A Consideration of Extra Dimensions and Simulated $G^* \to \gamma\gamma$ Production at the Upcoming Atlas Detector

Marco Almeida*
Vassar College
Poughkeepsie, NY 12604

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Columbia University, Nevis Laboratories
Irvington, New York 10533 USA†
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The Randall-Sundrum model is one of several extra-dimensional theories giving rise to a spectrum of massive graviton states. It is the nature of this particular model that the graviton states are well separated in mass, allowing for their detection in collider experiments such as the Large Hadron Collider (LHC) as resonances. This paper considers the possibility of detecting the graviton in the $G^* \to \gamma\gamma$ decay mode as spin-2 resonances reconstructed from the decay products using the ATLAS detector at the LHC. Specifically, this analysis examines in some depth the ability to detect and accurately reconstruct a range of photons. Furthermore, the minimal required luminosity to achieve a statistical significance of 5 or greater is also calculated.

INTRODUCTION

The Standard Model currently stands as the crowning achievement of particle physics. Spanning more than a quarter of a century in development and refinement the Standard Model is capable od describing all of the particles thus far observed in accelerators and the interactions in the form of a Quantum Field Theory (QFT). However, the theory as it exists today contains several notable shortcomings, the most notable of which is the absence of the fourth fundamental force, the gravitational force.

Particle physics holds a strong tradition of unification. In the 1860's, Maxwell successfully unified the electricity and magnetism into the electromagnetic force. A century later, the weak and electromagnetic interactions were merged into the singular electroweak interaction. Presently, work is being done so as to be able to combine electroweak and quantum chromodynamics (QCD), the theory of the strong interaction. It is for these reasons why many are hopeful for the successful incorporation of gravity as a difficult, yet crucial step beyond the Standard Model.

According to quantum field theory, the language of the Standard Model, models the fundamental forces of nature with force mediator particles. Under QFT, the gravitational interaction is mediated by the graviton, an approach which agrees with the equally successful theory of General Relativity on the classical scale. If this theoretical particle were to exist, it would consequently be massless due to the unlimited range of the gravitational influence and have a spin of 2. The following analysis focuses on the possibility of graviton detection in accordance with the Randall-Sundrum model under the $G^* \to \gamma\gamma$ decay mode.

RANDALL-SUNDRUM MODEL

According to our experience, it is clear that we live in a world of four noncompact dimensions. Were this not the case, observations would conflict with theory as standard model particles are confined to the three conventional dimensions. One recent solution to this has been the limiting of the standard model to a (3+1)-dimensional subspace, or 3-brane, of a higher dimensional universe. Once again, experiment appears to contradict this with the immense success of Newton's gravitational law and general relativity, both of which imply a universe of 4 noncompact dimensions. However, according to Randall and Sundrum the above statements implicitly depend on a factorizable geometry, meaning that the metric of the (3+1) dimensions is independent of the positions of the extra dimensions. Once this assumption is abandoned, it is argued, those conclusions no longer apply [1].

The Randall-Sundrum model states that the 3-space+1-time dimensional world with which we are familiar is in fact a brane that exists within a 5-dimensional non-factorizable geometry [2]. In this model, the graviton is the sole particle capable of propagating in the extra dimension and its scale Kaluza-Klein (KK) spectrum is expressed as $\Lambda_\pi = \overline{M}_{Pl} e^{-kr_c\pi}$, where $\overline{M}_{Pl}$ is the reduced effective 4-D Planck scale, r_c is the compactification radius of the extra dimension, and k is of the same order of magnitude as the Planck scale. The geometrical exponential 'warp factor' represents the model's solution to the weak-Planck hierarchy problem and is responsible for the relative weakness gravity within our brane, provided that $kr_c \approx 12$ [3]. The first KK modes, according to the RS-model, are predicted to be at the TeV-scale and should be observable at colliders such as the Large Hadron Collider (LHC) as spin-2 resonances capable of being reconstructed from their decay products.

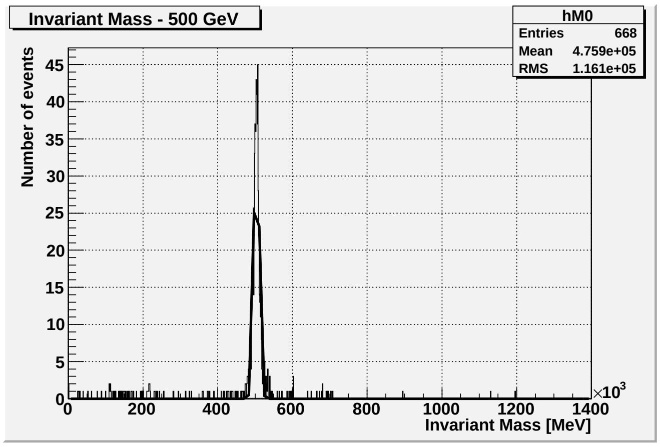

FIG. 1: Invariant mass of the diphoton product in the decay mode $pp \rightarrow G^* \rightarrow \gamma\gamma$, 500GeV signal. Fit Parameters: Mean: $5.03736e+05$ σ: $6.98805e+03$

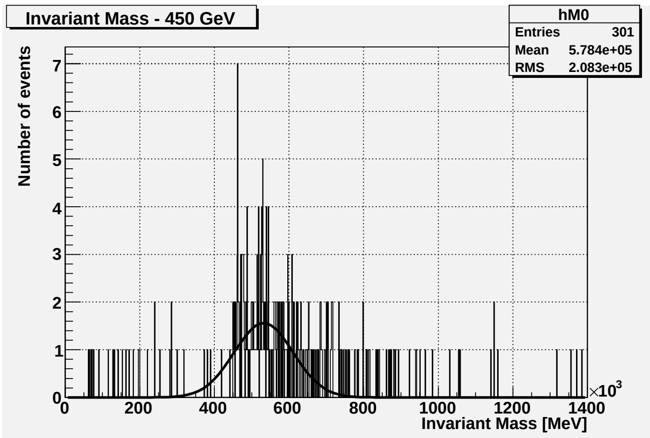

FIG. 2: Invariant mass of the diphoton product in the SM background. Mean: 5.32050e+05, σ: 7.89165e+04

SIMULATION AND RECONSTRUCTION

Research contained in this paper involved the use of the Pythia event generator to simulate high-energy particle physics events, particularly the signal process $pp \rightarrow G^* \rightarrow \gamma\gamma$. The electromagnetic energy deposited in the EM calorimeter is used to subsequently reconstruct information regarding the energy and momenta of the photons involved in the event using the Geant4 Atlas Detector Simulation. Given this product information one is able to reconstruct the invariant mass of the graviton from the four-vectors of the decay products.

For a given collision event, a 60 GeV transverse energy cut was determined to accurately determine whether a photon had likely emanated from the decay of a graviton. Simple combinatorics were used to analyze all possibly pairs of generated photons above this threshold energy. Using the reconstruction data regarding the four-vector of each respective photon, the invariant mass of

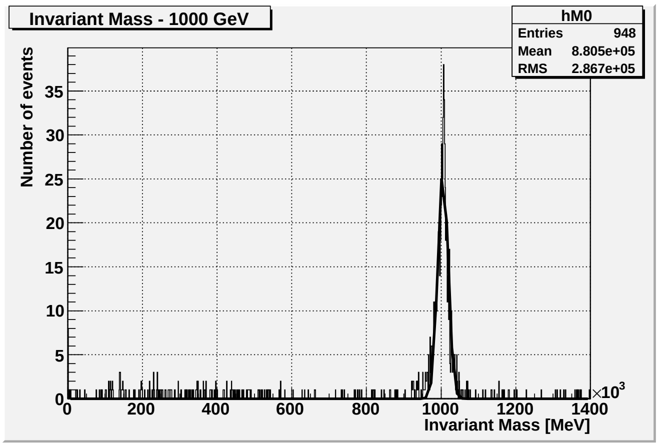

FIG. 3: Invariant mass of the diphoton product for a 1000 GeV mass resonance. Mean: 1.00502e+06,1.38183e+04 σ:

TABLE I: Masses m_g of the graviton resonances with the number of events and overall reconstruction efficiency for each mass.

m_g (GeV)	N_events	ϵ_{recon} (%)
500	850	85
1000	1000	86
1500	991	87
2000	838	87
2500	498	88
450	1000	71
950	1000	68

the diphoton pair or, equivalently of the graviton source, was computed (Figure 1).

Fitting a gaussian function to the obtained invariant mass distribution, mass windows of $\pm\sigma, \pm 2\sigma, and \pm 3\sigma$ were defined from the standard deviation parameter. The number of signal and background events within a mass window of the mean of the invariant mass distribution of the signal was then counted. The total number of signal or background events expected can then be expressed as $N_{events} = \epsilon \cdot \sigma' \cdot L$ where ϵ represents the efficiency, equal to fraction of the total number of signal or background events that lie within the designated mass window, $\sigma' = \sigma \cdot B_r$ is the product of the cross-section and the branching ratio, and L is the beam luminosity.

We wish to maximize the significance,

$$S = \frac{N_{signal}}{\sqrt{N_{bkgd}}} \tag{1}$$

The minimal luminosity required to obtain a significance greater than 5 can then be computed after some algebraic manipulation. This, along with other information regarding the simulations at each mass-energy point is summarized in Table I, including the overall reconstruc-

TABLE II: Table showing the minimum integrated luminosity required to attain a significance greater than or equal to 5 in units of pb^{-1}.

	500 GeV	1000 GeV
σ	4.56	417.7
2σ	4.07	385.8
3σ	5.87	455.4

tion efficiency, which is discussed at greater length further in this paper.

RECONSTRUCTION EFFICIENCY

The success of high energy particle physics is limited by the degree to which the ATLAS detector is capable of detecting and subsequently reconstructing the paths of all particles taking part in an event. Event simulation provide a means of estimating this numerically as it is the single arena in which we have full knowledge of the collision and subsequent decays.

A cut at 100 GeV was implemented on all generated photons so as to remove low-energy photons unlikely to have decayed from a massive graviton. For each of the reconstructed photons of the same event above this same cut, the value $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ was computed, where $\Delta\eta = \eta_{generated\gamma} - \eta_{reconstructed\gamma}$ and $\Delta\phi = \phi_{generated\gamma} - \phi_{reconstructed\gamma}$.By this definition, a reconstructed photon could be matched to a generated photon given that the value of ΔR between the pair was sufficiently low, which for our purposes was 0.1.

The overall reconstruction efficiency, ϵ_R, is given by simply counting the total number of generated photons which were successfully matched to reconstructed photons and comparing that number to the total number of generated photons. The reconstruction efficiencies for the respective mass-energy points efficiency are given in Table 1.

The design of the Atlas detector inherently contains a series of strengths and weaknesses. We set out to probe these strengths and weaknesses to determine whether the findings from simulation correspond with what one would expect given the design of the detector. Specifically, changes in the reconstruction efficiency as a result of varying either the transverse momentum (Figure 4) or the angle eta (Figures 5 and 6) were plotted. In Fig. 4, it is observable that as the transverse momentum of a photon increases, as does the likelihood of it being properly reconstructed. The line on the graph is merely a line of *trend* rather than fit, since a line of best fit would contain a horizontal asymptote at efficiency equals one as opposed to the simple order-2 polynomial trend behavior shown here. Graphs are similar for other graviton

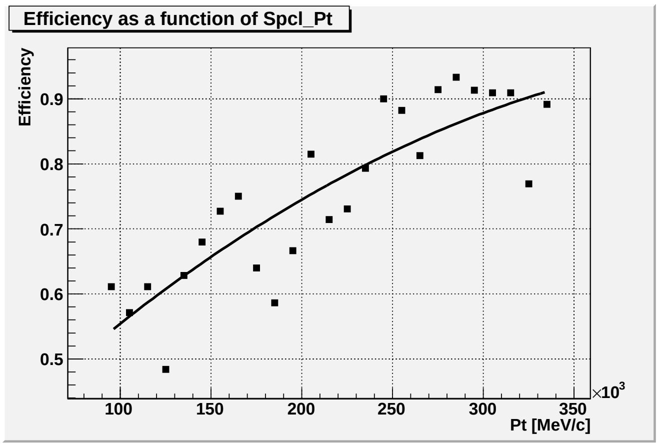

FIG. 4: Reconstruction efficiency versus transverse momentum of generated photon. 1000 GeV resonance mass.

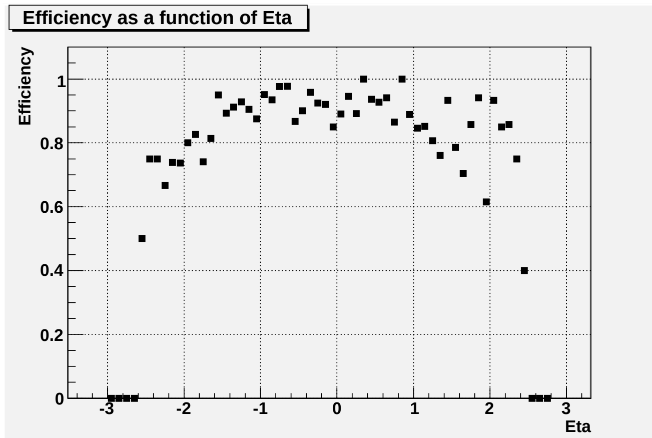

FIG. 5: Reconstruction efficiency versus angle eta of generated photon. 500 GeV resonance mass.

mass resonances with the same increasing trend toward the asymptote. In Fig. 5 and 6 there exist several points to notice. First, the detector is entirely incapable of detecting information for the region past $\eta = 2.5$. This is due simply to the design of the detector. Furthermore, the middle of the plot remains fairly constant, the most notable exceptions existing at eta spanning from 1.3 to 1.7, the very locations at which electronics are situated.

Resolution

To provide greater certainty that generated photons matched to reconstructed photons were indeed matched accurately, the difference between the transverse momenta were plotted as a function of the transverse momentum of the generated photon. As expected, the result is a Gaussian distribution with mean zero. Such a plot of the resolution tells us that in matching a generated photon, the P_t of the reconstructed photon is similar to

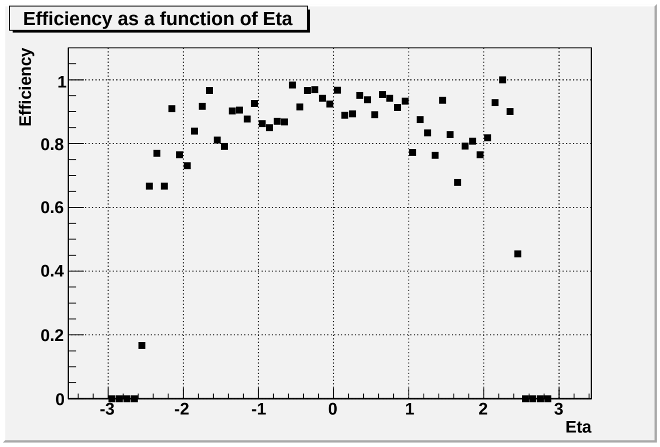

FIG. 6: Reconstruction efficiency versus angle eta of generated photon. 1000 GeV resonance mass.

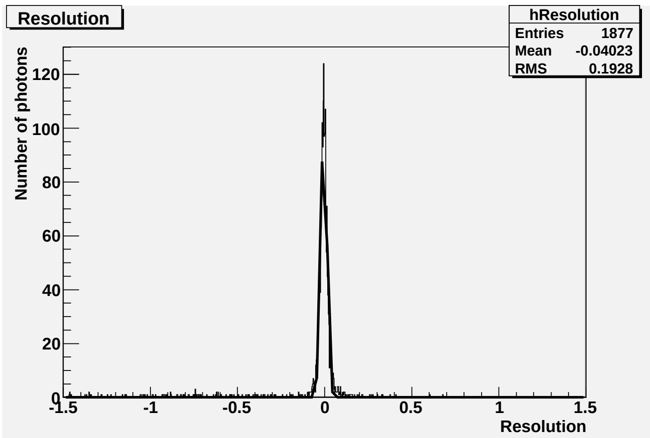

FIG. 7: Resolution Histogram, 1000 GeV resonance mass. Mean: -4.50758e-03 σ: -1.75518e-02

that of the initial generated photon.

FUTURE WORK

In the future, it would be advantageous to further examine the angular distribution with the intent of matching such a distribution to the function $1 + 6\cos^2\theta^* + \cos^4\theta^*$, where θ^* is the polar angle of decay photon and the beam direction in the diphoton center-of-mass reference frame. While the mass resolution for photon pairs is favorable, the background is poorly understood, making Monte Carlo simulations of the background, and thus ar distributions of the background, unreliable. Once the background discrepancy is taken care of, one may plot the angular distribution and compare it to that of the process $qq \to G \to \gamma\gamma, gg$. Angular distributions corresponding to spin-2 resonances are starkly different from distributions resulting from either spin-1 or scalar resonances, making an angular distribution of the processes occurring in the collider that resembles that of a spin-2 particle a strong indicator towards the existence of the graviton.

CONCLUSIONS

It is certainly true that $G^* \to \gamma\gamma$ is not the only decay mode through which the graviton might be discovered. In fact, the branching ratio of this particular decay remains a fairly constant 4% over the foreseeable range of graviton masses. Nevertheless, this decay mode warrants special attention simply due to the nature of the end decay products. Any number of anomalous diphoton pair productions above the Standard Model background could possibly be attributed to graviton decay given the fact that the graviton couples to universally. A focus on diphoton production would eliminate alternative models of high mass resonances on the basis that they do not couple to a final state consisting of two photons, as is the case with the $Z^{'}$ the heavier cousin of the Z boson. One must not eliminate the necessity of exploring alternative graviton decay modes, such as $G^* \to e^+e-$ and $G^* \to \tau\tau$, as they also hold significant potential for discovering the graviton. Still, $G^* \to \gamma\gamma$ appears to be one of the most promising decay modes if one is interested in discovering the graviton with the ATLAS detector.

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* maalmeida@vassar.edu

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