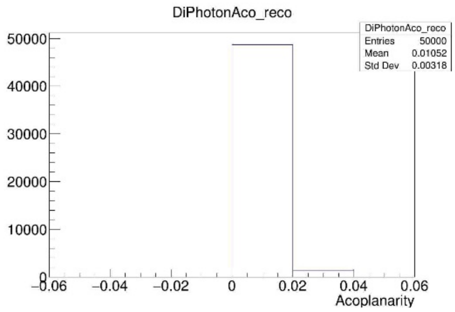


Figure 12 : Reconstructed Acoplanarity

As you can see there is not much difference between the truth and the reconstructed information. For the Acoplanarity the cut value will be changed to 0.02 this value has not a very important impact on the background reduction.

IV. Pseudo Data

In this section I will discuss our test for the cuts on the pseudo data, this pseudo data is constructed from all background and 20% of signal for each ALP mass. We have used `HistFitter` [7,8] to fit pseudo data on the signal and get the p-value of the estimated signal strength parameter μ_{sig} given the observed data in the signal regions. In addition HisFitter can calculate an upper limit on the signal strength.

HistFitter used the Likelihood method to estimate μ_{sig}, and the ordinary least square included in `Minuit2` package. For the exclusion test HistFitter used Likelihood Ratio to test the signal strength with 95% of confidence level (CL), and set an upper limit on the signal strength parameter (μ_{sig}).

The obtained upper limit on the signal strength can easily be converted into an upper limit on the excluded cross section of the signal model tested.

In the following we show the plot before and after the fit of pseudo data on the signal.

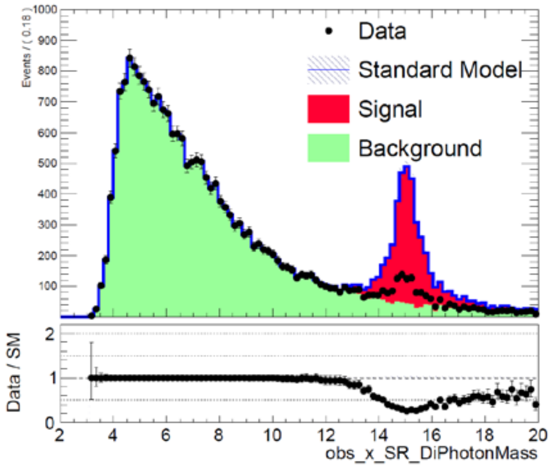


Figure 13 : pseudo data before the fit for $M_{ALP} = 15\ GeV$

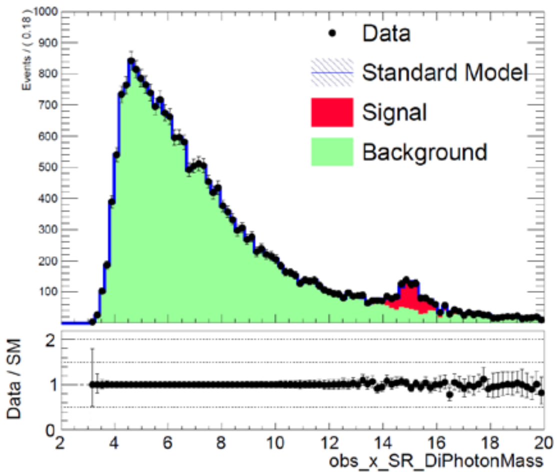


Figure 14 : pseudo data after the fit for $M_{ALP} = 15\ GeV$

The fit works nicely and `HistFitter` recovers the same amount of signal used to construct the pseudo data which is 20%. We do the same thing with all M_{ALP} mass.

For the MC signal with $M_{ALP} = 5GeV$, the expected upper limit on the signal strength μ_{sig} is $0.749 \pm\ 0.013$.

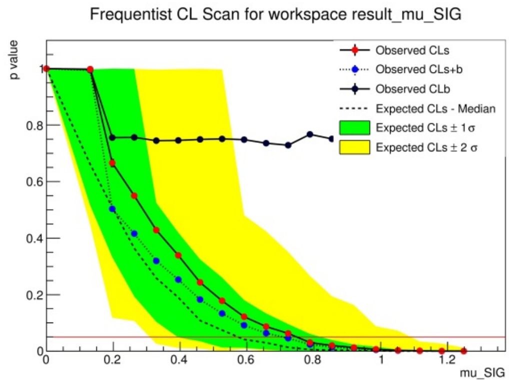


Figure 15 : p-value

This correspond to the point where the p-value goes below 0.05 (95% CL) which correspond the red line excluded at 95% CL.

V. Conclusion and Outlook

In the light-by-light scattering process, the axion like particle can be produce with a very low cross section (estimated using MadGraph), that make discovery of this particle difficult.

There is many case to studies in this process, in our analysis we have interested in mass range 5-20 GeV and the QCD axon is a very light particle in order of KeV, also in selected photons we have neglect all photons which close together in the case of events with more than two photons.

As an outlook, look to real data is the first things we can started with to qualify our job and used HistFitter to fit the real data with background and signal.

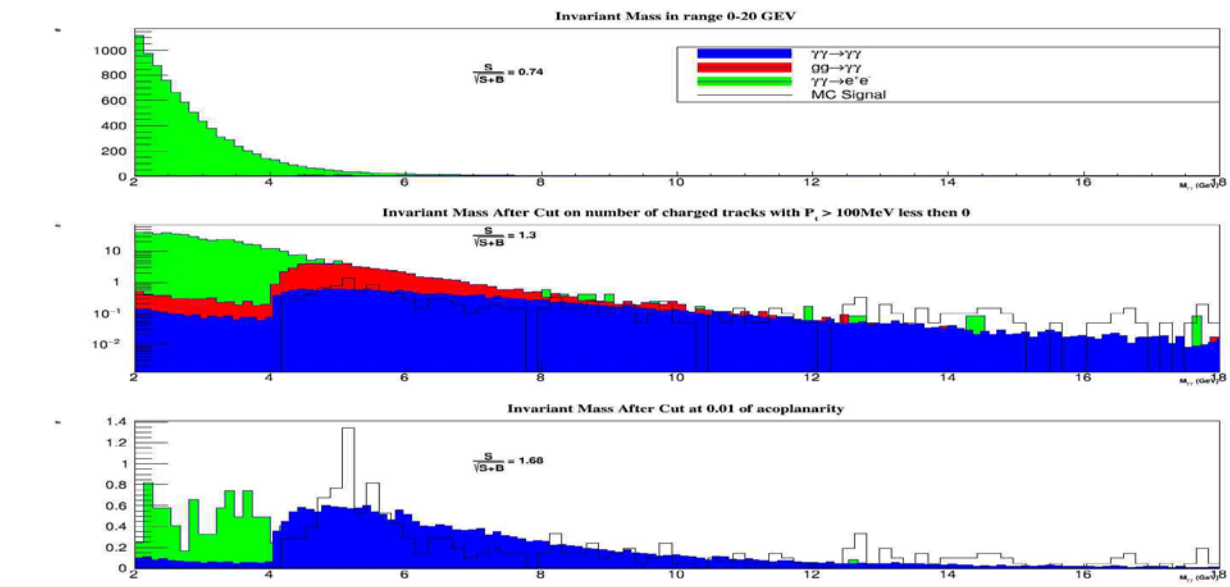
VI. Acknowledgements

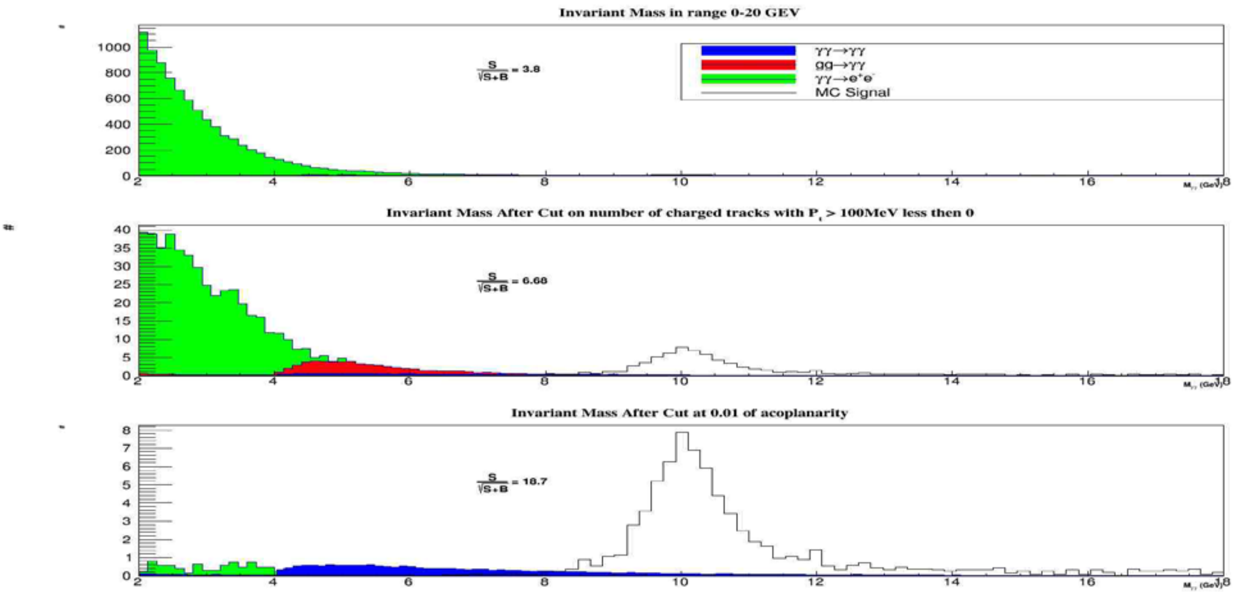
This project was very helpful for me as a master degree student in high energy physics and with outlook to join the ATLAS collaboration. I acquired in this project very import experience, in data analysis and improved my skills in ROOT, C++ OOP, particle physics, and more. An introduction into Monte Carlo simulation was very interesting for me. First experience in using Athena packages will also be very helpful.

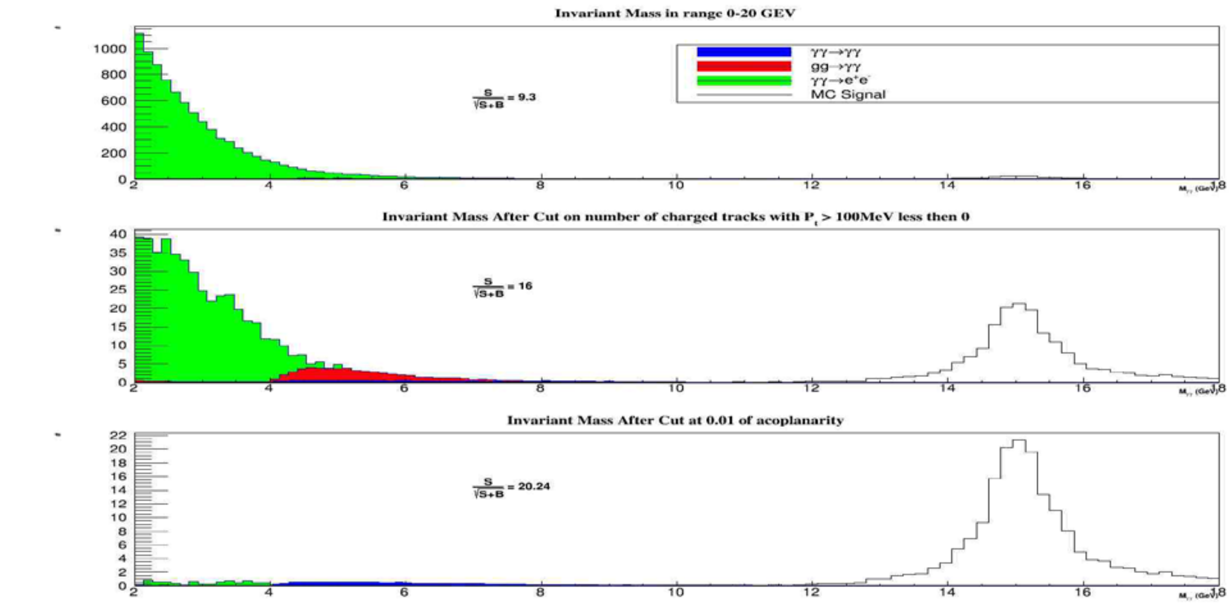
Finally, the more important experience is the idea how a complete data analysis is done with all different steps.

When finalizing this this project, the best things that can happen is the discovery of an ALP, if not an improved limit on the cross section can be set.

Appendix A


Invariant Mass in range 0-20 GEV
S/√S+B = 0.74
γγ→γγ
gg→γγ
γγ→e+e-
MC Signal
Invariant Mass After Cut on number of charged tracks with Pt > 100MeV less then 0
S/√S+B = 1.3
Invariant Mass After Cut at 0.01 of acoplanarity
S/√S+B = 1.68


Invariant Mass in range 0-20 GEV
S/√S+B = 3.8
γγ→γγ
gg→γγ
γγ→e+e-
MC Signal
Invariant Mass After Cut on number of charged tracks with Pt > 100MeV less then 0
S/√S+B = 6.68
Invariant Mass After Cut at 0.01 of acoplanarity
S/√S+B = 10.7


Invariant Mass in range 0-20 GEV
S/√S+B = 9.3
γγ→γγ
gg→γγ
γγ→e+e-
MC Signal
Invariant Mass After Cut on number of charged tracks with Pt > 100MeV less then 0
S/√S+B = 16
Invariant Mass After Cut at 0.01 of acoplanarity
S/√S+B = 20.24

Reference

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