An Exploration into Experimental Particle Physics

Mentors: Dina Ibrahimzade, Assistant Mentor: Mathi Raja

Pablo Castaño, Leah Kong, Gurpreet Singh, Aryan Sood, Connor Tumelty

University of California, Berkeley, Undergraduate Lab at Berkeley

Abstract

The study of elementary particle physics has created many open ended questions about the Standard Model. To name one example, the symmetry of matter and antimatter seems to be broken, as there exists more matter than antimatter, and the Standard Model has no means of reconciling this rift. Of course, to answer this and many other questions, we must know how to investigate elementary particle collisions through experiment and simulation. Our project aims to gain a deeper understanding of the current state of particle physics, as well as investigating means of simulating and measuring particle collisions. We chose to review Deepak Kar's 'Experimental Particle Physics: Understanding the Measurements and Searches at the Large Hadron Collider' for a fundamental understanding of the principles of experimental particle physics. [2]

Background and Groundwork

Elementary particles can be classified generally as fermions or bosons. A fundamental quantum property called spin is assigned to particles within the Standard Model. Fermions, the particles that encompass matter, possess half-integer spins. Fermions are further broadly classified as Quarks, and Leptons. Bosons, on the other hand, are further classified as W Bosons, Z Bosons, Photons, Higgs Bosons, or Gluons. Bosons are considered the 'force carriers' and possess integer spins. The quarks can be up (u), down (d), charm (c), strange (s), top (t), bottom (b). Furthermore, they can be arbitrarily Red (R), Green (G), and Blue (B). The leptons are subdivided into electrons, muons, and taus, and their counterpart neutrinos: electron neutrinos, muon neutrinos, and tau neutrinos.[2]

At CERN, the Standard Model is studied in detail experimentally, through investigations at the LHC (Large Hadron Collider). As in the name, most investigations here are based on Hadron acceleration and collisions. Hadrons are composite subatomic particles, made of multiple quarks that are held together by Gluon interactions (strong nuclear force). Mesons and Baryons are the two main types of Hadrons, made up of two and three quarks respectively. Baryons are the main focus at CERN, whose usual examples are protons and neutrons. These particles are accelerated and collided at extremely high energies; the particle speeds come close to the universal constant c, the speed of light. Hence, classical Newtonian mechanics fall short at measuring and calculating the results of such interactions; relativistic and quantum mechanics are the key.To perform any investigation on the particles, their parameters must be quantified and quantized. Dimensionless quantities are first defined—where the Greek lowercase β and γ become the ratio of the particles' speed to the speed of light, and the relativistic increase in the energy of a colliding particle (boost factor)— respectively. [2]

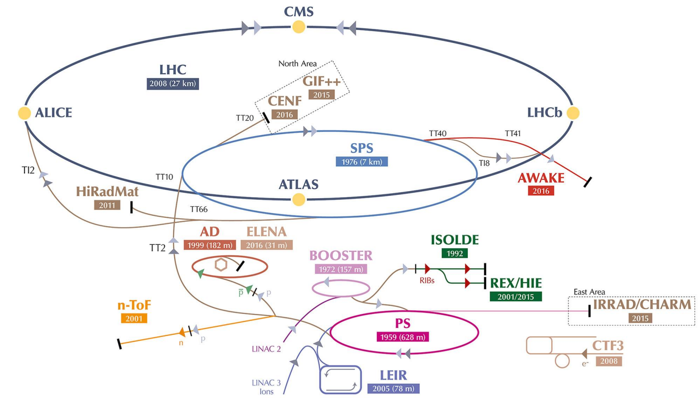


Figure 1.A diagram of CERN's LHC and the component parts as well as the portions that lead into injection into the accelerator.[2]

p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons)

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

CHARM Cern High energy AcceleRator Mixed field facility IRRAD proton IRRADiation facility GIF++ Gamma Irradiation Facility

CENF CErn Neutrino platForm

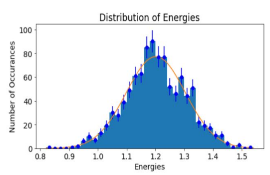


Figure 2: Histogram of distributed energies fitted to a model gaussian in python. [3]

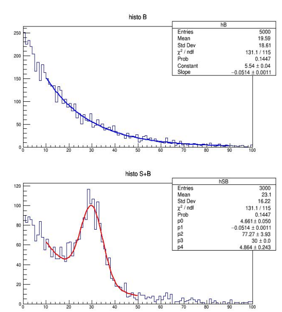


Figure 4: The images above are two more examples of fitting data based on a model in ROOT.[7]

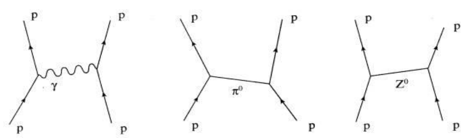


Figure 3. Feynman Diagrams depicting the fundamental interactions (shown left to right: Electromagnetic, Strong, and Weak) in the Standard Model. [9]

Collisions

Particle collisions occur naturally all over the universe, with particles interacting with each other via fundamental forces (the electromagnetic, weak, and strong interactions are characterized by the Standard Model) often in conjunction with energy transfer.[2]

In a controlled setting, such as a particle accelerator (e.g. Large Hadron Collider [LHC] [Fig.1]) physicists are able to replicate these collisions. To run the LHC, protons are isolated by applying an electric field to hydrogen gas, allowing for the disintegration of the hydrogen atoms. The isolated protons are then moved into the accelerator (held at a vacuum) and accelerated in stages in bunches that come together to form beams (in the magnitude of 100 trillion protons). These longitudinally Lorentz contracted protons move in opposite directions resulting in many collisions in which forces cause them to annihilate and form unique subatomic products. This is all done in order to observe the nature of how these particles and their emissions behave. New advancements in acceleration technology and higher performance detector and modeling equipment have let us observe collisions and products allowing us to discover additional fundamental particles and how they interact (e.g. The Higgs boson). These experiments allow us to answer questions such as: "What is all matter made up of?", "What creates the interactions of matter?", and "How can we model these interactions?".

Particles collide via the quarks and the strong force-carrying gluons from each proton (consisting of two up type and one down type quark) interact. Other quark-antiquark pairs are formed through quantum fluctuations throughout. Particles can collide in a variety of ways, which can be broadly classified into elastic and inelastic (single-diffractive, double-diffractive, and non-diffractive) (Fig.7). Elastic collisions are the most common and they result in no proton dissociation, particle formation, or energy loss and are thus not detected in the LHC. Single-diffractive collisions occur when one proton has a change in energy or direction and a double-diffractive collision occurs when both protons have a change in energy or direction. Non-diffractive collisions occur when they collide to form new particles and a large amount of energy is released. These non-diffractive collisions are the most widely studied. Non-diffractive collisions events consist of hard parton emission (which must form color-neutral hadrons as free partons cannot exist naturally), initial and final state radiation (I/FSR), multiple parton interactions (MPI), and beam-beam remnants (BBR). Collisions can be soft (little momentum transfer) or hard (significant momentum transfer) and are somewhat dependent on the impact perimeter (IP) which can contribute to the degree or magnitude of momentum transfer (Fig. 5). We can visualize particle collisions pictorially using a Feynman diagram which is made up of the initial event (the collision), an intermediary stage (a transition state often only existing for sub-femtosecond intervals), and the emission of the resulting particles over the axis of time (Fig. 3).

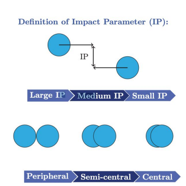


Figure 5. A pictorial depiction of different categories of IP.[3]

Theory and Simulation of Collisions

Colliders

Particle detectors are complex experimental tools that exploit a certain particle's fundamental properties to detect it in the most effective way possible. For example, at the IceCube Neutrino Observatory, physicists make use of the fact that relativistic charged particles emit Cherenkov Radiation when they interact with the ice in the South Pole to detect said particles. Even though all detectors strive to find new particles, they do so in very different ways. A relevant particle detection method is a collider, an experiment where several particles collided at high energies to use conservation of momentum to try and find new particles. The largest collider in the world is currently the Large Hadron Collider, in Switzerland.[2]

Feynman Diagrams

The particles we know from the Standard Model can interact with each other through gravitational, electromagnetic, weak, and strong interactions. However, not all particles 'are allowed to' interact in some ways due to the mathematical framework of the Standard Model. To represent said interactions in a simple and illustrative way, physicists use Feynman Diagrams, invented by 20th century physicist Richard P. Feynman as a tool to visualize and understand complex particle interactions[9] Feynman diagrams are pictorial ways to describe particle collisions, where everything happens around a horizontal axis representing time and a vertical axis representing space. Therefore, anything in the diagram is a particle moving through spacetime. However, to distinguish between the many different particles in the Standard Model, we draw different lines for the different types: solid lines with arrows indicate a fermion and wiggly lines indicate force carrying bosons[9]. In addition, where the collision takes place is denoted by a dot, called the vertex. As previously suggested, the momentum to the right of the vertex in a simple collision must equal that to its left. There are three types of lines in a Feynman diagram: internal lines connect two vertices, incoming lines show a particle coming into the system and interacting, and outgoing lines extend from the vertex to the future, supposedly after having interacted. Particle collisions are therefore shown by a collection of incoming, internal, and outgoing lines[2].

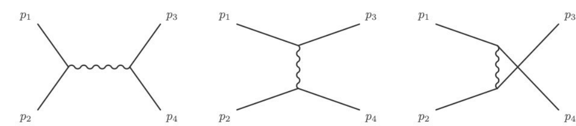
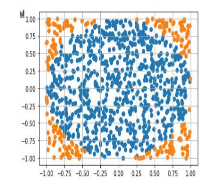


Figure 6. More Feynman Diagrams[2]

Mandelstam Variables and Monte Carlo Simulations

To simulate collisions, there are several methods. In this poster, we will be covering Mandelstam Variables and Monte Carlo Simulations. Both these concepts are tricks used in the simulations of collisions. Mandelstam variables are numerical quantities that encode the energy, momentum, and angles of particles in a scattering process. When two particles collide with two other particles, we have four different momenta in our Feynman diagram. If we let p1 and p2 be the momenta of the particles represented by incoming lines and p3 and p4 be the momenta of those represented by outgoing lines, the Mandelstam variables are the possible combinations of these four-momenta in the Minkowski Metric (1,-1,-1,-1). These combinations are given by s, t, and u, and their values are shown below[2]:

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_4 - p_2)^2$$
$$u = (p_1 - p_4)^2 = (p_3 - p_2)^2$$



Simulation programs, or event generators, simulate the final events of particle collisions in great detail. An example of a simulation method is the Monte Carlo method. Monte Carlo simulations are useful ways to simulate the probabilities or numerical outcomes of a certain event happening. It relies on repeated random sampling to obtain the probabilities or numerical outcomes, and are useful for events like particle collisions that may be impractical to actually simulate. They are simple enough to do computationally, like through Python or C++. A good way of envisioning how a Monte Carlo simulation can work through finding the value of pi. If we know the area of a circle inscribed in a square and the area of the square itself, by simulating random points within the total area (the area of the square), and counting the proportion in the circle vs in the whole square, we can find the value of pi by using the formula for an area of a circle, the formula for area of a square, and the proportion of points in the circle.

Parton Showers and Matching/Merging

At detectors like the LHC, detection is based on particle showers. When two bunches of particles collide at the core of the detector, the resulting daughter particles are shooted out in a jet-like fashion. These are called parton showers. When computer algorithms analyze what has been detected in the layers of the detector and try to understand the data they have, they need to make sure the data is clear and organized for its future analysis. Matching or merging programs are important for avoiding an overlap between possible jet sources.They define energy thresholds below which parton shower and above which matrix element will be used. This prevents parton emission double-counting[2].

Root and RootPy Applications

Root is a library that was developed by CERN for particle physicists and their data analysis needs. Often, measurements must be compared to theoretical models that depend on parameters. Visualizing the data and applying corrections or transformations as well as fitting data[1]. Normally in python, one would have to use various libraries and tedious lines of code in order to import, organize, and fit data. One would also have to create bins and even normalize your own data with previously learned statistical methods such as the least squares regression method. Root has powerful statistical tools and libraries such as RootFit And RootStats that are used for fitting and statistical analysis of data. Pyroot allows full ROOT accessibility in the language of python instead of the native C++. Python is one of the most used languages in the modern day. Pyroot was developed to harness the power of python.[3]

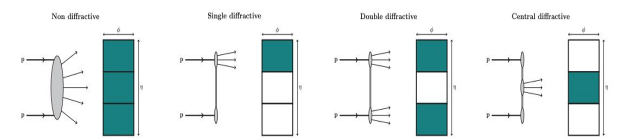


Figure 7: A visual depiction of the different modes of diffraction and their subsequent associated detection patterns[8]

Applications to Future Projects

In this project, we learned about the theoretical and computational sides of collisions and simulations. Being able to understand the physics behind collisions will enable us to improve our computational skills in ROOT and ROOTpy. Furthermore, for those of us who are interested in pursuing research in particle physics, this project will have taught us the theoretical minimum, and is a first step in our careers. Hopefully, some of us can put this into practice and work at CERN in the future.

Acknowledgements

We would like to thank Ermal Rrapaj, Yi Zhu, Carrie Zuckerman, Katie Lamar, and Ronan Alam for their support throughout this project.

References

[1].ROOT", "D. into. (n.d.). A ROOT Guide For Beginners. https://root.cern.ch/root/htmldoc/guides/primer/ROOTPrimer.html#motivation-and-introduction.

[2].Kar, D. (2019). *Experimental particle physics: understanding the measurements and searches at the Large Hadron Collider*. IOP Publishing.

[3].Bellenot, Bertrand and Axel Naumann (2018). ROOT. url: https : / / root . cern . ch / download/ROOT_CSC11-Handout.pdf.

[4]. Boos, Edward E et al. (1995). "CompHEP-Specialized package for automatic calculations of elementary particle decays and collisions". In: arXiv preprint hep-ph/9503280.

[5]. CERN (n.d.). CERN Accelerating science. url: https://home.cern/science/accelerators/ large-hadron-collider.

[6].Condon, E. U. and P. M. Morse (Jan. 1931). "Quantum Mechanics of Collision Processes I. scattering of particles in a definite force field". In: Rev. Mod. Phys. 3 (1), pp. 43–88. doi: 10.1103/RevModPhys.3.43.

[7].D, Piparo, Quast G, and Zeise M (n.d.). Diving Into Root. url: https://root.cern.ch/ root/htmldoc/guides/primer/ROOTPrimerLetter.pdf.

[8].Greene, Brian (2000). The elegant universe: Superstrings, hidden dimensions, and the quest for the ultimate theory.

[9].Hawking, Stephen (2009). A brief history of time: from big bang to black holes. Random House.

[10].*Particle Physics Tripod*. New Page 1. (1995). https://hors4th.tripod.com/a-level/ParticlePhysics/pa01_from_ph06_mod_questions_frame.htm.