TSP: Will the CMS and ATLAS at the CERN Supercollider be sufficient for finding a Quantum Unified Theory of Everything?

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Contents

1 Introduction

One of the greatest unsolved mysteries in Physics - and possibly in all of science - is the existence of a Quantum Unified Theory of Everything. Scientists have been trying to reconcile our two greatest models for explaining the Universe - General Relativity and Quantum Mechanics - for over a century now, with no complete unified theory having been achieved. Despite all efforts, there seem to be some core issues with such a theory, such as the non-renormalizable nature of the Graviton [1], or the need for higher dimensions [2]. However, there have also been significant advances in contenders for a potential Theory of Quantum Gravity, and throughout this paper I will attempt to explore whether our current technology at the Large Hadron Collider (LHC) in CERN, namely the Compact Muon Solenoid (CMS), and A Toroidal LHC Apparatus (ATLAS), will be able to provide us with the experimental proof needed to develop a complete theory, in order to once and for all unravel the true nature of our Universe.

2 What is Quantum Gravity?

2.1 General Relativity

Currently, Physicists have two main theories for explaining everything in our Universe. Both theories work exceptionally well when it comes to making predictions in their given domains, and very few problems have been found with either of them to date. In order to understand the nature of a Quantum Unified Theory of Everything - also called a Theory of Quantum Gravity - one must first understand what is represented by these two current models of the Universe. The first of these theories is General Relativity (GR). Developed by Einstein in 1915 [3], this is a model for gravity and space-time, which explains how matter moves in a curved space-time, and how space-time is curved by matter. General Relativity treats gravity as a geometric distortion of space-time, as opposed to a force, like Newtonian Gravity, and this geometric distortion can be described by Einstein's Field Equations [3]:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{1}$$

Which include both the Gravitational Constant, G, and the speed of light, c, highlighting their unification of gravity and special relativity. General relativity treats space and time as one, unified concept, space-time, which can be distorted by matter, and these distortions affect nearby objects, causing attraction towards the object creating the distortions. This is our current best way to describe the nature of gravity, and almost every observation we have made on a cosmological scale has been predicted by this theory. Some examples of things predicted by GR are: black holes, gravitational time dilation, gravitational lensing, gravitational waves, etc. [4], all of which have been directly observed in experiments.

2.2 Quantum Mechanics

The second of these theories is Quantum Mechanics (QM), which was gradually developed in the first half of the 20th Century by a collection of scientists, including Erwin Schrödinger, Niels Bohr, Werner Heisenberg, Paul Dirac, Max Born, and others [5]. Quantum Mechanics describes the Universe on a microscopic scale, down to the Planck Length, roughly $1.616255 \times 10^{-35} m$ [6]. Fundamentally, it describes particles as waves of probability, which propagate through space and time, and upon measurement, become observable objects. It states that the probability of finding a particle at a given location in space is equal to the integral of the square of the 'wavefunction' describing the motion of the particle, between the given ranges in space. This wavefunction varies for different types of particles, and can be deduced using the Schrödinger Equation [7]:

$$i\hbar\frac{\partial}{\partial t}\mathbf{\Psi}(x,t) = \left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x,t)\right]\mathbf{\Psi}(x,t) \tag{2}$$

This time-dependent variation of the Schrödinger equation contains the reduced Planck Constant, $\hbar$, which is commonly used within QM. It becomes evident, therefore, that a complete Theory of Quantum Gravity will incorporate all three of these fundamental constants - the speed of light, the Gravitational Constant and the reduced Planck Constant. Like GR, QM works exceptionally well in making predictions in its given domain, and has been used in a vast range of everyday technology, such as the semiconductors used in almost every device on the planet.

2.3 Quantum Field Theory

Quantum Mechanics has also been further superseded by another, improved theory, Quantum Field Theory (QFT), which is a combination of Special Relativity and QM. QFT incorporates 3 of the fundamental forces of the Universe, the weak nuclear force, the strong nuclear force and electromagnetism [13], with all of the fundamental particles representing matter and the interactions caused by these forces being represented in something called the Standard Model of Particle Physics. One of the major flaws with Quantum Mechanics is that it fails to describe systems in which there is a change in the number of particles, such as when a photon is absorbed by an electron. Another major flaw is that QM treats each particle separately, despite the fact that each electron in the Universe is identical [14]. Quantum Field Theory addresses both of these problems, by treating particles as excitations of certain fields. These fields fill all of space-time, and particles are only local manifestations of certain fields, which would explain why all particles of the same type are completely identical - the underlying field responsible for their origin is the same everywhere in the Universe.

These quantum fields also have certain restrictions imposed on them, such as conservation laws like energy and angular momentum, and the laws of Physics must still be obeyed after the fields undergo translations, rotations and changes of reference frame. Keeping this in mind, the quantum fields described by QFT must be able to exist in different configurations, like quantum particles, whilst still obeying these rules. The resultant field is a superposition of all possible configurations of these fields, and this resultant field has the property that it can only have an integer number of disturbances, resulting in the appearance or disappearance of quanta of energy - particles. This, in tandem with the different types of vector fields possible, such as spin-1 and spin-½ fields, gives rise to all of the particles found in the Standard Model, and assigns them the colour charges and electric charges which they possess. We are now able to see how QFT solves the other problem of QM - all of the possible interactions of particles in all possible configurations of the quantum fields, and their relative probabilities, superpose to give the situation observed in reality, such as a photon being transmitted between two electrons [14].

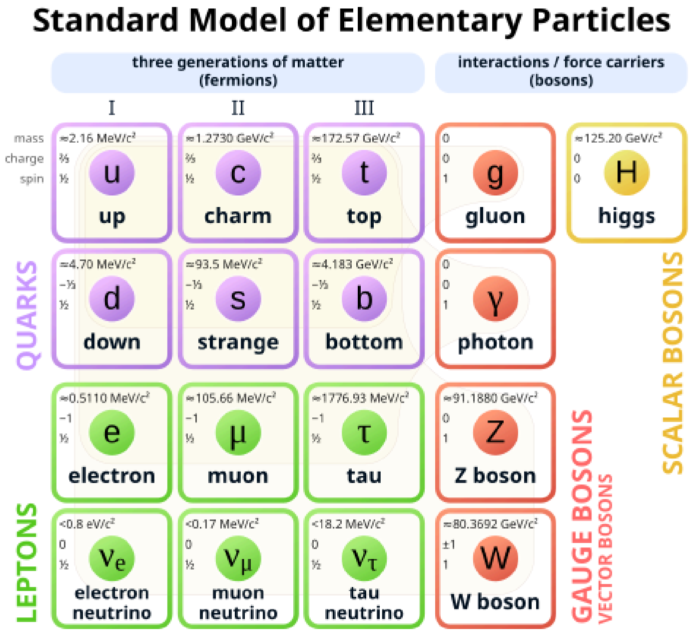


Figure 1: Diagram of the Standard Model of Particle Physics, showing the fermions which make up matter on the left, and the bosons which transmit forces on the right [11].

2.4 Quantum Gravity

As you may have noticed, the Standard Model does not include a particle to mediate gravity, like the other three fundamental forces. However, we cannot simply add a particle to fix this, as we will explore later on, when we explore the nature of the Graviton.

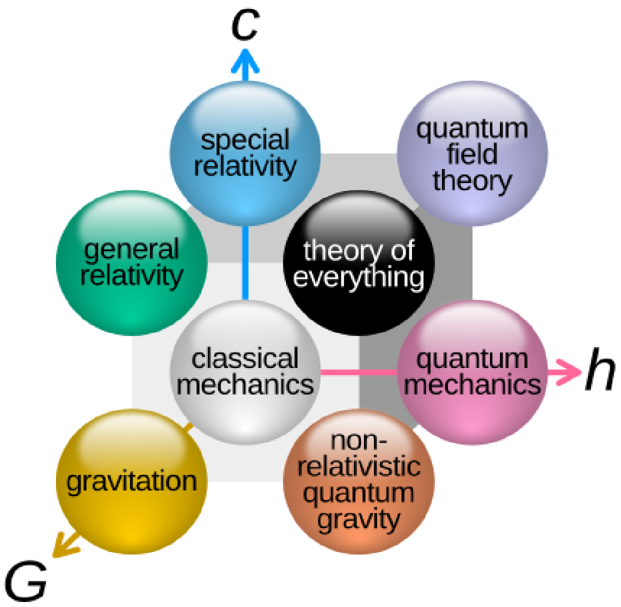


Figure 2: 3-Dimensional graph representing the different major theories in Physics, and the different constituent theories they combine, with a Theory of Everything shown in the centre [12].

Now that we have the theoretical framework needed to understand the foundations of a theory of Quantum Gravity, we are able to ask the question - why, if both of these theories work immaculately in their separate domains, are we unable to combine them into a single unified theory? That is the main problem to solve when it comes to developing a theory of Quantum Gravity (QG). Some of the problems that arise when we try to do so are; the Schrödinger Equation is sometimes violated by something called the 'wavefunction collapse', the Graviton appears to be non-renormalizable (which will be explained later in this paper), and problems with the continuity of GR [8]. Several different theories of Quantum Gravity have been proposed, such as M-Theory and different Supersymmetric Theories, but I will go into detail into two particular theories, which are believed to be the most widely-supported in the scientific community.

2.5 String Theory

The first of these theories is String Theory, and it is the theory that I will mostly focus on. String Theory (ST) seeks to describe the Universe by modelling the fundamental particles as 'strings', which have different modes of vibration, much like the vibrations on a guitar string, and so are able to have different properties as a result. One of the most crucial aspects of String Theory is its ability to model the Graviton, the particle which is believed to transmit gravity. When trying to incorporate a Graviton into the Standard Model of Particle Physics, a myriad of problems arise, and the model breaks down, and String Theory prevents a lot of these problems through the way that it models this new particle. More specifically, ST models these strings as either being open or closed, and the different vibrating modes behave on our scale as particles of different types. When Physicists performed the necessary calculations for this model, they discovered that some strings behave as particles currently in our Standard Model, and some even behave like Gravitons [9]!

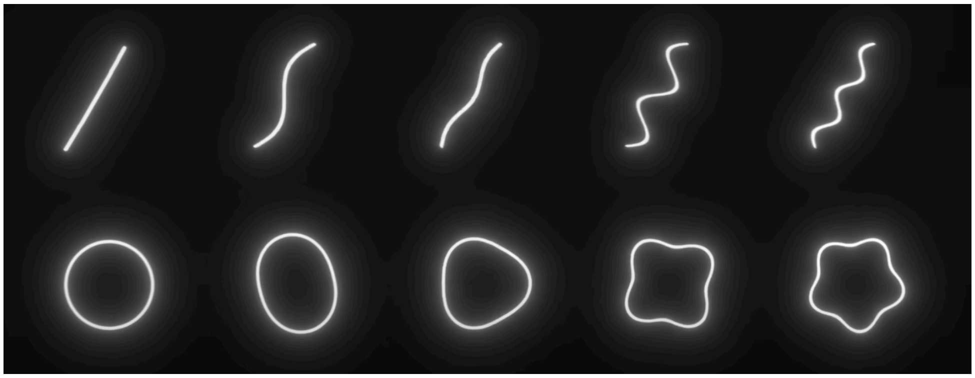


Figure 3: Diagram of the different vibrational modes of open and closed strings [9].

Like discussed with QFT, these strings can trace out different trajectories as they evolve through time, and the observed trajectory is the superposition of all possible paths the string could have taken and their relative probabilities. However, unlike in the Standard Model, the different interactions a string can undergo in its path are continuous, rather than instantaneous, such as a photon being gradually emitted. This solves one of the problems associated with trying to add the Graviton in the Standard Model, which will be explored more deeply in the following section, and this allows us to describe QG. However, ST also has numerous problems associated with it. The first of these is that the model is unable to predict the existence of fermions (matter particles), which constitute all of the matter in our Universe. The second problem is that one of the particles predicted by ST (the Tachyon) appears to have an imaginary mass, i.e. $m = \sqrt{-1}$, which is a mathematical flaw in the theory. The final, and arguably most significant problem with ST is that it appears to only work in a universe with 26 space-time dimensions, unlike the 4-dimensional universe we live in. Some of these problems can be fixed by adding spinors on the strings, which are the same mathematical ingredient used to describe fermions in the Standard Model. This allows us to represent fermions using ST as well as bosons, and the existence of the Tachyon is no longer predicted. This more complete theory is called Superstring Theory (SST), and although it solves most of the original problems with ST, one problem remains - the theory still needs 10 space-time dimensions to function properly. However, the key to solving this problem may lie in the LHC at CERN, as we will explore later [9].

2.6 Loop Quantum Gravity

The second contender for a theory of QG is Loop Quantum Gravity (LQG). LQG takes a very different approach to quantising gravity than ST, in that it aims to quantise space-time itself, as opposed to introducing a new particle for transmitting gravity. LQG describes the Universe as something built up from ‘connections’ which are mathematical functions which tell you how something, such as a vector, changes as it moves between two points in space. When these connections are evaluated over closed loops, it is possible to define any geometry in 3-dimensional space using a ‘weave’ of these loops, with each loop representing a closed circuit of gravitational field. This space of loops, representing space-time, can be quantised very neatly, and in a background-independent way, meaning that 3-dimensional space itself is built upon these loops. This results in LQG, a more complex way to describe space-time, built upon GR, and using specific building blocks for the Universe we live in to allow gravity to be quantised [15]. Although LQG allows for gravity to be quantised without making any additional assumptions, such as about the existence of strings, it too, like ST, has drawbacks. For example, LQG must provide the same equations given by GR when acting on a large, non-quantum scale, but so far there is no clear indication of it being able to do so. Also, the background-independence of LQG, while applying in 3-dimensional space, doesn’t appear to extend to 4-dimensional space-time, which creates problems when introducing the evolution of systems of particles over time [15].

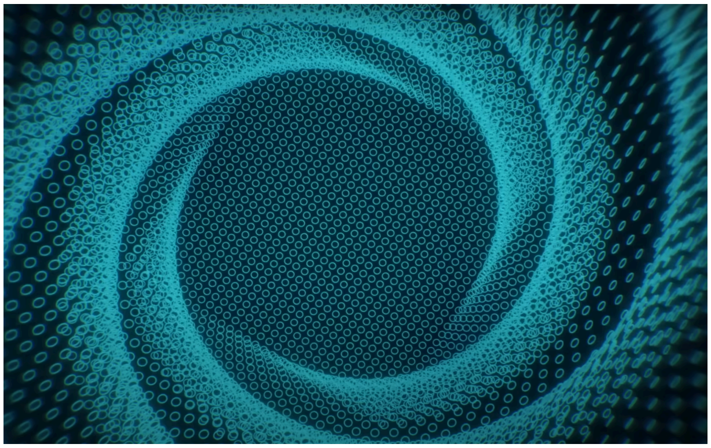


Figure 4: Depiction of the loops making up space-time [15].

Ultimately, understanding GR and QM is necessary for taking the steps required to create a theory of Quantum Gravity, and although we have promising suggestions for a Theory of Everything, there are several problems which must first be addressed, and this is what I will aim to do for the rest of this paper.

3 The Graviton

3.1 Non-renormalizability

As mentioned previously, the Standard Model of Particle Physics shows the different matter particles (fermions) and force-carrier particles (bosons) and the ways they are classified. The Graviton is the name given to the particle responsible for transmitting gravity between fermions, and although no such particle has been directly observed, there are strong hypotheses for the properties that the Graviton may have. Firstly, it is thought to be a massless particle, and so propagates at the speed of light, which is supported by the observation of gravitational waves given off in events such as black hole collisions. Another property of the Graviton is that it has a quantum spin of 2, due to the fact that the stress-energy tensor, which is the tensor responsible for gravitation, is a second-order tensor. Finally, the Graviton is believed to have neither a colour charge nor electric charge, making it an overall neutral boson [16]. At first glance, the Graviton doesn't seem that different from the other fundamental particles, so why is it so difficult to incorporate into the Standard Model? The main problem comes with its non-renormalizable nature.

Non-renormalizability refers to the inability to remove the infinities which arise in calculations by altering the values used in the calculations to account for the effects of their self-interactions [19]. At low energies, the classical action (a scalar quantity that describes how the balance of kinetic versus potential energy of a physical system changes with trajectory [17]) for GR in the presence of matter is:

$$S = \frac{1}{16\pi G_N} \int \sqrt{-g}\,(R - 2\Lambda + \mathcal{L}_{\text{matter}})$$

(3.1)

Performing a derivative expansion on the Lagrangian and ignoring the matter terms, and matter-curvature couplings, provides us with the Einstein-Hilbert term and higher curvature corrections:

$$S = \frac{1}{16\pi G_N} \int \sqrt{-g}\left(-2\Lambda + R + c_1 R^2 + c_2 R_{\mu\nu}R^{\mu\nu} + c_3 R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} + \cdots\right)$$

(3.2)

Finally, as are the rules of effective field theory, we will fix the coefficients by dimensional analysis:

$$\frac{1}{G_N} \equiv (M_P)^{D-2}$$

(3.3)

As is clear from the above, for D > 2, this term is not renormalizable, meaning that at the Planck scale, any calculations involving the Graviton would yield nonsensical results, and would therefore be unusable.

In order to fix the problems caused by this, new Physics must appear below the Planck length [1].

Another, easier to follow example of non-renormalizability (not for a Graviton) can be seen below:

$$\Delta m^2 = \frac{\lambda^2}{2}\int \frac{d^4p}{(2\pi)^4}\frac{1}{(p^2+m^2)((p+q)^2+m^2)} = \text{finite} + c\cdot\int^{\infty}\frac{dp}{p} = \infty$$

(3.4)

This is the result provided by the 1-loop correction to the mass in scalar $\lambda\phi^3$, used in QFT, and is an example of problems with non-renormalizability [18]. Since Physics is bound to break down at some scale, integrating to infinity in momentum space yields no useful results, and this is a very common problem when trying to quantise gravity using the Graviton. One way in which this problem can be treated is by modelling the Graviton as a string, as opposed to a point in space, such as how it is treated in String Theory. This means that the interactions a Graviton undergoes through time are continuous, rather than instantaneous, and removes a lot of the infinities which arise when performing calculations, making it renormalizable [9]. Another way in which this issue can be overcome is demonstrated in LQG. As LQG quantizes space-time itself, it has no need for a Graviton to transmit gravity, and so the problems associated with the Graviton do not apply. It is now clear that the Standard Model alone is insufficient to incorporate gravity into our current models for the fundamental forces and particles, but are they even necessary, and furthermore, is it even possible to try and measure them experimentally?

3.2 Energy of Gravitons

As shown by LQG, it is possible to have a potential Theory of Everything (TOE) without the need for a Graviton. However, the existence of a Graviton is strongly supported by the predictions made by ST for the existence of such a particle. Furthermore, all interactions between fermions seen in the Universe thus far involve the exchange of a boson, so there is no reason to suspect that this would not be the case for gravity as well. Assuming that detecting a single Graviton is physically possible, first we calculate the energy density in a gravitational wave, which is made up of these Gravitons:

$$\rho = \frac{1}{4}M_{\text{Pl}}^2\langle\partial_t h^{\mu\nu}\partial_t h_{\mu\nu}\rangle$$

(4.1)

,with M_{Pl} the reduced Planck mass. For a wave of strain h and frequency ω , this corresponds to:

$$\rho = \frac{1}{4}h^2\omega^2 M_{\text{Pl}}^2$$

(4.2)

Dividing this energy up into Gravitons of energy ω, we find that the number of quanta per de Broglie volume $\lambda_{\text{dB}}^3 = f^{-3}$ is:

$$n\lambda_{\text{dB}}^3 = \frac{\pi h^2 M_{\text{Pl}}^2}{2f^2} \simeq 2\times 10^{35}\left(\frac{h}{10^{-22}}\right)^2\left(\frac{1\text{ kHz}}{f}\right)^2$$

(4.3)

Where:

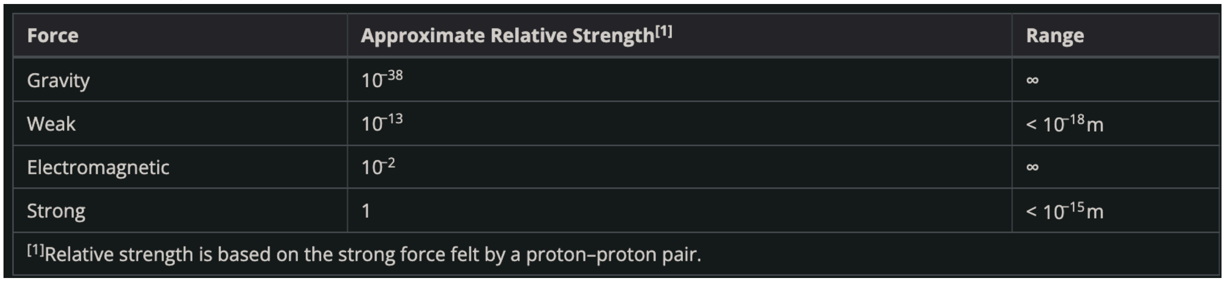
$$f = \frac{\omega}{2\pi}$$

(4.4)

is the linear frequency. It is clear from this result that the number of Gravitons in an observable gravitational wave is extraordinarily large, and even though high frequencies dilute the number of Gravitons in a given part of the gravitational wave, this is still far too many to realistically observe experimentally [20]. The exact parameters for the size of detector needed to observe individual Gravitons will be discussed later on, but for the time being we will continue under the assumption that doing so is not physically possible.

3.3 Strength of gravity

The reason for this extremely large number lies in the strength of gravity. Unlike the other three fundamental forces, which are relatively strong and able to act on an atomic scale, gravity is only able to dominate on very large, cosmological scales, such as in planets and stars. One of the only exceptions to this are black holes, which are able to have an extremely small volume whilst still retaining a strong gravitational attraction. As shown by Figure 5, gravity is 25 orders of magnitude weaker than the second weakest of the fundamental forces - the weak nuclear force [21], and it is due to this very low strength that the Graviton - if it exists - is extremely hard to measure. Furthermore, the hypothesised neutral and massless properties of Gravitons mean that their interactions with other particles would be extremely limited, if it all present, making them even more difficult to observe. Clearly the technology needed for the observation of Gravitons is very complex and requires much development, and I aim to justify by the end of this paper whether the LHC at CERN will be able to rise to the challenge, or whether a new approach entirely will need to be taken to produce experimental data.



Force	Approximate Relative Strength[1]	Range
Gravity	10^{-38}	∞
Weak	10^{-13}	$< 10^{-18}$m
Electromagnetic	10^{-2}	∞
Strong	1	$< 10^{-15}$m

[1] Relative strength is based on the strong force felt by a proton–proton pair.

Figure 5: Table showing the relative strength and ranges of the four fundamental forces [21].

4 The CMS and ATLAS at CERN

4.1 About the CMS and ATLAS

The Large Hadron Collider (LHC) located in CERN is the greatest scientific tool humanity possesses when it comes to studying Particle and Atomic Physics, and it is also at the forefront of the research for a TOE. It is the largest and most powerful particle accelerator in the world, first being started up on 10th September 2008. It consists of a 27km ring of superconducting magnets, with a number of accelerating structures to boost the energy of particles as they are being accelerated through the collider. Particles in the LHC are accelerated to speeds of up to 99.9999991% the speed of light - fast enough to smash them together and to peer into the Physics revealed in extreme conditions. Two particle beams in the LHC are accelerated in opposite directions down the supercollider in ultrahigh vacuum, and are guided around the accelerator ring by a strong magnetic field maintained by superconducting magnets, with other types of magnets being used to increase the chances of a collision [22]. These particle beams are made to collide in one of four locations around the ring, corresponding to the positions of the four particle detectors - ATLAS, CMS, ALICE and LHCb. I will examine in detail the former two of these detectors.

A Toroidal LHC Apparatus (ATLAS) is one of the two general-purpose detectors at the LHC, which aims to investigate things such as the Higgs boson, extra dimensions (which will be of significance later on) and candidates for dark matter particles. Although it has similar goals to the CMS detector, it has a different design and technical solutions to achieve those goals. The collision debris (new particles) formed from the interactions of the beams of particles being accelerated in the LHC scatter in different directions, and 6 different detecting subsystems arranged in layers around the collision point record the paths, energy and momenta of the particles, allowing them to be identified. A large magnet is used to bend the paths of charged particles so that their momenta can be measured [23]. Due to the sheer amount of particle data ATLAS is capable of collecting, it uses a trigger system to choose which data to ignore and which to collect, and the collected data is then analysed using computing systems and complex data-acquisition. ATLAS is the largest volume particle detector ever constructed, with more than 5500 scientists from 245 institutes in 42 countries working on the ATLAS experiment [23], so it should be of no surprise that many scientists have high hopes for it when it comes to breakthroughs in QG.

The Compact Muon Solenoid (CMS) is the other of the two general-purpose detectors at the LHC, which has a broader Physics programme than ATLAS, including studying the Standard Model more generally (including the Higgs boson), and like ATLAS, searching for particles which could constitute dark matter, and looking for higher dimensions [24]. The CMS is built around a large solenoid magnet, which is a type of magnet formed by a helical coil of wire whose length is substantially greater than its diameter, which generates a controlled magnetic field when an electric current is passed through it [25]. The solenoid magnet in the CMS takes the form of a cylindrical coil of superconducting cable which generates a magnetic field of 4 tesla, about 100,000 the strength of the Earth's magnetic field, and this field is confined by a steel "yoke" which forms the bulk of the detector's 14,000-tonne weight. Like the ATLAS experiment, the CMS experiment is one of the largest international scientific collaborations in history, involving about 5500 particle physicists, engineers, technicians, students and support staff from 241 institutes in 54 countries [24].

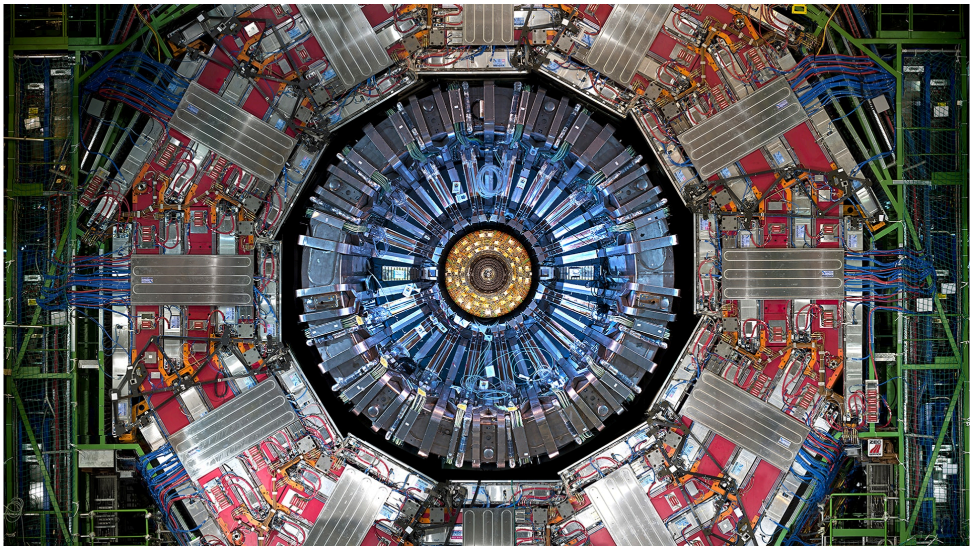


Figure 6: Image of the inside of the CMS at CERN [26].

QG and the Graviton are very advanced areas of research, so will the CMS and ATLAS even stand a chance at uncovering something? I will begin to answer this question by looking at the past achievements made by these detectors.

4.2 Achievements of the CMS and ATLAS

One of the newest and arguably greatest discoveries in modern Physics is that of the Higgs boson. The Higgs boson is a scalar boson, seen in Figure 1, which is responsible for giving the fundamental particles their masses through the Higgs field, and the existence of this field was confirmed in 2012 when CERN discovered the Higgs boson particle [27]. More generally, particles do not have their own mass, but by interacting with the Higgs field, they are able to gain a mass, with the stronger-interacting particles becoming heavier, whereas particles such as photons, which do not interact with the Higgs field, have no mass. The Higgs boson cannot be naturally observed, but rather must be created and then measured, which is exactly what was done by the LHC. Particle collisions in the LHC resulted in the formation of a Higgs boson particle, which then decayed into other particles, which were in turn detected by both the CMS and ATLAS detectors. Scientists were sure that the resultant particle was indeed the hypothesised Higgs boson, due to it being the only particle with a spin of 0, and also due to the fact that it was neutral and decayed very quickly [27]. This is a clear example of a new particle being discovered by the CMS and ATLAS detectors in CERN, highlighting how their near-perfect detection systems and advanced designs allow them to investigate the smallest scales in the Universe.

On top of this, the existence of every other particle in the Standard Model has also been confirmed, namely by ATLAS, confirming that the current theory we have for the Standard Model is correct to some extent. However, whether these discoveries prove that the detectors are capable of making significant contributions toward QG is a different question entirely. The first aspect of such research that needs considering is the much smaller size of the Gravitons, along with their hypothesised massless nature. Although both the Graviton and the Higgs boson have no charge, the very high mass of the Higgs boson means that it decays into other high mass particles, making it much easier to detect, whereas the Graviton possesses no such mass, and so is a lot more difficult to detect. Even taking into account the maximum possible mass a Graviton could have, deduced from observations made on gravitational waves, this would leave the Graviton with a mass of approximately $2 \times 10^{-62} g$ [28], which is still far less than any particle observed to date. This, on top of its extremely low cross-section for interaction with matter, makes it very unreasonable to expect our current detectors to be enough to observe such particles, despite their past achievements. Just how unreasonable, I will attempt to explore now.

5 Detector for measuring Gravitons

5.1 Detecting Gravitons

As mentioned before, the Graviton, if it exists, would be extremely difficult to detect, as a result of its very low mass and cross-sectional area, and neutral charges. According to some calculations performed by Freeman Dyson, the energy density of a single Graviton would be on the order of $3 \times 10^{-48} Jm^{-3}$, for gravitational waves with an angular frequency of 1000Hz and an energy density when they arrive at Earth of approximately $10^{-11} Jm^{-3}$ [29]. This provides an estimate of around 3×10^{37} Gravitons per m^3. For the model of our hypothetical gravitational wave detector, let us detect incoming gravitational waves by detecting the change in the distance between two masses. Furthermore, Dyson postulates that, in order to detect a single Graviton, we must be able to detect a change in distance on the order of a Planck length, and this requirement is independent of the frequency of the Graviton. As the Graviton moves past our detector, the masses move in and out by very small amounts. In order for the detector to be sensitive to that very small change in distance, it needs to measure the positions of each of those masses with a precision equal to half of that change. In other words:

$$\Delta x = \frac{1}{2}\Delta D$$

(5.1)

However, the precision with which we can measure the positions of the masses is limited by Heisenberg's Uncertainty Principle, something which is key to QM:

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

(5.2)

While the masses are being moved by the Graviton, their speed changes by an amount equal to the distance they travel divided by the time it takes for a single Graviton to pass by, equal to:

$$\Delta v = \frac{\Delta D}{t} = \frac{\Delta D c}{D}$$

(5.3)

This result is obtained using the assumption that Gravitons move at the speed of light, and this gives us the variation in our speed during our measurement. This, multiplied by the change in mass itself, provides us with the change in momentum due to the passage of the Graviton:

$$\Delta p = M\delta v = \frac{M\Delta D c}{D}$$

(5.4)

From Dyson's calculation, we obtain:

$$\Delta D = L_P$$

(5.5)

Where L_P is the Planck length. This provides us with an uncertainty in the position and momentum of the masses of:

$$\Delta x = \frac{L_P}{2}$$

(5.6)

$$\Delta p = \frac{M L_P c}{D}$$

(5.7)

Plugging this back into the equation for Heisenberg's Uncertainty Principle gives us:

$$\frac{L_P}{2}\frac{M L_P c}{D} \geq \frac{\hbar}{2}$$

(5.8)

Further rearranging gives us:

$$\frac{L_P^2 M c}{D} \geq \hbar$$

From the value of the Planck length we obtain:

$$L_P = \sqrt{\frac{\hbar G}{c^3}}$$

(5.9)

Plugging this back into our original equation provides us with:

$$\left(\sqrt{\frac{\hbar G}{c^3}}\right)^2 \frac{Mc}{D} \geq \hbar$$

(5.10)

Some further rearrangement provides us with:

$$\frac{\hbar GM}{c^2 D} \geq \hbar$$

Finally this provides us with:

$$D \leq \frac{GM}{c^2}$$

(5.11)

Which we then multiply by two, as we are working with the distance between two masses, not one:

$$D \leq \frac{2GM}{c^2}$$

(5.12)

This is a very, very bad result, since it is equivalent to the formula for the Schwarschild radius of a black hole:

$$r_s = \frac{2GM}{c^2}$$

(5.13)

In other words, this is the radius of the sphere that an object of mass M needs to be compressed to in order to form a black hole [30]. What this means is that, assuming Dyson's calculations are correct, any gravitational detector capable of detecting a single Graviton will form a black hole upon measurement of said Graviton, preventing any information from the measurement from being recorded or observed. Although there are other possible designs for a Graviton detector, all of them are far more complex than what humanity is currently capable of constructing, so it seems that, despite all efforts, measuring Gravitons seems far from the realm of possibility, especially with the CMS and ATLAS detectors we currently possess.

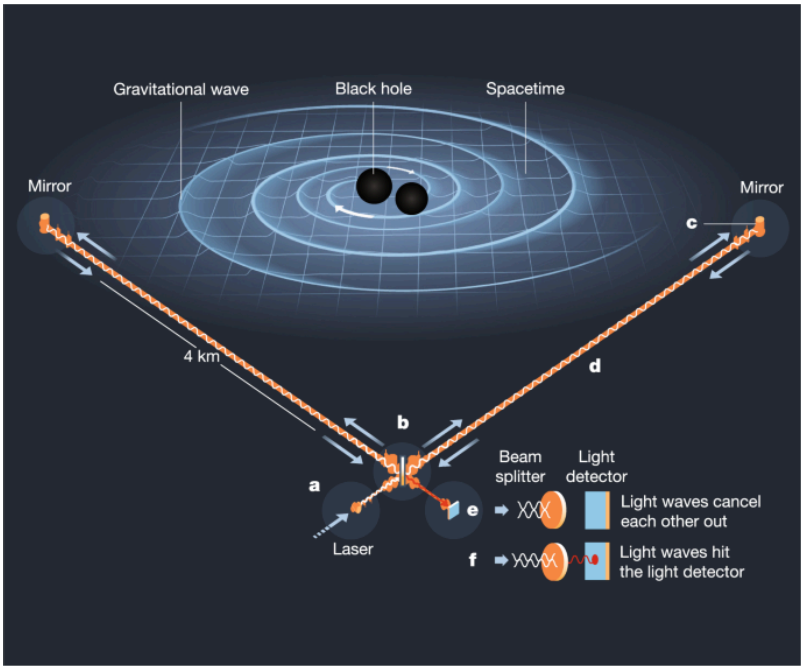


Figure 7: Depiction of a hypothetical Graviton detector [32].

5.2 Alternative Graviton-measuring experiments

Other, similar calculations show that, even with a detector with the mass of Jupiter and 100% efficiency, placed in close orbit around a neutron star, an object with an immensely powerful gravitational field, a Graviton would be observed only once every 10 years or so under the most favourable conditions. Furthermore, the neutrino shield that would be needed to filter out the interactions produced by this Graviton would be so large that it would inevitably collapse under its own weight to form a black hole [16]. In order to detect Gravitons, Physicists may need to search for the extremely rare hypothesised interactions between matter particles and Gravitons, but for now this seems unfeasible, due to the fact that there would be so few collisions that it would be impossible to collect sufficient evidence for the existence of the Graviton. Another alternative is inventing an extremely powerful source of Gravitons which can be fired at a detector, vastly increasing the chances of an individual Graviton being observed, but such Physics is very far outside of our current capabilities and understanding when it comes to technology involving gravity.

A final proposition for how to measure Gravitons is by using the principle of quantum entanglement. Quantum entanglement states that the properties of one particle may depend on the properties of another particle, no matter how far away the two particles are [31]. If scientists can cause two particles to become quantum entangled through a gravitational interaction, that would prove that the interaction itself has to be quantum, indirectly proving the existence of a quantum of gravity - the Graviton. Unfortunately, no such experiment has been successfully conducted so far, so it is clear that Physicists will have to take on a new approach to find a TOE, which doesn't involve the detection of a Graviton.

6 Extra spatial dimensions

6.1 Kaluza-Klein particles

However, all hope is not lost for the CMS and ATLAS. Although it may not be possible to detect Gravitons, there are other experiments which could be performed to further our research towards a theory of QG, and one of these is the investigation into the dimensions of our Universe. One of the current goals for the two detectors is the study of these higher dimensions, as their discovery could provide us with more evidence for certain TOEs, such as Superstring Theory (SST), as mentioned in Section 2. To recap, SST requires 10 dimensions to function properly, yet our Universe is only made up of 3 spatial and 1 temporal, and so 4 in total, dimensions. However, it may be possible for our Universe to be a 3-dimensional ‘slice’ of a larger, 9-dimensional universe (with 1 temporal dimension) - something known as the brane-bulk model. Another alternative is that other spatial dimensions with certain topologies exist in our Universe, which are simply too small for us to observe with our current technology. These 6 extra spatial dimensions would be curled up on themselves, such that they cannot be differentiated from our usual 3 dimensions of space at a large scale [9].

There are different ways in which these extra dimensions can possibly be detected. One approach is to observe massless particles which are travelling at the speed of light. If these particles travel partially through compact dimensions, they would appear slower to us than expected, due to the fact that at our scale, these dimensions cannot be observed. This could hint at the existence of smaller dimensions in our Universe, so one of the things that the CMS and ATLAS can search for are massless particles moving at a speed slower than the speed of light (approximately 299,792,458m/s). Such particles would therefore appear heavier than they actually are, with all of their other properties being identical to the original type of particles, and are known as the Kaluza-Klein states of particles. However, one drawback of the existence of these higher dimensions is that they allow for more variation in the vibrational modes of strings, and can also be compactified in a multitude of different ways. This leads to many different possible universes and particles existing, which would either imply that our current model of the Universe is far from complete, or that the existence of extra dimensions is impossible in the universe we live in. This holds true even if we attempt to alter the way in which the extra 6 dimensions are compactified, such that the resultant particles match the ones that our observed Universe contains [9].

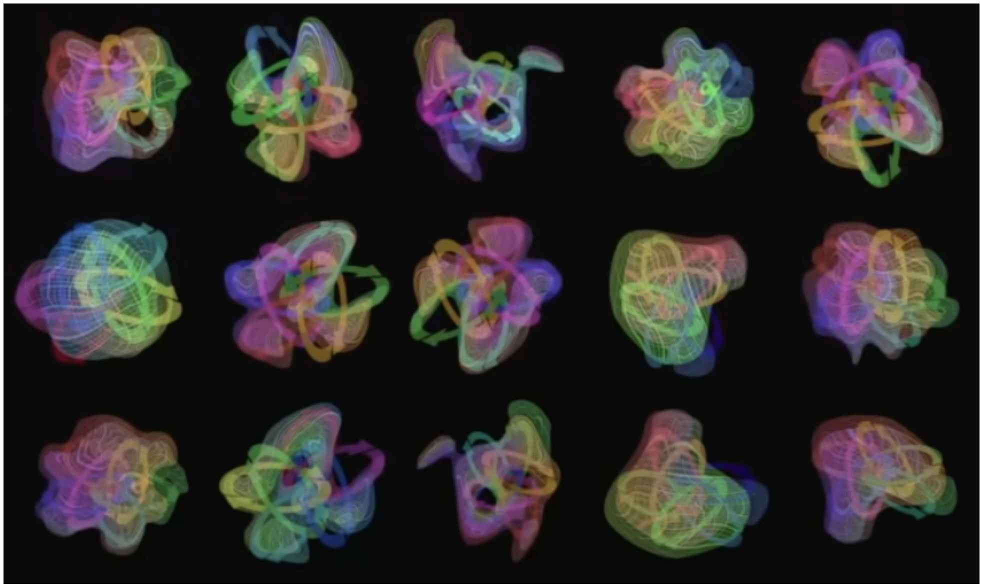


Figure 8: Artist depiction of the different ways that the extra dimensions can be compactified [9].

6.2 Microscopic black holes and dissipation of gravity

Another way of searching for extra dimensions is by looking for microscopic black holes. If such black holes were to be created in the LHC they would disintegrate in roughly 10^{-27} seconds, decaying into all of the particles in the Standard Model, and creating a signature that could be easily detected by the CMS or ATLAS [33]. The CMS has conducted searches for multi-object final states to look for such microscopic black holes, but none have been found as of yet. ATLAS has also searched for microscopic black holes in the LHC by taking a different approach to the CMS and looking for lepton jets which would be produced by the decay of these black holes, but there has been no success, like with the CMS experiments. However, that doesn't mean that the possibility of such events can be ruled out at this stage, as there are many different ways in which extra dimensions or microscopic black holes can be detected apart from the two listed above [34].

Moreover, there is another incentive for believing in the existence of extra dimensions - the strength of gravity. As highlighted by Figure 5, gravity is much weaker than the other fundamental forces - almost unrealistically so. One possible explanation for this very weak nature of gravity could be that the strength of gravity is dissipated amongst extra dimensions. This would mean that Gravitons produced in particle collisions in the LHC would seemingly 'disappear' into these compactified dimensions, which would leave behind an imbalance of energy and momentum [35]. As these two quantities must be conserved, this could hint at not only the existence of Gravitons, but also at the existence of extra dimensions. Like the microscopic black holes and Kaluza-Klein particles, these energy and momentum "gaps" are something that the CMS and ATLAS are actively searching for, in hopes of finding proof to guide us towards a complete understanding of the Universe.

Our current theories suggest that extra dimensions may not only be useful for furthering models such as SST (and therefore also favour one model over another, such as SST over LQG), but rather they may be essential for explaining our Universe, such as by providing a reason for the strength of gravity relative to the other fundamental forces. The two general-purpose detectors in the LHC are definitely essential for working towards the goal of finding such dimensions, if they exist, and any discoveries in this field are likely to provide scientists with the key insights required to find a Theory of Everything.

7 Benefits, limitations and alternatives to supercolliders

7.1 Benefits of supercolliders

Thus far, I have examined the feasibility of using the CMS and ATLAS detectors to aid us on the quest for a theory of QG, without considering the practicality of doing so and without looking at other alternatives. In this section, I will aim to do exactly that. One of the main benefits of using supercolliders and particle detectors for examining our universe and making experimental observations is that they are able to provide scientists with an extremely accurate view into the subatomic world. For example, the masses of many fundamental particles can be accurately deduced through the detection of the decays which occur during particle collisions, which in turn allows us to construct detailed models of our universe. Supercolliders are also capable of simulating extreme conditions which a lot of other equipment used for

Physics research is not, such as particles being accelerated to velocities very near the speed of light. This provides us with the capability to perform experiments which involve pushing the laws of Physics to the edge, which returns a high reward in subsequent observations and research. However, despite their advantages, supercolliders also have many drawbacks which must be addressed.

7.2 Drawbacks of supercolliders

One such drawback is cost. Due to the very high speeds which particles need to be accelerated to, supercolliders must usually be very long and have a large diameter. This, combined with the extremely expensive materials used in such supercolliders, such as superconducting magnets and large steel structures, make them extremely expensive. As an example, the CERN supercollider had an estimated total cost of production of around $4.75 billion [36]. Furthermore, the insane energy required to accelerate the particles to the speeds they reach in the collider, combined with the current that needs to be supplied to create the magnetic fields used to do so, and the energy used in the detectors to make observations, further increases the costs. There are also numerous other sources of cost, such as transportation, personnel required to operate the collider, and many, many more. As a result, a vast sum of money which could be put into other areas of Physics research is being poured into such structures, which, as will be discussed later on, may not be the best and only way to provide us with the evidence we need for a TOE.

Another drawback is time. The construction of the LHC took a little over a decade to complete [36], which is a very long time in the scientific community. The engineers and Physicists working on the construction of the LHC could have dedicated their efforts to other avenues of research, allowing for a much higher number of scientific advances throughout the time of its construction. On top of this, the larger the supercollider, the more likely it is to be able to yield promising results. This means that any future supercolliders are likely to have to be much larger than our current ones to achieve future goals, and so will take much more time to complete - so much so, that by the time of their completion they may no longer be required. It becomes apparent that, despite their past achievements, supercolliders and their detectors, such as the LHC and its two general-purpose detectors, the CMS and ATLAS, may no longer be the most economically viable, nor most time-efficient solution for probing new areas of Physics and working towards a theory of QG. If that is the case, what are some alternative approaches to researching QG?

7.3 Gravitational wave astronomy

One potential approach, which is currently being used, is using gravitational wave detectors, such as the Laser Interferometer Gravitational-Wave Observatory (LIGO). Gravitational waves, as mentioned earlier, are ripples in space-time created by violent cosmological events, such as the merging of neutron stars or black holes. These gravitational waves are believed to be made up of countless numbers of Gravitons, and so studying the nature of gravitational waves will inevitably lead to an insight on the properties of Gravitons, if they exist. Similar to the hypothetical detector I constructed earlier, gravitational wave detectors often work by having two distant mirrors which reflect light towards a detector [37]. Whenever a gravitational wave passes through the detector, it causes the mirrors to move by a very small amount, as space-time itself warps, and this change in distance between the mirrors can then be detected by the detector as the light from the laser is received differently from normal. Observing gravitational waves allows us to to learn more about the nature of gravity itself, and could possibly be the key to relating it to QFT and creating a quantum theory of gravity, meaning that gravitational wave detectors are on the frontier of the technology used for research into a TOE, and could be an equally good, or even better replacement to supercolliders for such research, due to their specialised focus and higher sensitivity towards gravitational phenomena.

7.4 Cosmic Microwave Background Radiation detection

Another equally viable approach is to use Cosmic Microwave Background Radiation (CMBR) detectors. These detectors observe the background radiation left over in the Universe after it formed, roughly 13.8 billion years ago. Due to the extremely high temperatures during this formation, a lot of very high frequency radiation was released, which has cooled over time as a result of the Universe's expansion, forming what is now known as the Cosmic Microwave Background (CMB). If String Theory or any related theory, is correct, then the Universe may contain what are known as cosmic strings. These are strings which were stretched out at the very beginning of the Universe, during its phase of rapid expansion [38]. These cosmic strings could lead to certain discontinuities or patterns in the CMB of the Universe, which can then be detected by our CMBR detectors, hinting at the existence of these strings, and as a result, string theory [39]. Another avenue of research is primordial gravitational waves. QG predicts the existence of powerful gravitational waves which occurred during the inflationary period of the early Universe, and which would also affect the patterns of the CMB, allowing them to potentially be detected using CMBR detectors [40]. This, along with many other possible observations, make CMBR detectors very important in the search for a TOE, just like supercolliders and gravitational wave detectors.

Overall, there are multiple alternatives to supercolliders when it comes to searching for a theory of QG, and many people could even argue that supercolliders are a waste of billions of dollars, and that this money should be spent developing other sectors, instead of searching for a theory which may not even exist. However, despite the controversial public opinions concerning these structures, it is an undeniable truth that the CMS and ATLAS at CERN have made discoveries which would not be possible with other types of detectors, and so there is a strong reason to believe that they will continue making useful contributions to our understanding of the Universe in the future, and are therefore a worthwhile investment.

8 Conclusion

The CMS and ATLAS at CERN have undoubtedly played a very important role in our quest for a theory of QG, both thanks to their past discoveries, and further discoveries they are likely to make in the future. Although directly observing Gravitons may not be the best way to go about developing our understanding of how gravity behaves on the quantum scale, there are still many alternative areas of Physics which these detectors allow us to probe, which can still help build upon our model of the Universe, such as the presence of extra dimensions. I personally believe that, although gravitational wave detectors and CMBR detectors are also very promising when it comes to investigating QG and can provide us with a lot of valuable insights, these general-purpose detectors at the LHC are essential for examining Physics at the most fundamental and extreme level - it is only possible to gain a complete understanding of the functionality of the Universe on a cosmological scale by considering the very building blocks which make up that Universe. Additionally, although many may view supercolliders as an unnecessary, and even damaging expense for a country, it is by furthering our current understanding of the Universe that we are able to progress as a species, and to explore the reason for our existence, in order to one day be able to develop a truly complete Quantum Unified Theory of Everything.

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