Why do we need a new supercollider?

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Devizes School 6th Form Extended Project Qualification

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Abstract:

In this project, I try to make a case for the construction of the Future Circular Collider (FCC) in CERN, under Geneva. I explain in some detail the workings of both particle accelerators in general, and, specifically, the large hadron collider.

Since the construction and operation of the collider, I discuss the progress made, and the benefits that would arise from a larger, more modern collider.

My research is collected from various places, mostly research papers from reliable publishers, and the CERN online website. Since there is not much research yet published on the future circular collider, I have tried to cover the width of the field instead of the depth, and have, at this point, seen almost every currently available up-to-date research paper regarding the FCC.

My research into the areas of interest in this project led me to believe that not only would the new supercollider be possibly ground breaking for particle physics, it could also revolutionise many areas of research and even produce economic benefits despite cost being its main source of criticism. My conclusion is that, as well as benefiting us in numerous ways in the short term, a new supercollider somewhere on earth, at some point, is essential for the progression of science, and therefore the progression of the human species in the long run.

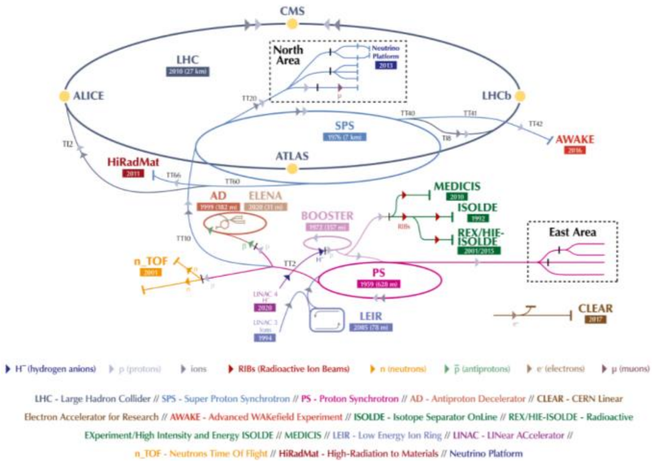
Chapter 1

What is CERN?

The acronyms CERN and the LHC are often used interchangeably to refer to the particle collider complex underneath Geneva in Switzerland, however the two are not the same thing. CERN (Conseil Européen pour la Recherche Nucléaire) is the provisional body established in 1952 with the aim of creating a Europe-wide organization for the research of fundamental physics. Its main laboratory is on the Franco-Swiss border near Geneva. It carries out a wide range of experiments including ones outside of the accelerator complex that it is most known for, like the AMS (Alpha Magnetic Spectrometer) which sits on the international space station and looks for dark matter, antimatter and missing matter by studying cosmic rays in space. [1a][1b]

The LHC (Large Hadron Collider), however, is specifically the particle collider residing in the 27km long tunnel that runs in a ring underground near the Swiss city of Geneva, and the large equipment used to start the machine and obtain results from it. A particle collider is a simple concept, where very small particles are accelerated to extremely high energies, then smashed together. The collisions are then studied to try to learn new things about the nature of the universe, like learning about rare particles that decay so quickly that it was previously impossible to confirm or study the particle, such is the case with the Higgs Boson which was finally confirmed by CERN in 2012, 48 years after it was first theorised by Peter Higgs. In simple terms, the Higgs boson is a particle that gives other particles their mass, it decays in just $1.56\text{x}10^{-22}$ seconds, which is essentially instantaneous. [1c][1d][1e][1f]

In reality, these machines are anything but simple. There are, at the time of writing, eight accelerators and two decelerators operated by CERN, many of these are used to supply the LHC with the particles that it will collide, like the PS (Proton Synchrotron) and the SPS (Super Proton Synchrotron) which both do experiments by themselves, and are utilised in the process of injecting protons into the LHC. Protons are supplied to the LHC through a chain of four accelerators (including PS and SPS) that speed up the protons and split them up so that they can be properly utilised inside the LHC. [1g]



Layout of the CERN accelerator complex [1h]

The collisions produced by the LHC are the most powerful of any currently existing collider; hadrons are sped up to nearly the speed of light, then smashed together with an energy of 13 TeV (Teraelectronvolts), about $2.1\text{x}10^{-6}$J. The fundamental particles produced by the collisions are then measured by huge and complex detectors. The 4 detectors that are used in the LHC are: LHC^{b} (LHC beauty), ALICE (A Large Ion Collider Experiment), the Compact Muon Solenoid (CMS), and the most famous, ATLAS (A Toroidal LHC ApparatuS, the acronym is a stretch I know, but it’s worth it for the cool name). If you’ve seen a picture of the Large Hadron Collider before, it’s a good bet that what you’ve seen is ATLAS. ATLAS is a cylinder with a huge 25m diameter, and a length of 48m; it weighs over 6000 tonnes and the cavern that it was placed into has an internal volume of half the size of Notre Dame. It’s reason for being was initially to discover the Higgs Boson along with the CMS, but now that the Higgs has been found it is open to all other experiments that can be run in it. The instrument is full of extremely precise equipment used to measure all sorts of things about the fundamental particles that are produced in the collisions. This includes many powerful magnets for tracking and 2 huge calorimeters for measuring energy, just to give you an idea of the scale and complexity of these experiments. [3]

Even with all the power of the largest particle collider in the world, the LHC is still very limited. For example, the Higgs Boson, an elementary particle responsible for mass, can only be produced by the LHC once every 10 billion collisions. Further Studying the Higgs could reveal important things in the realm of particle physics, however it is extremely hard to progress on the field with only the power of the LHC. Even heavier particles than the Higgs may also be possible to produce in a more powerful reactor, such as Weak Interacting Massive Particles which are a possible contender for dark matter. The LHC is not powerful enough to research these things. [3]

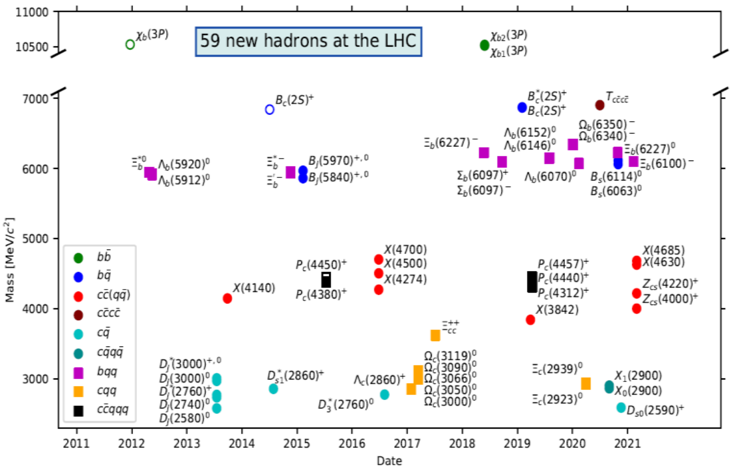
Finally, one of the main concerns from the general public is about the safety of experiments at the LHC. The fear of these experiments from the general public was large in the early years of the LHC before it was first turned on, amplified by the sensationalist media. For example, a legitimate paper by N. Arkani-Hamed, S. Dimopoulos, and G. Divali showed that string theory predicted the formation of mini black holes from the collisions in the LHC. Many media outlets took this to mean that the earth would be swallowed up by a black hole once the LHC is turned on, however scientists agreed that it was not going to happen. Steven Hawking stated that “The world will not come to an end when the LHC turns on. The LHC is absolutely safe. collisions releasing greater energy occur millions of times a day in the earth’s atmosphere and nothing happens”, and he was right. Cosmic rays with energies even higher than those seen at the LHC happen constantly all across the solar system. The point is, safety of the earth is not an issue when it comes to high energy particle collisions, no matter what the general public believes. [3]

CERN is an impressive marvel of engineering, but it is not the be all end all of particle physics.

Chapter 2

Past breakthroughs at CERN.

Between 2011 – 2021, CERN has found 59 new hadrons for the first time, including hadrons with 4 and 5 quarks. But why is this process of discovery important? [1i]



List of all 59 new particles discovered, organised by take on the x-axis and mass on the y-axis. [1i]

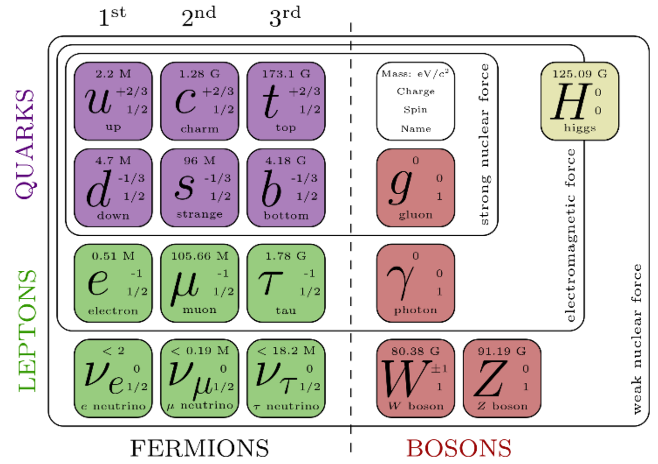
CERN has played quite a large role in the field of modern particle physics and as such has confirmed and made ground-breaking discoveries about the universe. The current most substantiated model of Physics we have is called the Standard model. The standard model formed from the need to combine theories about specific forces and particles into a single, all-encompassing theory. In this theory, there are categories of sub-atomic particles: Leptons are particles that aren't affected by the strong nuclear force but are affected by the other 3 fundamental forces (electromagnetic force, gravity, and the weak nuclear force). Hadrons are sub-atomic particles which are made of 2 or more quarks, this includes protons and neutrons. They are also split into two groups, baryons and mesons. Unlike the leptons, they do react to the strong nuclear force. Bosons are force-carrying particles, or interaction mediating particles. This croup includes the Higgs boson which gives particles their mass, photons which are responsible for the electromagnetic force, and the theoretical graviton, a particle that could be responsible for gravity. [3][7]

Since the particles that CERN strives to detect are so elusive, you can bet that they are hard to detect. This is because many of them only exist for a fraction of a fraction of a second, for example, the Higgs Boson exists for around just around 1.6^{-22}s or less than a trillionth of a billionth of a second, how do you detect something that exists for, what is essentially no time at all. The way this is done is by looking for the detection of particles that would be produced by the decay of certain other undetectable particles (whether that be because they exist for no time or because they do not interact with anything). For example, even though it is impossible to detect the Higgs Boson itself, it can be detected in the LHC by mapping the release of particles that can be detected in the collision event. This is because the Higgs Boson decays can decay into W and Z bosons, heavier fermions like the tau lepton, and on occasion, can decay into muons. [1f][1j]

The standard model is very useful, and the most accurate and the most experimentally substantiated theory of the universe so far. Every major discovery made by CERN to date has been predicted by the standard model, although the often more exciting results are ones that seem to show a small flaw in the standard model. Despite the reliability of the model, it has flaws. Scientists have not yet worked out how gravity fits into the standard model, there are ideas about gravitons as mentioned before, but this proposition still has severe problems that are yet to be fixed. String theory better explains the existence of gravity but is a totally different model with its own set of problems that has yet to be totally accepted by the scientific community. Whatever the solution, scientists need more powerful tools to probe the rules of the universe. [1k][8]

In 1983, the SPS (super proton synchrotron, as mentioned last chapter) discovered the W and Z bosons which are responsible for the weak nuclear force. It did this by looking for the products of W and Z boson decay (an electron and a positron) during collision events. The existence of these Bosons was theorised in 1968 by Glashow, Weinberg, and Salam, but were finally confirmed by these experiments in 1983. [5][6]

In 2012, the ATLAS and CMS detectors, that have also been previously mentioned, discovered the Higgs Boson, the particle which gives particles their mass. The particle was predicted in 1964 by Peter Higgs, it took 48 years to verify his prediction. The discovery of the Higgs Boson was a very major and long-awaited discovery for the standard model, part of the reason being because the Higgs Bosons explains why massless photons of light can exist, and without it the standard model of particle physics would be left with a gaping hole. [5]



Map of elementary particles in the Standard Model of Particle Physics

CERNs achievements are immeasurable and many of its discoveries have amazing real-world applications in fields other than high energy particle physics. In the medical field, CERNs work has let to progress in areas such as radio and hadron therapy for tumours that can't be treated by chemotherapy, medical imaging, as well as many others. It also has applications in areas such as the development of vastly more efficient cooling systems, and developments within quantum computing systems with ultra-high vacuum technology, plus, once again, many, many other areas. [1l]

Chapter 3

What is the FCC?

The FCC stands for 'Future Circular Collider'. It is the planned extension of the facilities at CERN to make way for the most powerful collider ever built. The effectiveness of a collider comes down to a group of specs and parameters that we can compare between all different colliders. The main ones to think about are: Energy, peak luminosity, average turnaround time, Dipole field strength, and run time. [9]

Usually in the headline of most articles on the FCC, the possible energy of the collisions in the accelerator is an extremely important part of what the collider can achieve. It is measured in eV (electron volts) which is a measure of energy. It is approximately equivalent to $1.6*10^{-19}$ J (joules), a tiny amount of energy when compared to what we come across in everyday life. [9]

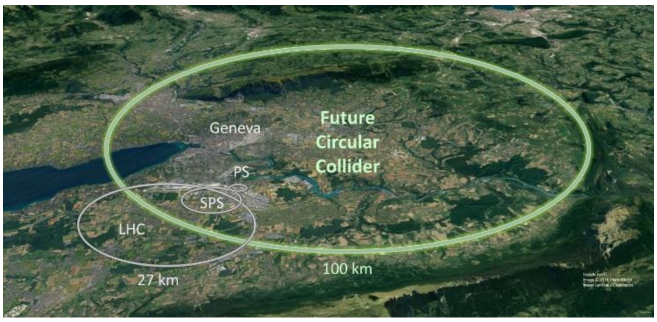
The most complex of these parameters at first glance is luminosity. Luminosity is the ability of the accelerator to produce the number of required interactions. It is the measure of events per time per area, hence its units are $cm^{-2}s^{-1}$, a higher luminosity means more events in a smaller space, and therefore more data that is available for analysis later. [9][10]

Average turnaround time is exactly what is sounds like, it's the time (or assumed time in accelerators that are not yet finished) between physics runs at the accelerator, measured in hours. Although people would argue that it is not as important as many other factors when looking at the specs of a particle accelerator, it is an important factor to take into consideration, as even an hour difference means less efficient experiments and therefore less data, vital time is being wasted refiling beams instead of making discoveries. [9][12]

Dipole field strength sounds daunting, but it is pretty much a fancy way of saying the strength of the magnets. This value is measured in T (Tesla). In SI units, a tesla is $kgA^{-1}s^{-2}$, but all you need to know is that the higher the tesla number, the stronger the dipole magnet that is used in the accelerator.[9][11]

Run time is also a very obvious measure, it's the optimal time that the machine should run for to get the best results, again measured in hours. [9]

Under the City of Geneva in Switzerland, a 100km long tunnel will be dug to house the collider and all of its equipment, similar to the previous particle accelerators built at CERN, except to a much larger scale.



A comparison of the size of the FCC compared to the LHC. The position is not confirmed [1m]

Here is how the FCC would compare to the current LHC (before and upgrades such as HL-LHC or HE-LHC which will be talked about in later chapters):

The current LHC has a proton-proton collision energy of 14 TeV, compared to the FCC's 100 TeV collision energy. The luminosity of the FCC is 5 times higher than the LHC's luminosity, at 5 $cm^{-2}s^{-1}$ compared to just 1 $cm^{-2}s^{-1}$, which results in a large difference in the amount of data that can be obtained during events. [9]

Next, the average turnaround time. In the LHC, the average turnaround time is around 10h, and the average turnaround time of the FCC is around 5h. A pretty significant improvement, meaning in the FCC, the beam will be in a more optimum operating state for longer. [9][12]

Dipole field strength between LHC and the FCC highlights particularly well the scale of the advancements in superconducting magnet technology. The dipole field strength of the LHC is 8.33 T (for reference, the junkyard magnets used to pick up cars have a field strength of about 1Tesla). The FCC was planning to use magnets with a field strength of double that, around 16 T, but they may decide to use high temperature superconductors, in which case they will be able to reach 20 T of dipole field strength, an absurd amount. This means that the beams will be able to be accelerated to much higher speeds than previously. [9][13]

The optimum run time for the current LHC design is 15.2 hours, however the optimum run time for the FCC was planned to be around 12.1 hours but could be made to be as low as 10.7 hours A 5-hour difference between the LHC and the FCC doesn't sound like much, but it adds up. [9]

Of course, the main parameter to note is the cost verses the scientific insight that will be gained from the construction of the collider. The estimated total cost for the first stage (FCC-ee) from a conceptual design report in 2019 was 10.5 billion CHF (8.5 billion GBP), but the scientific insight that it will give is a little harder to quantify. [14]

Chapter 4

A closer look at the FCC.

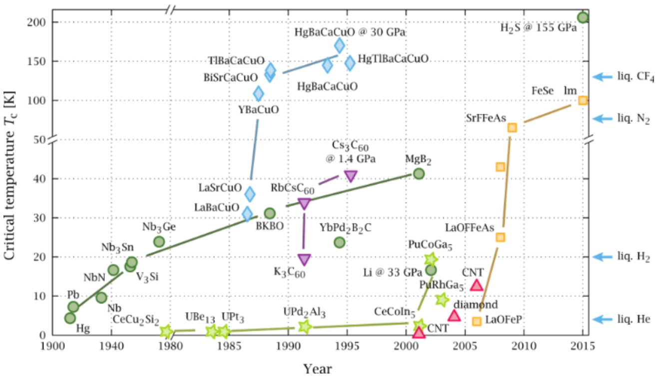
The FCC can be built in 2 parts, FCC-ee can be the first of 2 stages, and is an electron-positron collider. Its equipment would then be reused into the FCC-hh, or hadron-hadron collider. Both colliders use the same tunnel and mostly the same equipment, because of this the FCC-ee can run while the FCC-hh is being constructed, meaning that experiments can be run even while waiting for the final integrated future collider programme to be completed. [15]

The FCC-ee is also designed to be a very good Higgs factory, meaning that it will be able to produce Higgs bosons at a good rate, for experimentation and deeper probing into the particles. [15]

If the FCC-hh was made without implementing the FCC-ee first, it would take 23 years: 8 years of preparation and 15 years of construction. [15][16]

If the FCC-hh was made after first making the FCC-ee, almost everything needed for its construction would already be in place. Additional things would need to be constructed, however, including two caverns for lower luminosity experiments, two beam dump tunnels, and two more tunnels that connect the 100km tunnel to the old 27km LHC (the LHC would be reused as an injector for the FCC). In this setup, the FCC-hh construction is completed around 10 years after the FCC-ee finishes its operation, this involves dismantling parts of the FCC-ee, making the FCC-hh infrastructure, and then installing the FCC-hh equipment. This all results in the final integrated Future Circular Colliders programme being finished 20 years later, in the 2060s instead of the 2040s, but does allow for thorough investigation of the Higgs Boson, and other possible discoveries, such as possible observations of dark matter in the decays of Z and Higgs bosons. [15][16][17]

New and future technological breakthroughs mean that the FCC will use high-temperature superconducting magnets with magnetic fields of strength 20 T, Superconducting is a quantum phenomenon wherein metals conduct with 0 resistance once they reach below a certain critical temperature. Since V=IR, 0 resistance means that current can be maintained with zero potential difference. The critical temperatures of the first superconducting materials discovered was incredibly close to absolute 0 (-273 C), but more recent research has led to recent superconductors working all the way up to 150k (-123 C) and above. [9][18]



Comparison of the date of discovery on the x-axis, to critical temperature on the y-axis (keep in mind most of the higher ones need high pressures to operate) [18]

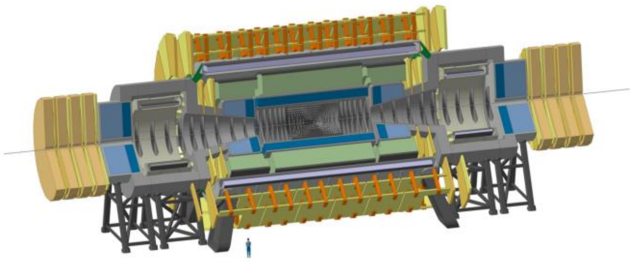
The LHC uses 8.3 T magnetic fields with copper-clad titanium-niobium cables and have a critical temperature of 4k (-269 C). [1n][19]

Detectors are one of the most important parts of an accelerator, as it determines the quality and quantity of data that can be received from each event. Detectors include 3 main components: the calorimetry, tracking, and the muon system. [20][21]

Calorimetry is the process of measuring the energy of a particle. In detectors, there are EMCALs (electromagnetic calorimeters) and HCALs (hadronic calorimeters). EMCALs measure particle energy through the electromagnetic force, and hadronic calorimeters measure particle energy through the strong force. This enables the detector to detect particles like neutrons, which don't interact with the electromagnetic force but can be detected in a hadronic calorimeter. [21][22][23]

Tracking consists of identifying and finding the paths of most particles that come from the collisions. They find the particle's velocity. Since the energy has been calculated in the calorimeters, the mass of the particle can be easily calculated. Velocity is usually detected a few ways such as distance travelled over time, or by measuring the ionisation level of the matter that the particle passes through. Scientists then interpret all of these results to get the full picture of the collision. [21][25]

Muon detection is related to this, muons only interact with the weak nuclear force, so they can't be detected by electromagnetic calorimeters or hadronic calorimeters. They usually use gas detectors, like argon which is used in the ATLAS detector of the LHC. [20][21][22]


The reference detector layout for the FCC, showing the tracker (grey), the electromagnetic calorimeter (dark blue), the hadronic calorimeter (green and light blue), the 4T solenoids (purple), and the muon system (yellow). [20][21]

Chapter 5

What could the FCC achieve?

It is not yet clear what big breakthroughs the FCC can bring, and lots of scientists are reluctant to promise anything since there is hardly any certainty about what it will bring, which is a part of why the FCC will be built.

Known unknown:

Known unknows are things that we know we don't know. There are some things that scientists working on the FCC are hoping will be revealed by the collider. For example, to verify the existence of Weakly Interacting Massive Particles (WIMP), the major candidate for dark matter. The collider will be able to definitively say whether or not 2 different candidates for WIMPs (higgsino and wino-like) [16]

The FCC's main aim is, however, to further study the Higgs Boson that was previously confirmed to exist at this site. This could lead to explanations on why there is more matter in the current universe than antimatter, despite the only possibility being an exactly equal amount of matter and antimatter existing at the very start of the universe, as well as opening doors to other important and exciting discoveries. [16]

Unknown unknowns:

Unknown unknowns are possibly even more exciting that known unknowns. They are things that we don't know that we don't know. One form this usually takes in experiments like this is the disproving of part of the standard model. Recently (April 2022), experimentation found that the W boson had a mass that differed from the mass predicted by the standard model. This kind of finding has potential to flip physics on its head and tell us that how we thought the universe worked was wrong all this time, which sounds like something scientists would be scared of, but in reality, it is extremely exciting. [26]

Other hopes for the FCC include the deeper probing of the true nature of gravity, and the confirmation, or the rejection of the idea of preons, particles which make up quarks, by a quark with an excited state. [3]

The FCC is a large step towards the progression of particle physics, and therefore a step closer to the knowledge of the nature of the universe. Even if the FCC doesn't make any major breakthroughs at all, it will still have taught us that what we are looking for isn't in the 100TeV range, and if we want to know more, we need to keep going. There is a chance that the FCC is still not powerful enough to do some of what is expected of it this time around, but without the FCC we'd never know if a big discovery was just around the corner, and we wouldn't have a stepping stone to future discoveries.

Chapter 6

Social and Economic Costs of the FCC.

A large talking point in media about the FCC is its costs: social, environmental, and, most widely talked about, economic. Obviously costs greatly matter when talking about projects like this, and they give the public a good idea about the scale and complexity of the project, without having to explain the details. [16]

The economic costs of the FCC depend on the decisions about the construction of the stages of the accelerator. Earlier I talked about the different options for the timeline of the FCC, building just the FCC-hh (the final hadron collider) is estimated to amount to 24 billion CHF, 19 billion GBP, including £7.6 billion for the magnets alone. If, instead, the FCC-ee would be built first (as talked about in chapter 4), then the total costs would 'only' come to £13.8 billion in total. [28]

The cost of the FCC is the main criticism from the public and from the media (you'll find few headlines about the FCC without the price tag), and it's easily understandable why. £13 billion is a huge amount of money if it was anything else, but it is important to remember that this money isn't coming from any 1 country, but from a collaboration from many different ones, this project could never be achieved without a lot of international support, and as such, the money makes a relatively little dent in each country's wallet. [1o]

This is quite a short chapter, since the main cost of the programme is a monetary cost, but there are other costs too, a lot of research is being focused on the FCC, which could perhaps be time better spent on many other things. Others may consider the cost to be a risk of the world ending, according to some public speculation. [29]

Chapter 7

Social, Economic and Scientific Benefits of the FCC.

Obviously, the FCC at CERN wouldn't even be under consideration unless there were sufficient benefits. Scientific benefits have already been discussed in previous chapters, so I will first go over the outcome for possible findings. How will what is discovered, benefit the population of earth directly?

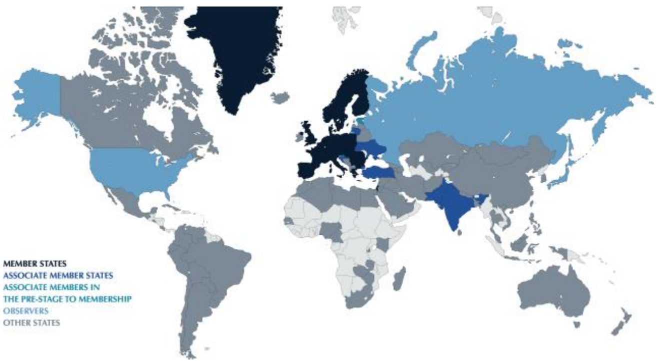
In the past, discoveries at supercolliders have led to huge advances in medical innovations. Almost all of the technology that is developed and advanced by the research conducted at CERN for the hadron colliders, including for the FCC, is useful in other fields. Emerging technologies that need additional research can get an invaluable boost if they're picked up by facilities like CERN, which often happens. [1l]

As a good example, the treatment of cancer using hadron therapy was derived from the technologies developed for use in particle accelerators. Most imaging techniques are greatly advanced through the research published by CERN involving magnetic technologies and superconductors. [1p]

It's not just additional development of currently existing technologies either, the research that is published during the development and operation on colliders is often very applicable in other cutting edge scientific fields, even when at first, they don't seem to be completely linked. For example, the problems that need to be overcome in colliders like the FCC are very similar to problems that need to be overcome in quantum computing. Funding for public research is never truly wasted, even if the project ends up going nowhere. [1q]

The economic benefits are an important part of projects like this because it encourages investment for the completion of the project. Funding for CERN comes the organisations 23 'member states', and many other countries with international co-operation agreements with CERN. Securing the huge funding required from these countries takes convincing evidence that it will be beneficial.

CERN member states, associate member states, associate members in the pre-stage to membership,



observers, and other states. [1o]

A study on the cost / benefits of the high-luminosity large hadron collider (one of the stages on the way to the full FCC), showed that for every Swiss Franc invested pays back around 1.7 Swiss francs in social benefit, and that the programme would economically benefit society. There aren't yet any in depth studies like this for the final FCC, although this gives an idea on how projects like this benefit countries economically. [16][27]

The project benefits are not only directly economic, however. The training provided from the construction and the running of the colliders helps society as a whole, with more highly trained workers in construction, electronics, programming, et cetera. It also encourages the participation of the general public, being such a large science project in the public's eye, increasing scientific literacy and inspiring young people. [16]

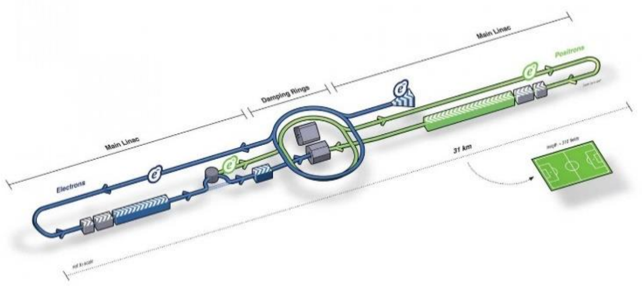
Chapter 8

Possible Alternatives

Although one of the most ambitious projects, the future circular collider is not the only option for a collider that that can reach the TeV range.

In China, there is a planned accelerator program by the CAS IHEP (Chinese Academy of Sciences Institute of High Energy Physics), to make a similar collider to the one at Geneva. They would start with a Higgs factory called CEPC (Circular Electron-Positron Collider) with an energy of 120 GeV and a circumference of 54km – 61km. It would be optimised as a Higgs factory and allow deep probing of the Higgs, with a resolution up to 100 times more powerful than the LHC. The SPPC would then be built in the same tunnel, similar to the FCC-hh at CERN. This accelerator would have a beam energy of 70 TeV, less than the FCC, however as previously mentioned the design is optimal for the exploration of the Higgs, including studying the particles self-interaction. The timeline for the Chinese collider is also much sooner than the collider at cern, with the ee version starting collisions in 2028, and the hh version starting in 2042. That's not to say that it is a choice between one or the other, an FCC presentation in 2014 by Michael Benedikt proposes 'Fruitful collaboration & competition with fcc (joint meetings)'. [30][31][32][33]

International Linear Collider (ILC) schematic [37]



There are also more options. Including the Compact Linear Collider (CLIC) at CERN and the international Linear Collider (ILD) in Japan. Linear colliders have positives and negatives, namely that the beams can be polarised, and it's much easier to upgrade down the line, but also that energies cannot be brought as high as a circular collider, and there is only one collision point. The collision energy of the ILC will be 250 GeV. Again, these are expected to be built alongside the FCC, and to compliment it, however there is argument as to whether it is worth constructing the FCC-ee version at CERN if the ILC and CLIC can do what it can, and that the FCC-ee should be skipped and the FCC-hh should be built. Conversely, some argue that CLIC and ILC are useless due to the plan for the FCC-ee. Either way, the ILC or CLIC can be upgraded down the line, effectively allowing for a permanent, upgradable FCC-ee, for later experimentation down the line. [34][35]

In the end, these are only 'alternatives' if it is completely impossible or impractical to build the FCC, if they were all built to completion, then nothing would be lost.

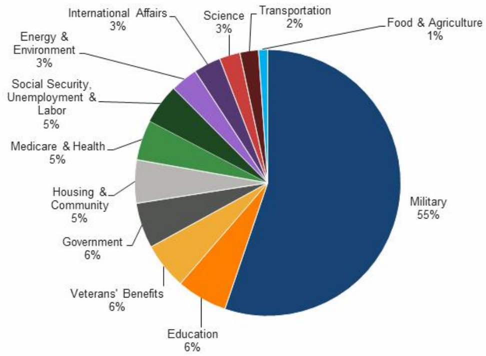
Chapter 9

Conclusion

I believe that particle colliders, as expensive as they might be, are absolutely essential in the progress of physics, and is the only way to work towards a complete and final theory of the universe, unifying gravity, and quantum mechanics, effectively the end goal of physics.

Some people will argue that colliders are too expensive, and that the money should be spent elsewhere. I couldn't disagree stronger with this sentiment. A comparable event with likeness in complexity and excitement in the scientific community is the apollo programme of the 60s. Nowadays, I don't think many people could tell you many of the actual, tangible, scientific advancements given to society directly from those missions, however almost every single field of science was advanced over the duration of the project, being one of the largest scientific undertakings ever. In total, it cost £203 billion adjusted to inflation, which makes the costs of the international collider schemes look like pocket change. [36]

In the end, a lot of the problems within these fields of science are down to a lack of funding.



USA Proposed Discretionary Spending (Fiscal Year 2015) [39]

In 2015, American nondefence research spending was around 60 billion USD (48 billion GBP), around 1.6% of their yearly 3.69 trillion USD total spending at the time. The science budget includes Nasa which received 18 billion USD of funding in 2015. The pie chart above shows how important the US government feels science is, in fact it shows how important everything is to them compared to military. An entire future circular collider could be built just from the money wasted by pharmaceutical companies on convincing doctors to recommend their medications. A lack of funding leaves the sciences to fight among themselves for research money and causes unnecessary conflict and more money wasted in the act of attempting to secure funding. Some fields of physics, like astrophysics, are notoriously underfunded for what they need to be able to do. They don't get much more funding because what they produce is not as tangible as a 100km long tunnel filled with huge machinery, and not as talked about publicly, which is the biggest problem afflicting most scientific projects, and is not easy to fix without alternate methods of funding or government approval [38][39][40]

Chapter 10

Afterword and Methodology

Most of my sources come from academic research papers published in free journals or freely available from archive websites like https://arXiv.org. Finding information was a case of looking up the relevant terms that I needed to know about in google scholar, then looking through all the results until I found what I was looking for. Occasionally, the paper I needed was locked behind a paywall in a journal, looking up '[name of paper] open source' in google then often gave me access to the paper for free on some archive sites.

Google scholar was incredibly helpful for me, as it collects a lot of useful scientific articles in one place. Many of the articles I ended up using and referencing are directly from CERN or other international research organisations (such as [32], a huge collaboration project from many individuals within the Chinese Academy of Sciences across 128 universities). Google scholar has some downsides, such as the results often varying in quality and reliability. I did not have to worry about this much because nobody except for respected experts in the fields writes papers on these colliders, and any papers that do get written are heavily peer reviewed since they are in a spotlight within the physics field. Dispite this, I still made sure my sources were trusted, and they are all from trusted journals or (as mentioned previously) trusted international science organisations.

Another source of information for me were two books, found while looking for information on google books. These were 'Experimental Particle Physics by Deepak Kar' [5], and 'Particle Accelerators, Collider, and the Story of High Energy Physics by Raghavan Jayakumar' [3]. They not only helped me greatly in the search for information to use in my project, but also helped me understand the subject so that I could better explain the complex processes behind the machines that I was talking about.

As you will notice in my references, a large amount of the information I used was found through CERNs official website: https://home.cern/. They do an extremely good job on making what they are doing at cern viewable by the public (this is also clearly visible on their YouTube channel where they make constant posts about the status and science of the LHC: https://youtube.com/c/CERN). The reasons for this are obviously diverse: to inspire people into working in the fields that will contribute to cern, to get people interested in their project and therefore secure more future funding for new machinery and continued experiments, and due to a love for the profession and for the amazing site that they get to work on. Since a lot of information was on this site, I used it many times in order to get simple information that I needed, much of the more complex parts of the LHC and FCC are not included on the website (there is not much information about the FCC on the website in general).

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