Excited gravitons in 4 lepton final states (G*→ ZZ → l+l-l+l-)

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Contents

1 Introduction

Graviton as a concept was first introduced by Blokhintsev and Galperin in 1934[BG34]. It is postulated to be the quantum of gravity, and an elementary particle that mediates the force of gravitational interaction. A possible way of creating gravitons has been through the Large Hadron Collider at CERN[CER24]. The precise way for an observation of a graviton has been through that it might have escaped the existing detectors, leaving an empty zone that is noticed as an imbalance in momentum and energy in the event.

As a response to the acclaimed physicist's Freeman Dyson's suggestion that a graviton might not be detectabe in the real universe[DYS], Rothman and Boughn devised what a detector that could detect gravitons might look like[RB06]. By having M_s as the mass of the source, L as the total luminosity, and $f_\gamma = L_\gamma/L$, we get:

$$\frac{f_\gamma}{4\pi}\frac{M_d}{m_p}\frac{M_s}{R^2}\frac{1}{\epsilon_\gamma} \geq 1 \tag{1}$$

With it being ≥ 1 to exceed mean path. The remarkable part of equation (1) was the detector mass M_d. This was calculated to be at the mass of Jupiter (the largest planet in our solar system) for the gravitational forces to not overwhelm the electrostatic forces, and thereby being able to detect a potential graviton[RB06]. It suffices to say it would be a tremendous task to observe a graviton, with such requirement at place.

With that in mind, it is fitting to explain that this project is an analysis on whether the potential for finding a graviton in the ATLAS Open Data is there. The actual probability of finding a graviton is minimal. Much research has been done within the field, and it has so far proven difficult to find any traces. After the investigation of the data, a closer look at the theoretical foundation of the graviton will be done.

While it has been difficult to find evidence of the elusive graviton produced in particle colliders, scientists within the field of semiconductors have proven more successful[LLY+24]. Liang et al. have in fractional quantum Hall (FQH) states, found novel collective excitations that are called chiral graviton modes (CGMs) and are proposed as quanta of fluctuations of an internal quantum metric under a quantum geometry description. Such modes are condensed-matter analogues of gravitons that are hypothetical spin-2 bosons. After an Open Data analysis, a closer look will be made on gravitons in semiconductors, and this will be later transferred to the particle physics field, and in particular the process of G*$\rightarrow$ ZZ $\rightarrow$ l+l-l+l-.

2 Theory

2.1 Graviton

The graviton is the mediating field particle for the gravitational interaction force[Hsu23]. It is a spin-two particle[Hol06], compared to the spin-one photon. The source of gravitation is the stress–energy tensor, which is a second-order tensor. This is in contrast to electromagnetism's photon, which arises from the four-current (a first-order tensor)[Asp20]. A walkthrough of the search for a theory that could describes the quantum behavior of the full gravitational field show that, like loop quantum gravity, covariant and sum over histories do not provide explicitly with graviton as individual particles, while string theory does[Rov01]. This means that this project concerns a particle that is, at this stage, only hypothetical and several of the main school of thought within the field do not rely on it for fulfillment/acceptance. Many of the considerations around the particle suggests it exhibit behaviour like photon with both being of zero mass[Hol06].

In order to understand why the graviton is a spin-2 particle, we imagine a thought process akin to the Schrodinger's experiment[Hsu23]. A bunch of electrons rest inside a small box, and we boost it. The charge density J(x) transform like the time component J^0 of a four-vector density because L $\longrightarrow$ L/γ. While the energy density E(x) transform like the T^{00} component of a 2-indexed tensor $T^{\mu\nu}$ because L $\longrightarrow$ L/γ and m $\longrightarrow$ γ m for E. We see that the photon arises from the four-vector and the graviton arises from the stress-energy tensor. Graviton cannot be over spin-2 because higher spin particles have to be coupled to conserved currents, and there are no conserved currents of high spin in quantum field theories.

Graviton is an elementary particle. This is based on the Weinberg-Witten theorem[Wik24]. The theorem states that massless particles with spin j > 1/2 cannot carry a Lorentz-covariant current and that massless particles with spin j > 1 cannot carry a Lorentz-covariant stress-energy tensor. We interpret this as meaning that graviton with j = 2 cannot be a composite particle, but rather an elementary one. The graviton would be a massless particle that travelled at the speed of light, just like it's electromagnetic analogue the photon[oEB24]. Graviton would be identical to it's anti-particle, and this would mean that anti-gravity would be possibly rendered impossible. However, if graviton were to be proven to exist, it would suggest much more research into the nascent field of anti-gravity would be required.

One area of graviton research that proven to be a difficult conundrum is the lack of renormalization of gravity. Renormalization is a procedure where divergent parts of a calculation leading to infinite results are absorbed by redefinition into a few measurable quantities and yielding finite answers. One explanation for why gravity is not renormalizable comes from Shomer[Sho07] and is as following: The very-high energy spectrum of any d-dimensional quantum field theory is that of a d-dimensional conformal field theory. This is not true for gravity. While for example the field theories of condensed matter are often described as non-fundamental compared to the Standard Model, they are as effective descriptions just given at different energy scales. Shomer explains that if General Relativity was a renormalizable quantum field theory then its extreme high energy behavior should be that of a conformal field theory in the appropriate number of dimensions. Furthermore, we have according to theory that the large energy asymptotics of the density of states (DOS) in a theory of gravity in asymptotically flat spacetime is not that of any conformal field theory.

2.2 ATLAS Open Data

The data used in this project is from ATLAS Open data 13 TeV. ATLAS is the largest general-purpose particle detector experiment at the Large Hadron Collider (LHC), a particle accelerator at CERN in Switzerland[ATL20]. The data has been collected at 13 TeV during the year 2016 and corresponds to an integrated luminosity of 10 fb-1. The pp collision data is accompanied by a set of MC simulated samples describing several processes which are used to model the expected distributions of different signal and background events.

2.3 Relevant solid state physics

While it has proven difficult to find graviton at the relativistic scale, the effort at non-relativistic has proven more fruitful[Swa24]. A team in China attempted by cooling a GaAs semiconductor to near absolute zero and applying a magnetic field 100,000 times stronger than the Earth's, the team managed to excite the semiconductor's electrons to move in unison. This collective motion caused the electrons to spin in a manner consistent with predictions about gravitons[LLY+24]. The novel collective excitations are called chiral graviton modes and are found in fractional quantum Hall states [LLY+24]. The excitation arise in strongly-correlated topological fluids[KBH+22] and are massive and non-relativistic. They are characterized by polarized states with chirality of +2 or -2 (hole conjugate of electron and electron respectively), and energy gaps coinciding with the fundamental neutral collective excitations (called magnetorotons) in the long-wavelength limit[LLY+24].

Some simulations have shown that obtaining graviton-like excitation is possible in graphene-like systems [SRP23]. However, the emphasis of most current research focuses on the fractional quantum Hall effect (FQH) in 2D gases under strong perpendicular magnetic fields B. In the FQH states, only chiral graviton modes (CGMs) are allowed[KBH+22]. In the previously mentioned long-wavelength limit, the magnetoroton forms a spin-2 degree of freedom representing a quantum metric $\hat{g}$. This metrics fluctuations can be exposed by breaking rotational symmetry. $\hat{g}$ is the shape of the magnetic flux attachment in a FQH fluid. $\hat{g}$ is asymmetric unimodular matrix, similar to the fluctuating space-time metric in a theory of quantum gravity. It is due to this it is called the FQH graviton[KBH+22]. Primary evidence, outside the experiment in previous paragraph, comes from study of magnetoroton in large momenta, given as k $\approx l_B^{-1}$.

2.4 Relevant Quantum Mechanics and machine learning

The intersection of quantum computing and machine learning is called quantum machine learning. In this project, as a secondary method of investigation, we will use quantum machine learning to see if the prospect of finding a graviton particle increases. In quantum computing one uses quantum logic gates with a set of properties somewhat analogous to the gates found in electronic to create basic quantum circuits operating on a small number of qubits[BP24]. Associated with these quantum logic gates are a set of unitary matrices that are used as a representation. These matrices can be found on Figure 1. Two important terms to consider result-wise are the quantum measurements and quantum

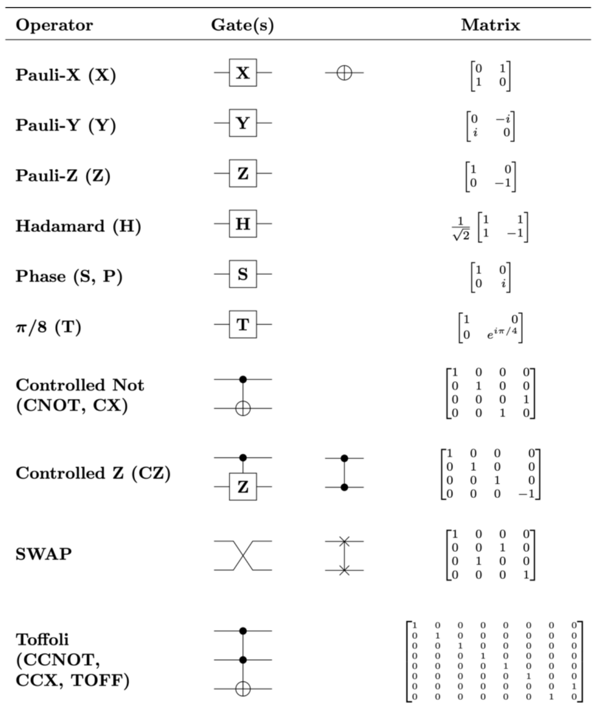

Figure 1: Schematic shows the most important quantum logic gates and their matrix representation

entanglement. The outcomes of quantum measurements constitute quantum data[RD23]. Quantum entanglement is that the quantum states of a group of particles cannot be described independently of each other, regardless of distance. Quantum entanglement is achieved in quantum circuits by introducing CNOT and CZ gates in to the circuit. Entanglement can occasionally increase the accuracy of Quantum kernels, but other times not depending on the circuit used.

Quantum encoding is an expression used to explain the transformation of classical information to quantum status. Several methods for this transformation. In this project we will focus on angle encoding. In this method we embed the data using rotational gates. The value to encode (i.e. the feature) is passed as an angle parameter, and the resulting state depends on the rotational gate applied. Quantum gates use rotation operations around different axes (X, Y, or Z) for changing quantum state. For example, the rotation around the X-axis, denoted as $R_x(\theta)$, is represented as:

$$R_x(\theta) = e^{-i\theta X/2} = \begin{bmatrix} cos(\theta/2) & -i\ sin(\theta/2) \\ -i\ sin(\theta/2) & cos(\theta/2) \end{bmatrix} \tag{2}$$

The final aspect necessary to run a quantum machine learning analysis of a data set is to have a kernel. Kernel, K, is defined as the dot-product. We set X as the input space. A function K: X $\cdot$ X $\rightarrow$ R is called a kernel if there exists a function, f, such that for any two datapoints x, z we have K(x,z) = f(x) · f(z)[DC19]. With Quantum Kernel we mean that the definition holds and the kernel can be evaluated by a quantum computer[PEK23]. We will use a Support Vector Machine (SVM) to do the quantum machine learning. SVM is a form of a kernel and is a supervised machine learning algorithm, which means that it involves a training set of already classified data[RML13]. The SVM classifies vectors in a feature space into one of two sets, given training data from the set[CV09].

3 Method

The primary intention of this Method section (and the project itself) is to investigate whether the graviton elementary particle exist or not. As a minimum we should aspire to get closer to solving this conundrum. We begin with focusing on if there is any proof of the graviton in the ATLAS Open Data made public for the use of researchers. There are more BSM MC signals in the 13 TeV release, with more than 50 samples including graviton, excitation, supersymmetry and so on[ATL20]. Then we continue to investigate the data through a quantum mechanical machine learning circuit. The last part of this project is a theoretical investigation of graviton.

3.1 ATLAS Open Data

One often refers to the collisions at LHC as being between protons, however in reality it is the hadrons that collide between them. A hadron is a composite subatomic particle made up of two or more hadrons held together by the strong interaction[Tho24]. The actual collision number to the amount of 1.7 million per second and it is important to have a good signal to background ratio. In this task triggers and event selection is important to filter out unwanted background events. The equation for signal to background ratio is given according to:

$$Signal\ to\ background\ ratio = \frac{Number\ of\ signal\ events}{Number\ of\ background\ events} \tag{3}$$

Another important criteria or cut is the missing transverse momentum. Momentum for collision of particles with opposite direction, at relativistic speed, should be zero because of the p = mv relation. Missing transverse momentum occurs when this value is non-zero. A related concept, missing transverse energy, is used to infer the presence of non-detectable particles and is expected to be a signature of many theories of physics beyond the Standard Model[col14]. Another important part of the method is the resonance. A resonance is a peak located at certain energy values. They are associated with subatomic particles and their excitations. These particles come together to form a single resonance which act as an intermediate state of the incoming colliding particles and the final products of the collision[DG20]. The resonant particle could be seen as the excited level or bound state of two colliding particles. Some particles exist only for a very short time before decaying into others. The particles cannot be discovered directly, but rather from indirect evidence of their decay products.

We first collect ATLAS Open data, include Monte Carlo simulations (seen as histogram bars) not depending on luminosity and plot the data in the same cartesian x-y axis. If data coincide with the Graviton bar, we could see it as either a graviton excitation candidate or some other beyond the Standard Model phenomenon. Many of the shell codes that exist for finding 4 lepton invariant mass are based on [col18]. But their limits were set on the Randall–Sundrum (RS) model with a warped extra dimension giving rise to a spin-2 Kaluza–Klein excitation of the graviton. The investigation of ATLAS Open Data in this project is much simpler in comparison. Code for project can be found on [Yek24].

3.2 Quantum Machine learning

A quantum machine circuit with a corresponding quantum kernel was chosen for the task of searching for graviton excitations. This has been done in other research as well[KBH+22]. With the reason being that the fractional quantum Hall (FQH) "graviton" has issues with strong correlations, topological order and non-equilibrium dynamics which suggest that a quantum circuit might be better suited for the task of analysis.

Two data sets were angle encoded in a parameterized quantum circuit. The circuit can be found in Figure 2. The circuit is R_x and R_z alternating. And with it's adjoint circuit attached to it. No entanglement layer, nor another variational layer were introduced as these were not deemed to improve it's accuracy. A SVR regression was done with a custom kernel, and the two data sets were compared for excitations/abnormalities in the feature vs mllll map. The two data sets were one composed of 550

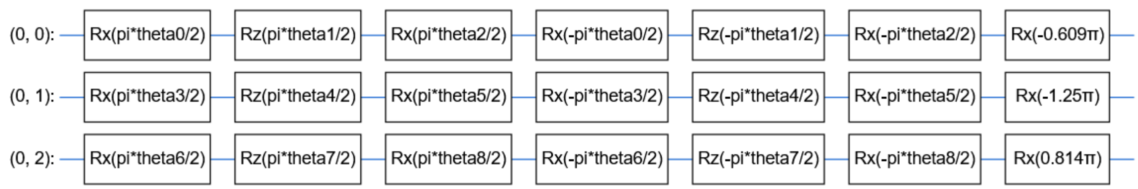

Figure 2: Schematic shows the parameterized quantum circuit used in the angle encoding for the quantum machine learning.

000 entries and were MC simulations. This set is only called llll, and the other set represents data measured and is called data.

4 Results

The result section will go through the different findings of the work done.

4.1 ATLAS Open Data

The investigation of the ATLAS Open Data suggests that a candidate for graviton could be viable. On Figure 3 we see that the data points are black dots and the light-green histogram is the theoretical graviton bar. And we see that it is possible that graviton could contribute to data. This would of course just be a theoretical candidate for the mediating force of gravity.

4.2 Quantum Mechanical Machine Learning

Two data sets were run through a quantum machine learning regression application. Regression is widely used for prediction and forecasting, and highly useful on large, continuous data sets as those retrieved by the ATLAS detector at CERN. The first Figure 4 shows the MC simulation data run through a quantum machine learning regression circuit. And the plot itself has mllll (GeV) in the y-axis and the features on the x-axis. This plot is included to confirm that the circuit works properly and to show the relationship between features and target. Figure 5 shows the quantum machine learning procedure being done on Monte Carlo simulation data. In the previous section a candidate for a Graviton excitation was seen on 500 GeV roughly. This can be seen again in these samples at around sample 5000, sample 12000 etc. We compare the Monte Carlo simulations with data from measurements found on Figure 6. The data has 800 samples and we see small turqoise excitations at around 500 GeV. They can be seen at sample number 180 and 300. This is in line with other results we have obtained so far, with different methods and somewhat different samples (we refer to code for this).

5 Discussion

Two different methods were used to explore whether graviton can be discerned from relativistic data. Both indicate that the presence of a graviton particle can be true. There are excitation found at approximately 500 GeV (and are in line with Monte Carlo simulations) that suggest that there could be such a particle. Data point confirm this. However, no conclusive proof of relativistic graviton has so far been given.

One reason for why graviton has not been discovered is that it is just too weak. Some fanfare has been given to novel collective excitation chiral graviton modes, though these are massive and

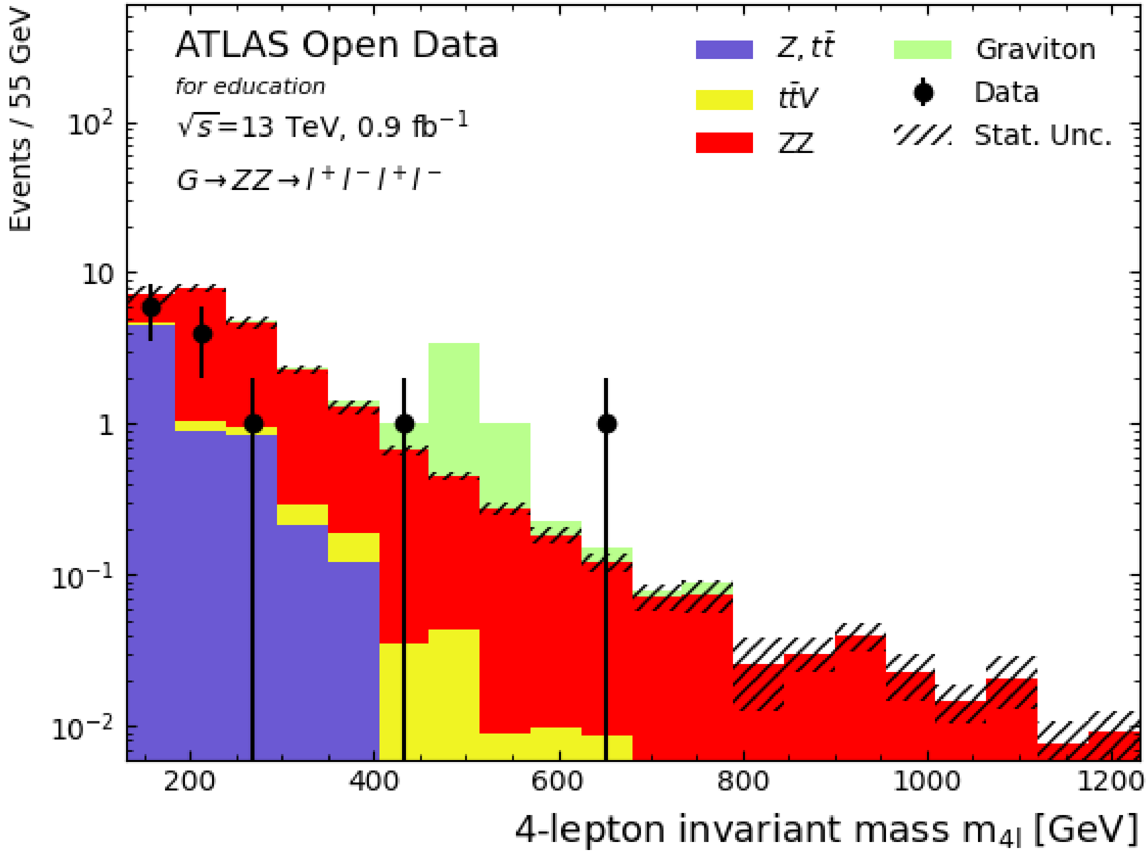

Figure 3: Plot shows the number of events on the y-axis and the 4 lepton invariant mass on the x-axis. Data points are black dots while the bars are Monte Carlo simulations. Graviton bar is the light-green coloured bar. We see that the graviton could contribute to data due to one of the data points being on the bar.

non-relativistic[KBH+22]. With the excitation from relativistic data being so weak and the graviton research being at an impasse for such a long time as it has (including during the development of LIGO[Ban16]), a more logical approach could be by taking the chiral graviton modes and scaling them up to relativistic speed and nano-particle size (and smaller). An attempt at this is done in the next subsection.

5.1 Investigation of the theoretical foundation of graviton

The underlying pretext of this subsection is that graviton excitations are seen in Open ATLAS data through two different methods. But the effect is so small that it is not measurable with current technology. Massive, non-relativistic gravitons, on the other hand, have been experimentally verified with a chirality of $\pm$ 2, suggesting that unlike it's counterpart photon (with spin-1, massless and no anti-particle), it could have an anti-particle. The FQH states, v, are given according to the equation:

$$v = \frac{p}{2p+1} \tag{4}$$

where p is an integer. At $v = 1/3$, the magnetoroton has an energy minimum and can be described by a quasiparticle-quasihole separated by a distance proportional to wavevector q. When q is approximately 0, the spectral weight of the magnetoroton vanishes as ql_B. The equation for the magnetic length l_B is given according to:

$$l_B = \sqrt{\frac{\hbar c}{eB}} \tag{5}$$

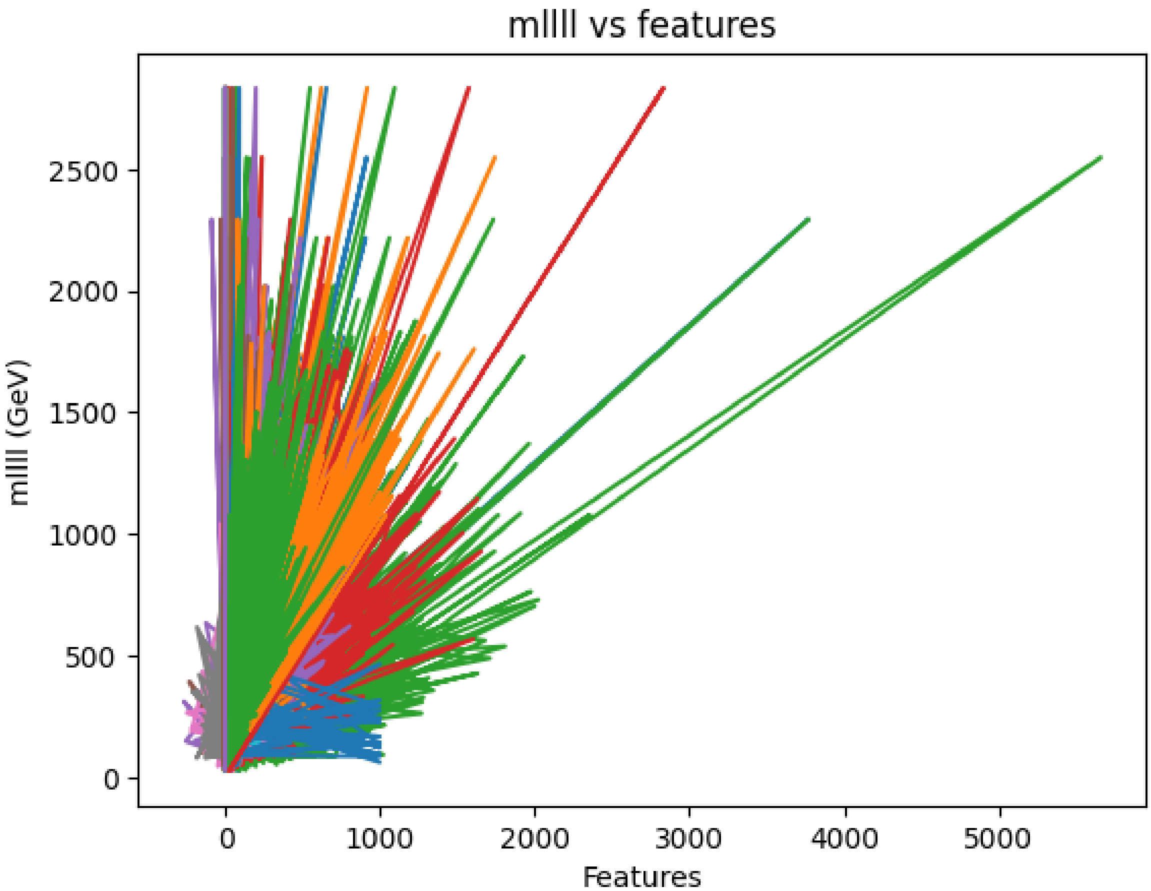

Figure 4: Plot shows the mllll vs features map. The features can be found in [Yek24].

Because the mass of the magnetoroton vanishes when q $\approx$ 0, we can apply conformation field theory on the graviton particle. In conformation field theory when the coordinates of the system changes, the physics of of the system remain the same. One such system is the stress-energy tensor. Normally, if the speed of a system is increased from non-relativistic to relativistic, we would expect many changes to the system. In conformal transformations, we expect the physics of the system to not change, but the symmetries of the system to change at relativistic speed. Because Weinberg-Witten stated that a spin-2 particle is unique in symmetry, and we have SU(N) = 2N + 1 for higher dimensional groups that include quarks and gluons[Wu10], we can surmise that the FQH under conformational analysis will under SU(2N+1), meaning that the symmetry will be invariant from the transformation from non-relativistic to relativistic speed under the appropriate FQH state.

When we investigate whether it is symmetric, we check if it is bijective functions. A function is bijective if it is both injective and surjective. Meaning that each x-value has one unique y-value (in mathematical terms) and that there is only one y-value for each x-value. Here we see state, x,y,z cartesian coordinates fulfill that definition, and from this we can conclude that it is symmetric. Meaning that for chiral gravitons to be considered gravitons seen in LHC, we would need the to do the transformation during a set of prerequisitive requirements as: FQH state, conformational transformation and rotational angle.

6 Conclusion

This project was intended to investigate the G* $\rightarrow$ ZZ $\rightarrow$ l+l-l+l- through different means. Excitations that could be gravitons (compared with Monte Carlo simulations) were found for two different meth-

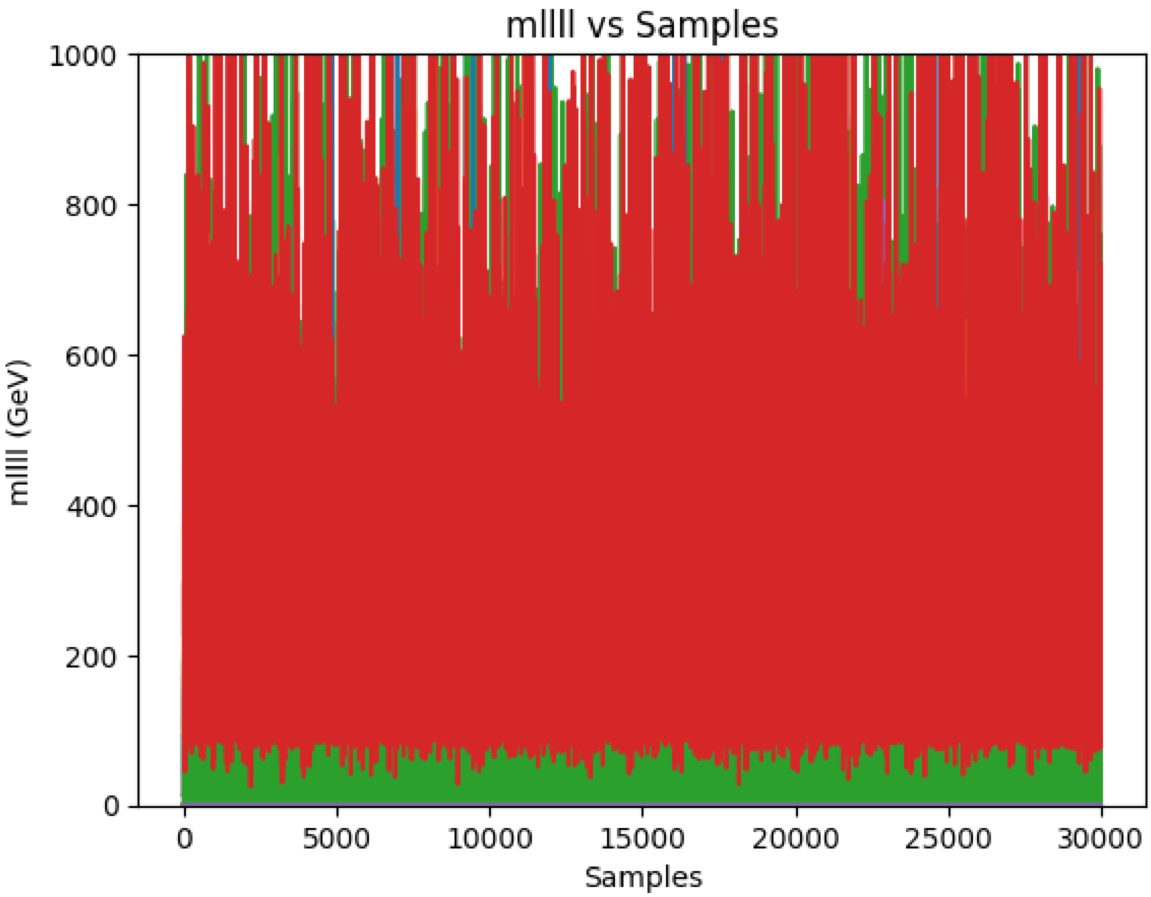

Figure 5: Plot shows the mllll (GeV) vs Samples for Monte Carlo simulations. The training data was done on 30 000 samples. The graviton was found on around 500 GeV before, and again we see excitation in the Monte Carlo simulations at around 5000 sample, 12000 and so on.

ods: code that investigated ATLAS Open Data, and data run through a quantum machine learning algorithm. Both indicated graviton could exist, although the methods are fair to simplistic compared to technology that would be necessary to detect gravitons. However, there has been graviton-like particles found in 2D gases, and this was later compared with graviton. It was found that they could be equal, and meaning graviton would exist, provided some pre-requisites were fulfilled.

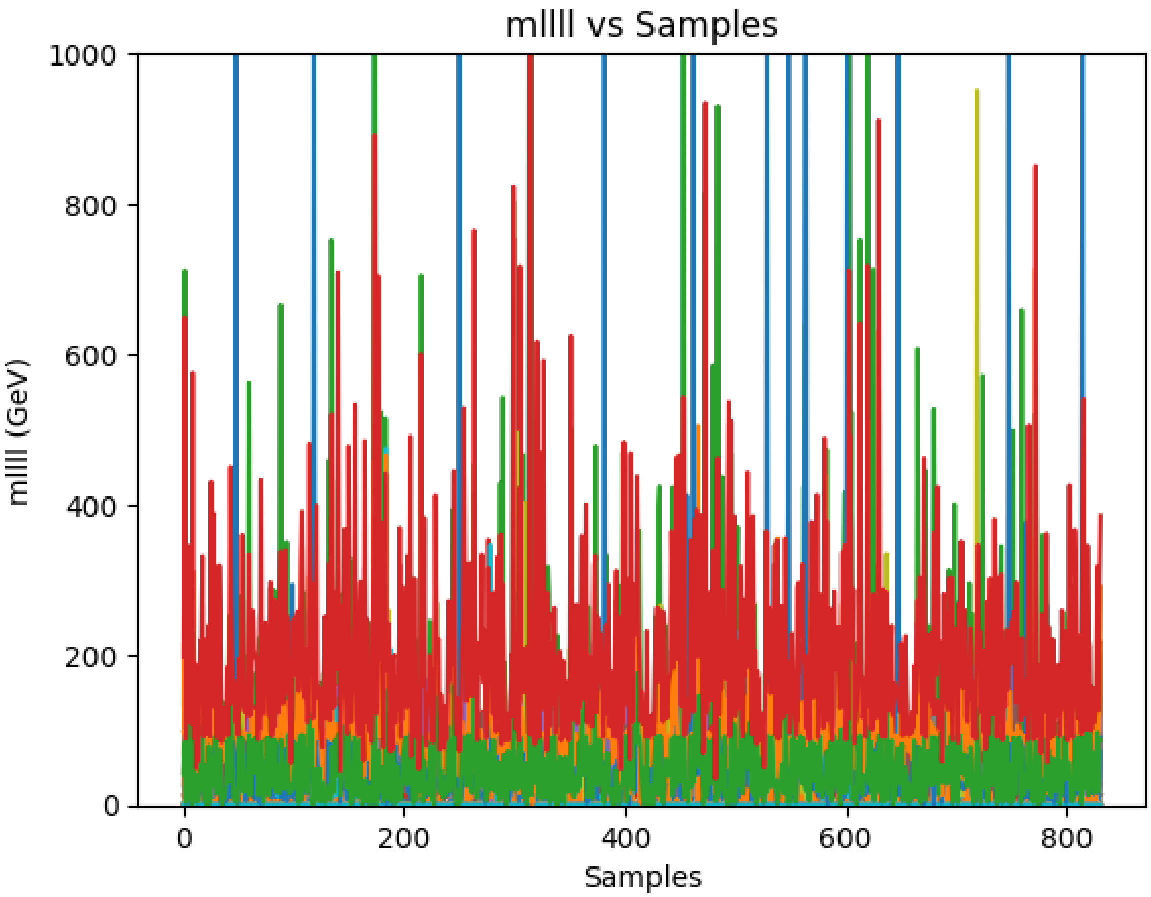

Figure 6: Plot shows the mllll (GeV) vs Samples for measured data. The training data was done on 800 samples. The graviton was found on around 500 GeV before, and again we see turquoise excitations at around 500 GeV. They are very small, but can be seen at sample number 180 and 300. These could be graviton excitations.

7 Appendix

The appendix features links to the notebooks where the codes used to obtain the results in the ATLAS Open data and the quantum machine learning can be found. Small explanations are also available.

7.1 Code for the ATLAS Open Data investigation

The code that was used for investigating the graviton candidate in ATLAS Open Data took to much place in the main text, and is found here instead. One can also find the notebook on this link[Yek24]k, as previously mentioned.

The code used for the ATLAS Open Data is called Gravitonanalysis.ipynb.

7.2 Quantum machine learning code

The code in the analysis concerning Quantum machine learning is called QuantumMachinelearning-graviton.ipynb. The code demands installation of some quantum mechanical libraries like circ and tensorflow, in addition to scikit used for the SVM. It might therefore be difficult to run if the installation of these libraries does not occur as planned.

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