The Data Science of Particle Physics

Module within AIMS AI for Science Msc.
Introductory notes and assignment guidelines
(2 page max) write-up to be submitted by agreed deadline.

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1 Introduction

The field of experimental particle physics explores nature at the smallest scales by studying the properties and interactions of elementary particles. In a somewhat brutal, but outrageously successful approach, particle physicists collide particles at extremely high energies. As Einstein famously clarified, energy and mass are equivalent. Therefore an energetic collision can produce a particle with a much greater mass than that of the colliding particles. The most energetic collider ever built is the Large Hadron Collider at CERN, Geneva. It collides protons at energies up to 13 tera electron volts (TeV), and has the potential to produce new particles with masses at the TeV-scale predicted in theories such as Supersymmetry, Extra Dimensions, and the various models of Dark Matter. The essence of experimental particle physics is the analysis of the data produced by these collisions. Decades of steady progress in this field has led to a deep understanding of nature at quantum level that is encapsulated in a theoretical framework known as the Standard Model (SM). The SM accounts for three of the four fundamental interactions of nature as well as the generation of masses for the elementary particles. Even though its Lagrangian is short enough to fit on a coffee mug (see Fig. 1), its predictions have been experimentally confirmed to an extraordinary degree of precision. One of these predictions is that a particle, known as the Higgs, boson should exist. The Higgs boson is the excitation or quantum of an underlying, all-pervasive Higgs field. The SM explains the masses of the fundamental particles as arising from their interaction with this Higgs field. Let's stop to think about this for a moment. Without the Higgs field, all fundamental particles would be massless and do what massless particles do: travel around at the speed of light. This would have catastrophic consequences for the universe as we know it. For example, a massless electron would not find a stable orbit around a proton, therefore no atoms could form. Needless to say, the action of Higgs field in generating particle masses is extraordinarily important. Therefore it was one of the greatest scientific discoveries of the past century when, in July 2012, the ATLAS and CMS experiments at CERN jointly discovered the Higgs boson.

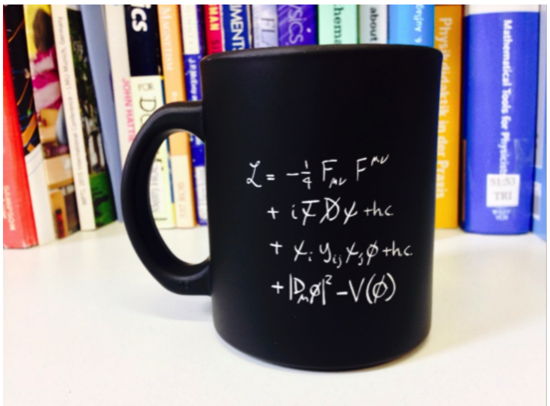

Figure 1: Left: The SM Lagrangian on a coffee mug. Right: The ATLAS experiment under construction around 2005. Don't worry, the dude was safely removed before LHC was turned on.

In this mini-project, we will use real 13 TeV proton collision data to learn how experimental particle physics works and attempt to rediscover the Higgs boson.

2 The ATLAS experiment and Open Data

The ATLAS experiment at CERN is the largest particle physics experiment ever built. Between 2015 and 2018, ATLAS recorded the largest and most energetic proton collision dataset ever. It consists of ≈ 140 $fb{-}1$[1] of proton collisions at 13 TeV, and it yields incredible potential to increase understanding of the universe at the smallest of scales. In January 2020, ATLAS released 10 $fb{-}1$ of this data to the public along with extensive software tool and example analyses. You can find much more detail about ATLAS Open Data at [1]. Let me emphasise, this is **real** data. This exact data was used countless physics publications since it was recorded in 2016. The ATLAS experiment released this *Open Data* earlier this year so that anyone can learn how important scientific advancement such as the Higgs discovery work and to inspire the next generation of particle physicists[2].

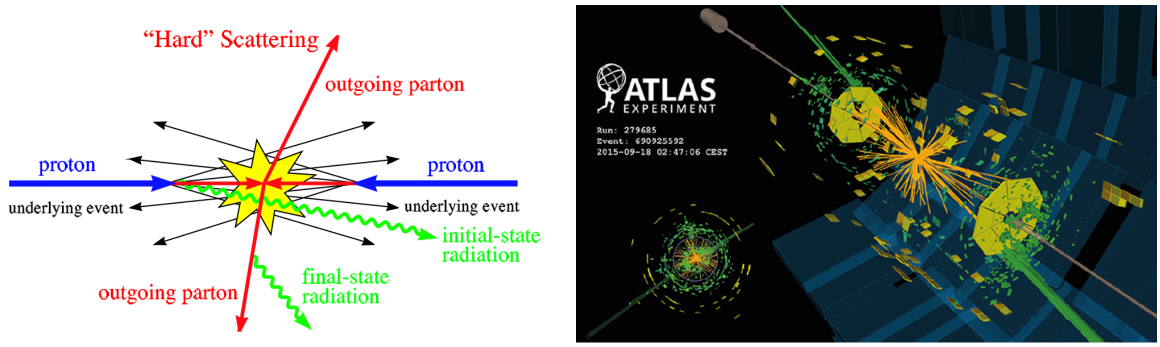

Figure 2: Left: A sketch of a typical proton collision within ATLAS. Right: a computer-generated, 3D, illustration of a read proton collision and resulting particles in the ATLAS detector.

To understand what information is available in the Open Data, we need to learn a bit about how ATLAS works. So let's start at the start, with a high-energy proton collision. It looks a little something like the left-hand image in Figure 2. Two protons, each with kinematic energy of 6.5 TeV, collide approximately head-on, at the centre of the ATLAS detector, yielding a total centre-of-mass energy of 13 TeV. We know that protons are composed of three quarks. However, at high energies the color charge of these quarks cause them to interact with each other by exchanging gluons. Therefore each colliding proton behaves more like a bag of quarks and gluons, collectively known as partons. It is these partons that provide the collisions we are interested in. In the diagram shown in 2, a parton collision has produced two new partons that travel out from the collision point. As partons are electrically-, weakly- and color-charged, they will continue to radiate other particles and interact until stable, colorless hadrons are formed. This is an incredibly complex and not fully understood process, but the bottom line is, a single LHC proton collision can result in a huge amount of particles being produced within ATLAS. The ATLAS detector attempts to detect, identify, and measure the momenta and energies of each of these particles. To do this, we need a big detector. To give you a sense of the scale of the ATLAS detector, a photo is shown in figure 3.

In ATLAS we use a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector where the protons collide, and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse (x-y) plane, ϕ being the azimuthal angle around the z-axis and r being the distance from the z-axis in the transverse plane. The pseudorapidity (η) is defined in terms of the polar angle (θ) as $\eta = ln[tan(\theta/2)]$. Transverse momentum and energy are defined as $p_T = psin\theta$ and $E_T = Esin\theta$, respectively. The kinematics of all particles measured in ATLAS are usually expressed with the variables p_T , η, and ϕ. In figure 3 an illustration of this coordinate system is superimposed on a diagram of the ATLAS detector.

[1] We refer to the size of a dataset in particle physics as its integrated luminosity. If the number of times a given process is observed (N) is given by $N = \sigma * L$ where L is the integrated luminosity and the cross section, σ is given in barns, then the unit of integrated luminosity is inverse barns b^{-1}. Such is the enormity of the datasets at the LHC, that the unit of inverse femtobarns fb^{-1} is more commonly used ($1\ \mathrm{fb}^{-1} = 1 \times 10^{15}\ b^{-1}$).

[2] You?

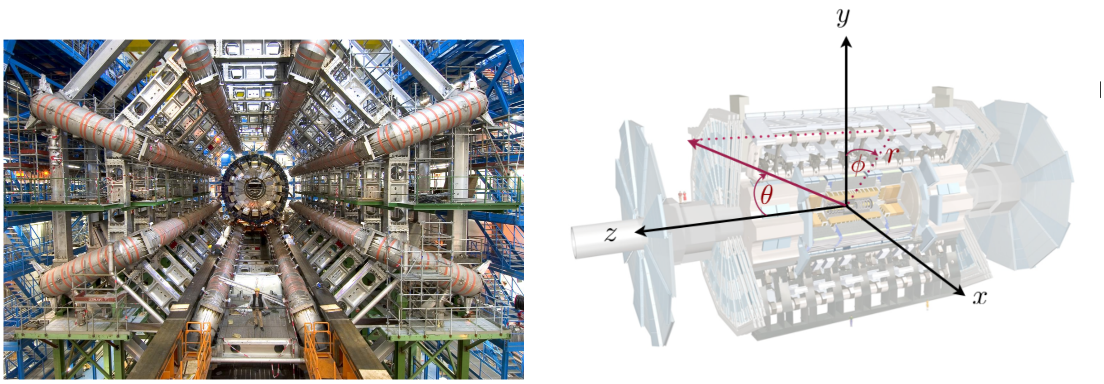

Figure 3: Left: The ATLAS experiment under construction around 2005. Don't worry, the dude was safely removed before LHC was turned on. Right: The right-handed, cylindrical coordinate system of ATLAS is shown superimposed on the ATLAS detector.

The LHC provides these collisions at a rate of about 40 MHz. That's right, one of these collisions happens about forty million times per second. The LHC and ATLAS can run 24 hours per day and more than 100 days per year. I'll leave it to you to work out how many collisions that is, safe to say it's a huge number. The problem we face as experimental particle physicists is that the vast majority of these collisions is completely uninteresting. That enormous number mainly corresponds to processes that are already well-studied from the data of previous experiments. Therefore, the basic challenge of modern particle physics is to sift through the gigantic datasets and isolate the rare and interesting processes that can further our understanding of nature. The filtering of the data to seek out interesting collisions (usually called "events") is at the heart of particle physics.

Once we are happy with the events we have selected we usually apply a statistical analysis to come up with a meaningful scientific result. This mini-project will demonstrate the both the event selection and statistical analysis. Events satisfying certain criteria have already been selected for you and only the relevant information for each event has been stored. Therefore those enormous datasets have been reduced such that you can analyse them in minutes in a web browser. In the next section we'll learn how we perform selections and analyses without installing any software apart from a web browser using a modern tool known as a *Jupyter Notebook*.

3 Jupyter notebooks

The Jupyter Notebook is web application that allows you to create and share interactive documents that contain live code, equations, visualizations and narrative text. They are ideal for simple and quick analyses of ATLAS Open Data. The Jupyter notebooks for this lab are entirely written in Python. Python's clear syntax and user-friendliness make it a great choice for statistical analysis in particle physics.

The Jupyter Notebooks can be launched with the following steps after cloning the Repository

4 Part I: Measuring the Z boson mass

In your particle physics studies, you will have learned that there exists a heavy, electrically-neutral particle involved in the weak force called the Z boson. At the LHC, a Z boson is produced when a quark and antiquark from the colliding protons interact via the weak interaction. The Z boson is pretty massive, ($m_Z \approx 91200$ MeV (1 MeV $= 10^6$ eV)). Because of this large mass, the Z decays pretty much instantaneously. We do not detect Z bosons directly as they don't live long enough to traverse the ATLAS detector. Instead we directly detect the particles to which the Z decays and use the kinematic information of these *decay products* to confirm that a Z was produced. The Z can decay into a pair of quarks, neutrinos, or charged leptons. Among these possibilities, the decay to a pair of muons ($Z \to \mu^+\mu^-$) is by far the easiest to spot. Muons have a special place in experimental particle physics, they give an especially distinct signal in our detectors that is not easily mimicked by other particles. So when ATLAS says it has detected a muon, there is large probability that it has indeed detected a muon. In the left diagram of Figure 4, you will see the Feynman diagram for Z boson production with a decay to a muon pair. In the right diagram of Figure 4 you will see a computer-generated 3D visualisation of a simulated $Z \rightarrow \mu^+\mu^-$ event along with the responses of the ATLAS detector. The two red lines are the trajectories of the two muons produced in the Z decay and the green segments that intersect the red lines are the parts of the ATLAS detector that detected the muons. The thin orange lines correspond to all the other hadronic particles in the event. Most of these additional particles are uninteresting so we would like to reject them from our analysis and just select the muons. However you can see this might be difficult as there is a lot more orange lines (hadronic particles) than red lines (muons).

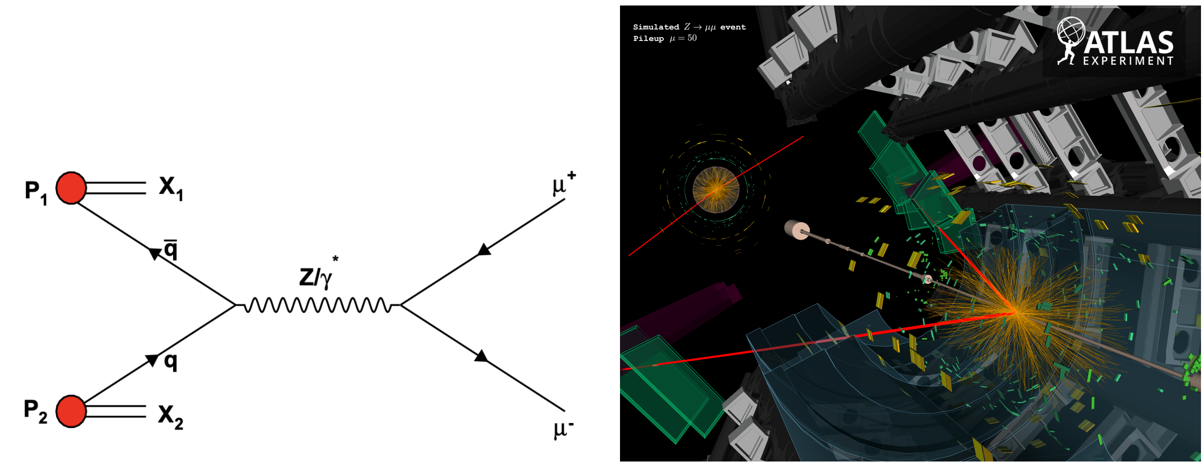

Figure 4: Left: The Feynman diagram for the process $pp \rightarrow Z \rightarrow \mu^+\mu^-$ at the LHC. Right: A 3D graphical illustration of how a $Z \rightarrow \mu^+\mu^-$ would look in the ATLAS detector.

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Therein lies the challenge of particle physics: separating the rare but interesting signal from the abundant but uninteresting background. You might notice that the Z boson itself is nowhere to be seen in the 3D illustration. This shouldn't surprise us, as we know the Z lives for such a short time that it doesn't directly interact with the ATLAS detector. All we have to go on are the two muons. However, as you may know, there are many particles that decay to muon pairs, so how do we know a Z boson was produced and not some other particle? This first part of the lab is about answering that that question. First we want to make sure we select muons that are likely to be from Z boson decay. The large m_Z mass produces muons with large p_T mostly produced in the *central* (low $|\eta|$) region of the detector, therefore we first apply appropriate criteria to select those muons. A common background to the muons from Z decay is the muons from the decay of heavy hadrons as depicted in Figure 5. These background muons are typically surrounded by other particles from the hadron decay. Therefore we require our selected muons to be isolated from other particles. This is done by defining an isolation variable I as the ratio of the summed energies of the particles in a cone around the muon and requiring it to be small for both selected muons as below.

$$I_\mu = \frac{\sum_i E_i}{p_T^\mu} \tag{1}$$

where E_i is the energy of the i^{th} particle within the cone. It is also common to sum over the p_T of the particles in the cone.

Finally, we exploit the large m_Z to identify events from the $Z \rightarrow \mu^+\mu^-$ process. As quantum processes such as the Z decay conserve momentum and energy, we should be able to write down a relationship between the four-vectors of the two individual muons and the combined $\mu\mu$ system which represents the four-vector of the decaying particle from which they arose:

$$\begin{pmatrix} E^{\mu^+\mu^-} \\ p_x^{\mu^+\mu^-} \\ p_y^{\mu^+\mu^-} \\ p_z^{\mu^+\mu^-} \end{pmatrix} = \begin{pmatrix} E^{\mu^+} \\ p_x^{\mu^+} \\ p_y^{\mu^+} \\ p_z^{\mu^+} \end{pmatrix} + \begin{pmatrix} E^{\mu^-} \\ p_x^{\mu^-} \\ p_y^{\mu^-} \\ p_z^{\mu^-} \end{pmatrix} \tag{2}$$

As the ATLAS detector measures the four-vectors of the μ^+ and the μ^-, we *reconstruct* the four-vector of the $\mu\mu$ system by simply adding the two four-vectors. This, in turn allows us to calculate the

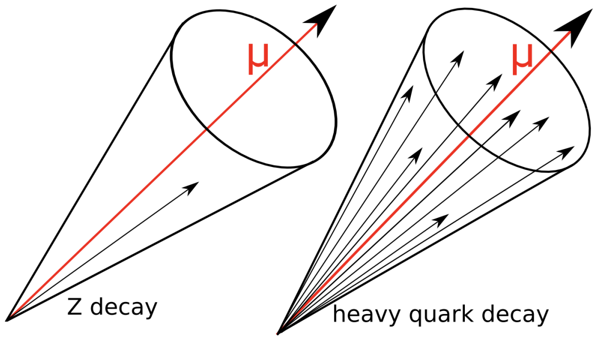

Figure 5: Muon from a Z decay (left) and heavy quark decay(right) are shown with imaginary cones corresponding to a fixed ΔR values from the muon's trajectory.

mass of the $\mu\mu$ system as special relativity showed:

$$m^2 = E^2 - \mathbf{p}^2 \tag{3}$$

One might naively expect m to be exactly equal to m_Z in every event produced by the $Z \to \mu^+\mu^-$ process. However, due to the very short lifetime of the Z and Heisenberg uncertainty principle, the values of $m_{\mu\mu}$ **approximately** (ignoring relativistic, radiative, and detector resolution effects) follows a probability distribution function (σ) given by :

$$\sigma(E_{\mu^+\mu^-}) \propto \frac{1}{(E_{\mu^+\mu^-} - m_Z)^2 + (\Gamma_Z/2)^2} \tag{4}$$

where $E_{\mu^+\mu^-}$ is the energy of the $\mu\mu$ system in the lab frame, m_Z is the mass of the Z boson and Γ_Z is the *decay width* of the Z boson. For all particles, Γ is related to the lifetime (τ) via $\Gamma = \frac{\hbar}{\tau}$. The probability distribution described by equation 4 is often call the "non-relativistic Breit-Wigner", or "Cauchy", distribution. As this function is directly available in the *scipy.stats* python package, we can use it as a convenient first guess in modelling the $\mu\mu$ mass distribution. As the only variable in equation 4 is $E_{\mu^+\mu^-}$, we expect $\sigma(E_{\mu^+\mu^-})$ to be maximised when $E_{\mu^+\mu^-} = m_Z$. In other words, the peak of the $\sigma(E_{\mu^+\mu^-})$ distribution will correspond to m_Z. This fact forms the basis of the following measurement of m_Z from the ATLAS Open Data.

In the first Jupyter Notebook ("Part1_MeasureTheZBosonMass") you will use a sample of events containing two muons to measure m_Z. As we are studying the $Z \to \mu^+\mu^-$ decay, the first thing we should look for in our events is a pair of oppositely charged particles that have been well-identified as muons by the ATLAS detector. As we discussed, the muons should have pretty large transverse momentum and low $|\eta|$. An event selection procedure has already been applied such that each event contains two particles that have been identified as muons by ATLAS, each with $p_T > 25000$ MeV. Starting from these dilepton events, we will apply a series of analysis steps towards measuring m_Z. Once we have a histogram of the $\mu\mu$ mass distribution in data, we can *fit* the cauchy model to the data and measure m_Z by **finding the m_Z value that minimises the χ^2 between the data histogram and the model prediction**.

Let's explicitly define Pearson's χ^2 in this case:

$$\chi^2(\theta) = \sum_i \left[\frac{(x_i - p_i)^2}{(\sigma_{p_i})^2} \right] \tag{5}$$

where θ is the model parameter being measured (in our case, $\theta = m_Z$) x_i is the observed number of events in the i^{th} bin, p_i is the predicted number of events from our model in the i^{th} bin and $\sigma_{p_i})^2$ is the standard deviation of p_i (otherwise known as the variance of p_i). Evaluating χ^2 as a function of m_Z not only allows us to measure a value for m_Z, it also allows a well-defined estimation of the uncertainty on this value known as a *Confidence Interval.* In many typical physics measurements, the χ^2 vs θ function will have a quadratic shape. The minimum of this function defines the measured value. The region between the points where the χ^2 has increased by 1.0 from its minimum value is called the *68%* Confidence Interval. **If we were to perform a large number of identical but statistically independent measurements, the 68% Confidence Interval would contain the true value of**

m_Z **in 68% of these experiments.**. In estimating the Confidence Interval, we are only interested in the change in this curve from its minimal value (χ^2_{min}) to ($\chi^2_{min} + 1.0$). Therefore typically the curve of $\Delta\chi^2$ vs θ is used, where $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ In figure 6, a $\Delta\chi^2$ vs θ for a hypothetical measurement is shown for illustrative purposes.

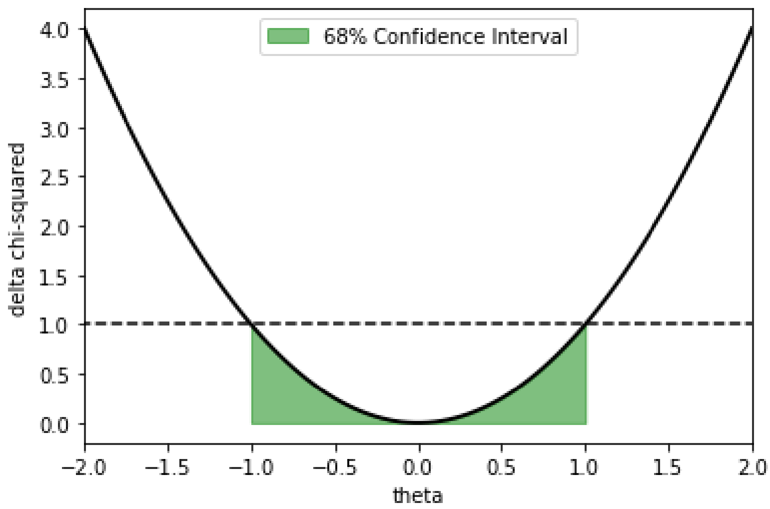

Figure 6: A quadratic $\Delta\chi^2$ vs θ curve is shown for a hypothetical measurement of θ. The 68% Confidence Interval corresponding to the region between the values of θ for which $\Delta\chi^2 = 1.0$ is indicated by the shaded green area.

There is an fantastic interactive simulation tool to demonstrate the concept of the Confidence Interval at this link CI Demo. I strongly recommend having a look at it and playing with the simulation to deepen your understanding.

The explicit steps to be followed in order to execute an simple analyses and measure m_z are detailed in the Jupyter Notebook "Part1_MeasureTheZBosonMass". The notebook also allows a comparison of your measured value of m_Z to the most precise value ever measured, from an average of the values measured by the four experiments at LEP. LEP (Large Electron-Positron Collider) was the pre-cursor to the LHC at CERN. As the these agreed-upon, average vales are published by the Particle Data Group (PDG) [2], we refer to them as the "PDG values" in the notebook.

Once you have successfully completed these steps you are expected to discuss and critique the simple approach and implement changes in the notebook to produce a more accurate measurement of m_Z. The improved analyses should form the bulk of your work. The emphasis here is not on producing a measurement of m_Z that agrees perfectly with the expected value. Rather you must asses where the limitations of the simple approaches may lie, how they might be improved and demonstrate the effect your improvements by re-running the analyses with your changes and comparing results to those from the simpler approaches. An improvement here is likely to be a better estimation of uncertainties rather than a result that is closer to the PDG value. You must describe the refinements you implement and record and describe the relevant plots you make to demonstrate the method and it's impact. It is also valuable to demonstrate changes that do not improve the analysis or make it worse, as long as you adequately discuss your reasoning for this. To conclude this part, I include below a non-exhaustive list of refinements that may improve the analysis:

Suggested refinements of the the simple measurement of m_Z:

- Modify the the event selection scheme (e.g. p_T and η requirements, number of bins in the $\mu\mu$ mass distribution, along with the total number of events analysed) and monitor the effect (if any) on the fit results. Do certain criteria bring the three measurements into better agreement? Can you suggest reasons for any changes in agreement?

- Might there be some events from background processes such as heavy hadron decay that remain in our final data sample even though we have required our muons to be isolated? How might we account for these events in our fit?

- Discuss if the single cauchy function is sufficient to model the $\mu\mu$ distribution. Could a more complex function account for components of the data other that the $pp \to Z \to \mu^+\mu^-$ process? One example is the phenomena of *Final-state radiation* where the muons emit a photon. As the four-momenta must be conserved, the muon's energy will be reduced by this radiation. What effect would this have on the $\mu\mu$ mass distribution? Similarly, ATLAS cannot measure the muon energies and momenta with infinite precision. What effect would this have?
- From our discussions of the ATLAS detector, are there source of systematic uncertainty in this distribution that increase the uncertainty in the measured Z boson mass? For example, ATLAS measures muon momenta with a finite resolution. Therefore the height of each bin should carry some uncertainty to account for the fact that the $\mu\mu$ mass might be incorrectly measured. Is it possible to increase these uncertainties by some reasonable factor such that that your measured Z mass values agree with the PDG values within uncertainties? Such effects may be investigated by increasing/decreasing the uncertainties in the calcChi2() function and re-running the minimisation to measure m_Z.
- **You are encouraged to come up with your own critiques of the simple analysis and demonstrate more sophisticated approaches.**

4.1 Part I a: Simultaneously measure the m_z and Γ_Z

The $m_{\mu\mu}$ distribution contains sufficient information to **simultaneously** measure m_z and Γ_Z. To accomplish this, you should scan over pairs of m_z and Γ_Z and calculate the $\Delta\chi^2$ between the Cauchy (or a more sophisticated PDF) and the data histogram. Make a plot of the $\Delta\chi^2$ function in the 2-D (m_z, Γ_Z) plane. Similar to the previous fit of m_z, the 68% Confidence Interval is estimated as the region between points where the $\Delta\chi^2$ function reaches critical values. However, the number of parameters that we have varied in the fit (N_P) is now 2 instead of 1 in the previous. This changes the appropriate critical value we must apply in order to derive the 68% Confidence Interval from 1.0 to 2.30. These critical values come from the quantiles of the χ^2 distribution with N_p degrees of freedom. For a full explanation of the application of critical values of the $\Delta\chi^2$ function for arbitrary number of fitted parameters in order to derive Confidence Intervals, read chapter 9 of Cowan, especially section 9.7.

The implementation of this 2-D fit is left to you. The goal should be to produce a 2-D plot of $\Delta\chi^2$ vs. m_z and Γ_Z and use this to estimate the 2-D confidence interval by drawing a contour corresponding to the critical value. An incomplete version of this procedure is provided in the "Z_2D.ipynb" as a guide towards utilising the neccessary python tools.

5 Part II: Rediscover the Higgs boson

In the second part of this mini-project we are going to attempt to re-discover of the Higgs boson. Specifically, we are going analyses the entire 13 TeV ATLAS Open Data and select events that contain two photons. We seek the process in which a Higgs boson is produced and decays to two photons $(H \to \gamma\gamma)$. The bad news is this process is incredibly rare and has large background processes that looks very similar to our signal process in the ATLAS detector. The good news is the resolutions of the ATLAS detector in measuring energetic photons is so good that we should be able to see faint signs of this process for events with $m_{\gamma\gamma} \approx 125$ MeV (the measured mass of the Higgs boson). Studying $(H \to \gamma\gamma)$ demonstrates the essence of modern particle physics: searching for an incredibly interesting "needle", in an extraordinarily large "haystack".

Again we will use a Jupyter Notebook to demonstrate a relatively simple data analysis and you will then explore how to make the analysis better by exploring the data selections and more advanced statistical techniques. Some of the data filtering has already been applied such that each event contains two photons that have been identified with a high degree of certainty and are isolated from other particles. Both of these criteria are key in rejecting background processes that produces signals in ATLAS that mimic that of a real photon. Only the components of the of four-vectors of the two photons are stored in the data file as well as the mass of the $\gamma\gamma$ system.

Contrary to Part 1, where we had a large $Z \to \mu\mu$ signal, in this analysis we are not completely sure if the $(H \to \gamma\gamma)$ signal is present in our data. Therefore our final goal here is to determine how likely it is that the signal is present. The concept of *statistical significance* will be very helpful. To understand it, let's imagine a simple experiment. We wish to know if an object is radioactive or not. Our experiment simply places a Geiger counter close to the object and we measure the number of counts N in a time t.

From measurements without the object present, we know that background sources on average provide a count $N_B = 25 \pm 5$ in a time t. We run our experiment and observe the total counts $N = N_S + N_B = 35$. What can we conclude about the radioactivity of the sample? How likely is it the increased count rate is just due to a random upward fluctuation in the activity of the backgrounds? The statistical significance S provides a robust and well-defined means of answering these questions. Defining S as:

$$S = \frac{N_S}{\sigma(N_B)} \tag{6}$$

where $\sigma(N_B)$ is the total uncertainty on N_b. We see that S is simply the estimated signal count $N_S = N - N_B$ divided by the uncertainty on the estimated background. If S is large, it is likely there is a signal present as the estimated signal is large compared to the fluctuations we would expect from the background. Conversely if S is small, what we are seeing is perfectly explainable as a fluctuation of the background processes. In particle physics we define certain threshold values of S to determine if a signal is present or not. For example, for ATLAS to publicly announce that a new process has been discovered, S must exceed 5. However this is a very stringent requirement, the average particle physicist will get pretty excited if they observe a signal with $S > 3$. Measuring S for the potential $(H \to \gamma\gamma)$ in your dataset will be an excellent way of establishing whether or not you have re-discovered the Higgs boson.

The explicit steps to be followed in order to execute a simple analysis to extract the basic information needed to measure S as a function of $m_{\gamma\gamma}$ are detailed in the Jupyter Notebook "Part2_RediscoverTheHiggsBoson". You will notice that less guidance is provided in part 2 with respect to Part 1. This is to encourage you to explore and build your own analysis with the tools and techniques you have learned in Part 1.

Once you have gone run and understood each step of the simple analysis, you must write your own code to estimate the significance of the estimated signal as a function of m_γ and comment on the evidence (or lack thereof) for the Higgs signal. You should try to modify the event selection and analysis to both increase the significance of the signal and make the measurement of its significance more precise. Consider what factors might affect the size of the significance and how precisely we estimate it. I include a short, non-exhaustive, list of suggestions and considerations:

- Could changes in the binning of the m_γ distribution could help increase the significance. Reason why is this so and explore if the default binning of the notebook is already optimal.
- Photons produced in the central $(\eta < 0.75)$ region of ATLAS are better measured that other photons. However, only using central photons will increase statistical uncertainties as we will select fewer events. Test if restricting your analysis to these central photons increases significance.
- In the default selection, selections are applied on the ratio between each photon's p_T and m_γ

Again, you are encouraged to explore and try out your own ideas as long as you explain your reasoning and conclusions.

6 Lab report guidance

- Please limit your mini-project report to four typed A4 pages including figures and tables.
- Pay close attention to the visual presentation of figures (axis labels and units, font size, descriptive and clear captions)
- While numerous ideas for data selections and statistical analyses are suggested, **you are strongly encouraged to try out and implement you own ideas**. In such cases, it is particularly import to explain clearly what you are trying to achieve with the analysis, what your results are, and how you interpret them.
- Have fun and don't hesitate to contact me when you need guidance. Best of luck!

References

[1] The ATLAS Collaboration. *ATLAS OpenData website*. URL: https://atlas-opendata.web.cern.ch/atlas-opendata/.

[2] The Particle Data Group. *The PDG group: Z boson*. URL: https://pdg.lbl.gov/2018/listings/rpp2018-list-z-boson.pdf.