Initial-State Graviton Radiation in Quantum Black Hole Production

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Abstract

Monte Carlo simulation of quantum black hole production in the ATLAS experiment that allows for graviton radiation in the initial state is discussed and studied. It is concluded that, using trapped surface calculations and graviton emission, a black hole signal would be significant for Planck scales up to 4.5 TeV given a proton-proton luminosity of 37 fb^{-1} in the 13 TeV LHC configuration.

1. Introduction

The Planck scale is the energy scale where gravity affects the interactions of fundamental particles. Studying such interactions could provide valuable insight into the nature of quantum gravity. However, estimates based on quantum field theory and general relativity put the Planck scale at around 10^{18} GeV, making these interactions inaccessible to the LHC.

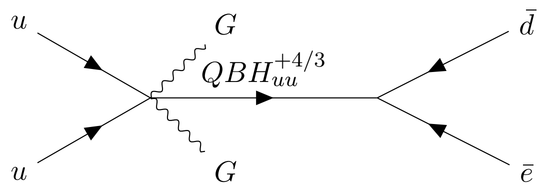
Theories with large extra dimensions of space can allow for an increase in the strength of the gravitational interaction at smaller scales. Essentially, large extra dimensions "dilute" the strength of the gravitational interaction over larger distances, but this dilution does not occur at smaller distance scales. It has been shown theoretically that such a theory would allow the Planck scale, M_D, to be on the order of a few TeV, which could be accessible in the LHC.

One interaction that would be expected around the Planck scale is the formation of quantum black holes. Quantum black holes are black holes that are just above the minimum possible black hole mass, which is taken to be M_D for simplicity. Such objects would not last long enough to emit thermal Hawking radiation, they would either settle into a remnant or decay with a very short lifetime into two fundamental standard model particles. In this research, the decay into standard model particles is considered.

In order to look for quantum black holes at the LHC, we must be able to understand and simulate the properties of their interactions. The project presented in this report is to modify and use an event generator, QBH [3, 4], based on the calculations of Yoshino and Rychkov [1], in order to test the limits of our ability to find this phenomenon at the LHC. Yoshino and Rychkov studied the formation of black holes using a trapped surface calculation, that is by considering the formation of an apparent horizon around the two incoming particles. Using this method they were able to study the cross section of the production process. These trapped surface calculations had already been included in the QBH event generator by the author's supervisor, Doug Gingrich. However, the calculations also required that a portion of the center of mass energy must be radiated away from the black hole in the form of gravitons, which had not been implemented in QBH. The author added this feature into QBH, the exact algorithm is detailed in section 2. Section 3 explores the outcomes of simulating events according to the Yoshino-Rychkov calculations, outlining useful cuts for analysis and observational limits. Section 4 summarizes and concludes the report, and Section 5 (after the bibliography) houses all of the figures and tables.

2. Kinematics

The following diagram illustrates an example of a possible QBH event.



Note that the initial vertex involves 2 incoming fermions, which is not possible under any Standard Model interaction. It also includes the graviton radiation produced in the first interaction, which is the main focus of this research and is required from the calculations of Yoshinio-Rychkov. Also, this interaction violates the conservation of lepton number and baryon number; these violations are optional in the QBH code and are used in this analysis.

The trapped surface calculations tell us the probability distributions for the ratio of the black hole mass to the initial center of mass energy of the interacting partons. In a system without graviton emission, this ratio will always be 1. To start our kinematics calculation, we sample from this distribution to obtain the mass of the black hole. The leftover center of mass energy from the interaction, $E_{CM} - M_{BH}$, is released in the form of gravitons and kinetic energy of the black hole. Many gravitons are likely generated at this time, but it is not useful to record the energy and momentum of each graviton since they cannot be detected; therefore, we generate a single 4-momentum for the sum of the 4-momenta of all the produced gravitons. Thus, we can treat the many body decay problem as a simple two-body decay.

In adding together 4-momenta, the mass of the resultant 4-momentum is not (in general) equal to the sum of the masses of the individual particles. In fact, one can easily show that the invariant mass resulting from summing N gravitons with energies $E_1, E_2, \ldots, E_N$ is

$$M_G = 2 \sum_{j=2, i<j}^{j=N} E_i E_j (1 - \cos(\theta_{ij})), \tag{1}$$

where θ_{ij} is the angle between the momenta of the i^{th} and j^{th} graviton. Therefore, the only way our resultant graviton can have zero mass is if all the gravitons are emitted in exactly the same direction. Since this is not likely, we have to choose a mass for our graviton system. This mass must be between 0 and $E_{CM} - M_{BH}$, so the QBH algorithm chooses a fraction, $0 \leq \xi \leq 1$ and sets the graviton mass to $M_G = \xi(E_{CM} - M_{BH})$. QBH chooses ξ from a polynomial distribution, $P(\xi) = (p+1)\xi^p$,[1] to match CHARYBDIS2 [6], a classical black hole event generator.

Having the two masses chosen, we can easily work out the energy, E_G, and momentum, p_G, of the graviton system in the center of mass frame using the following equations:

$$E_G = \frac{E_{CM}^2 + M_G^2 - M_{BH}^2}{2E_{CM}}, \tag{2}$$

$$p_G = \sqrt{E_G^2 - M_G^2}. \tag{3}$$

A random direction for the momentum vector is chosen from a uniform distribution and conservation of energy and momentum is used to find the 4-momentum of the black hole. Then it is a simple matter of Lorentz boosting these 4-momenta from the center of mass frame into the lab frame.

At this stage, the kinematics of the gravitons and black hole are solved. The graviton 4-momentum is saved and deposited in the event record. The black hole 4-momentum is used to calculate the 4-momenta of the two outgoing particles by a very similar calculation to that described above. These two particles are also stored in the event records, to be processed by Pythia.[5]

After these changes were implemented into QBH, it was validated by typical ATLAS procedures.

3. Cross Sections and Limits

The natural question when considering new types of interactions is "can we see such events in our detectors?" To test this question, signal samples of 20000 events were generated using QBH assuming 6 extra dimensions and allowing violation of baryon and lepton numbers. Such samples were generated for values of M_D values of 3.0, 3.5, 4.0, 4.5, 5.0, and 5.5 TeV. The samples were then run

[1] The default value of p is chosen to give a mean of 0.99. This mean is a parameter in QBH and is given by $(p+1)/(p+2)$. The 0.99 default was chosen to match the default in CHARYBDIS2.

through Pythia for hadronization and standard ATLAS Monte Carlo truth reconstruction that allowed the use of realistically reconstructed jets and missing transverse momentum. ATLAS Pythia8 dijet datasets 361020-361032 were used as the background.

For the trapped surface black hole production, there are two large obstacles to observation. Firstly, due to the large number of strongly interacting fundamental particles, there is a preference for the simulated black holes to decay into quarks and/or gluons. Therefore, we expect the dominant final product of these interactions to be dijets or multijets. This is confirmed in Figure 1 which counts the multiplicity of jets with transverse momentum greater than 50 GeV in QBH events with $M_D = 3$ TeV. The problem arises from the fact that these types of events are also very common products of generic QCD interactions, meaning a large background.

The second challenge is that adding in the trapped surface calculations greatly reduces the production cross section of the quantum black holes, as can be seen in Figure 2. The horizontal line indicates the cross section where we would expect 1 event with a luminosity of 100 fb^{-1}. The solid lines indicate the cross sections for black hole production without graviton radiation, whereas the dashed lines are the cross sections with the trapped surface calculations and graviton radiation. This difference in cross section means it is more difficult to detect the trapped surface black holes than those considered in previous studies.

Notice also that the trapped surface lines do not extend to Planck scales above 8 TeV. This is a consequence of the graviton radiation. Since a portion of the center of mass energy available to the black hole must be released as gravitons, there is a limit on how massive the produced black holes can be. This limit is the product of the total interaction energy ($\sqrt{s} = 13$ TeV) and the maximal possible ratio between center of mass energy and black hole mass. This maximal fraction changes depending on the number of extra dimensions being considered. Figure 3 gives these limits. This can be interpreted as the highest Planck scale that can be probed by the 13 TeV LHC, given the trapped surface calculations.

These features of the trapped surface calculations make it much more difficult to probe the effective Planck scale than in previous analysis; however, the trapped surface calculation also provide a great tool for selecting the signal events out of the background, in the form of missing transverse momentum. The gravitons are completely invisible to the ATLAS detector but carry a significant fraction of the total energy and momentum; therefore, it is expected that these events will have a large missing transverse momentum. This is confirmed in Figure 4, which compares the reconstructed missing transverse momentum for the signal events and the background. Notice that the QCD background tends to have small missing transverse momentum whereas there is a long tail in the missing transverse momentum of the signal. Thus it is possible to discard most of the background events while maintaining the majority of the signal.

In order to optimize this selection, a series of cuts were tested to determine whether the signal could be significant above the background for different values of M_D. Cuts on the leading jet transverse momentum p_1^T, the missing transverse momentum (from the gravitons) E_{miss}^T, and the ratio of the missing transverse momentum to the sum of the transverse momentum of the two leading jets, $H = E_{miss}^T/(p_1^T + p_2^T)$, were all considered. A signal was considered significant if, when applying given cuts, there existed a mass threshold, M_{th}, such that the number of signal and background events with dijet mass above this threshold (N_s and N_b respectively), followed these criteria:

$$N_s \geq 10, \tag{4}$$

$$\frac{N_s}{\sqrt{N_b}} \geq 5. \tag{5}$$

Tables 1 and 2 show the various values given under some of the considered p_1^T and E_{miss}^T cuts[2] with a luminosity of 37 fb^{-1} and $M_{th} = M_D$. Using the criteria, it was found that using a 450 GeV cut on p_1^T and a 150 GeV cut on E_{miss}^T produced the best results of all the tested cuts. They allowed for significance with up to $M_D = 4.5$ TeV (using $M_{th} =$ 4.0 TeV). No additional benefit was found in using

[2] All of these also have an inherent cut of 50 GeV on P_2^T and cut of $|y^*| = |y_1 - y_2|/2 < 1.2$ where y_i is the rapidity of the i^{th} jet. The p_2^T cut ensures a detectable dijet event and the $|y^*|$ cut matches the cut used in [2].

the H cuts. Figure 5 shows the $N_s/\sqrt{N_b}$ ratio at different values of M_D given these cuts. The threshold mass is chosen to be M_D for this plot.

Also, given these cuts, we can determine what luminosity is needed for significance for each value of M_D considered, since N_s and N_b both scale linearly with luminosity. Figure 6 shows these luminosity limits when the threshold mass is chosen to be M_D.

The best observable to look at in order to detect quantum black holes is the invariant mass of the dijet system. This is easily calculated from the energies, E_i, and the momenta, $\vec{p}_i$, of the two jets. It is given by

$$m_{jj} = \sqrt{(E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2}. \quad (6)$$

This should be a good indicator of the mass of the quantum black hole unless other decay products play a significant role. We can see this in Figure 7, which demonstrates that the distribution of m_{jj} is peaked at the Planck scale for each generated signal. Figure 8 shows how this compares to the background. Notice that the signal is clearly visible up to 4.5 TeV.

4. Conclusion

In this report, the author detailed the changes made to the QBH event generator in order to incorporate the graviton emission as predicted by the trapped surface calculations of Yoshino and Rychkov. The results of the generator were used to determine the limits on the Planck scale at which quantum black hole objects could be detected by the ATLAS experiment. The discovery limit was found to be approximately 4.5 TeV. A proper comparison with data will be needed to place a lower bound on the physical Planck scale.

Acknowledgements

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Figures and Tables

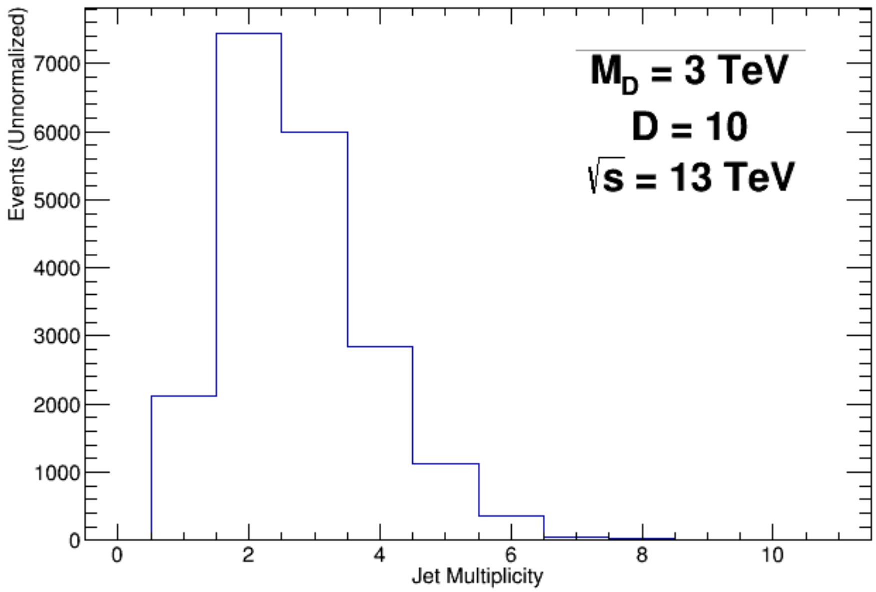

Figure 1: Histogram of the jet multiplicity for QBH events generated with $M_D = 3$ TeV.

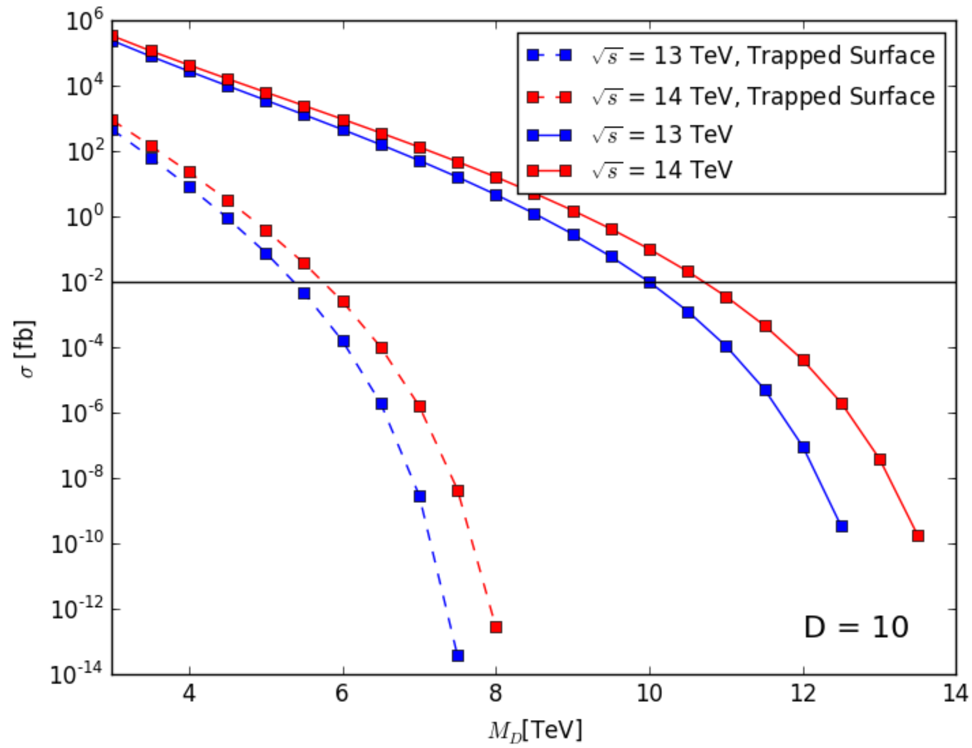

Figure 2: Comparison of the cross sections between the trapped surface model and a model without graviton emission for different Planck scales and beam energies ($\sqrt{s}$) in 10 dimensions.

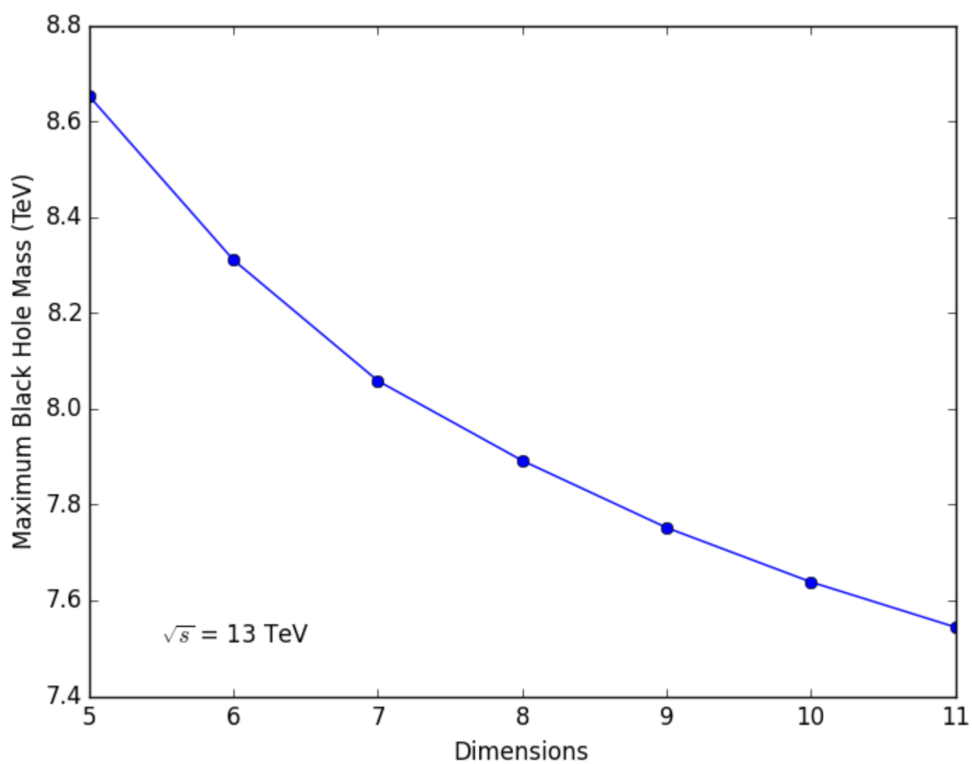

Figure 3: Limits on the maximum accessible black hole mass in the LHC at 13 TeV given the trapped surface calculations of Yoshino-Rychkov.

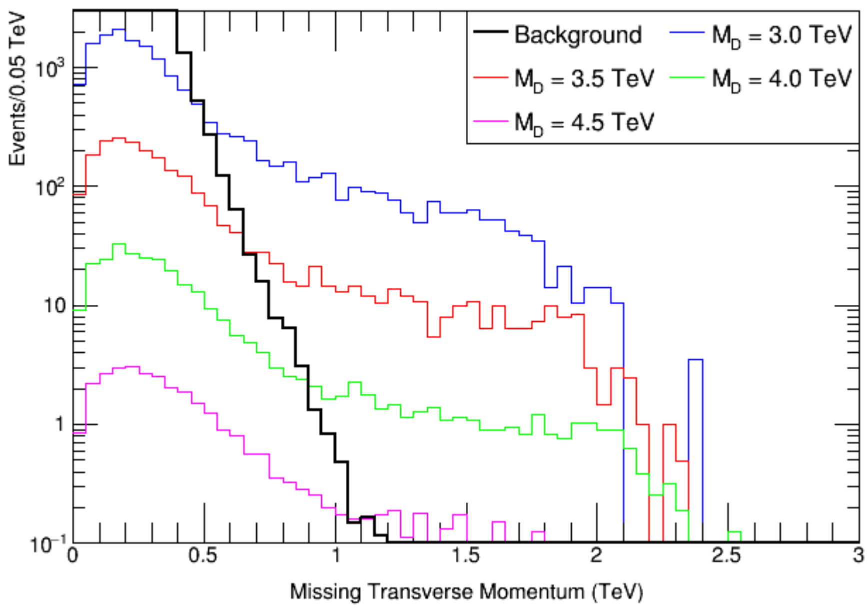

Figure 4: Comparison in the missing transverse momentum distributions between QBH events with graviton radiation and QCD background events.

P_t	E_t	$M_D = 3$ TeV			$M_D = 3.5$ TeV			$M_D = 4$ TeV		
		N_s	N_b	$N_s/\sqrt{N_b}$	N_s	N_b	$N_s/\sqrt{N_b}$	N_s	N_b	$N_s/\sqrt{N_b}$
0.050	0.000	6838.667	13137.017	59.665	913.597	4062.573	14.334	111.312	1330.726	3.051
0.050	0.050	6423.135	270.723	390.378	862.154	84.050	94.041	107.191	26.437	20.847
0.050	0.150	4440.556	63.840	555.765	640.062	20.306	142.040	84.244	6.414	33.264
0.050	0.350	1183.209	7.854	422.206	209.232	2.691	127.551	31.124	0.897	32.858
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Table 1: Significance calculation for various cuts on QBH version 4 events. P_t and E_t refer to the cuts placed on transverse momentum of the leading jet and missing transverse momentum, respectively. N_b and N_s refer to number of background and signal events, respectively. All calculations are done assuming an integrated luminosity of 37 fb^{-1}. Also, cuts require at least 50 GeV for second leading jet momenta and $|y^*| < 1.2$.

P_t	E_t	$M_D = 4.5$ TeV			$M_D = 5$ TeV			$M_D = 5.5$ TeV		
		N_s	N_b	$N_s/\sqrt{N_b}$	N_s	N_b	$N_s/\sqrt{N_b}$	N_s	N_b	$N_s/\sqrt{N_b}$
0.050	0.000	12.135	449.150	0.573	0.993	154.961	0.080	0.057	53.301	0.008
0.050	0.050	11.613	8.794	3.916	0.957	2.943	0.558	0.055	1.023	0.054
0.050	0.150	9.200	2.182	6.228	0.781	0.723	0.919	0.046	0.238	0.094
0.050	0.350	3.665	0.317	6.513	0.348	0.098	1.112	0.023	0.032	0.128
0.250	0.000	12.135	449.150	0.573	0.993	154.961	0.080	0.057	53.301	0.008
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Table 2: Significance calculation for various cuts on QBH version 4 events. P_t and E_t refer to the cuts placed on transverse momentum of the leading jet and missing transverse momentum, respectively. N_b and N_s refer to number of background and signal events, respectively. All calculations are done assuming an integrated luminosity of 37 fb^{-1}. Also, cuts require at least 50 GeV for second leading jet momenta and $|y^*| < 1.2$.

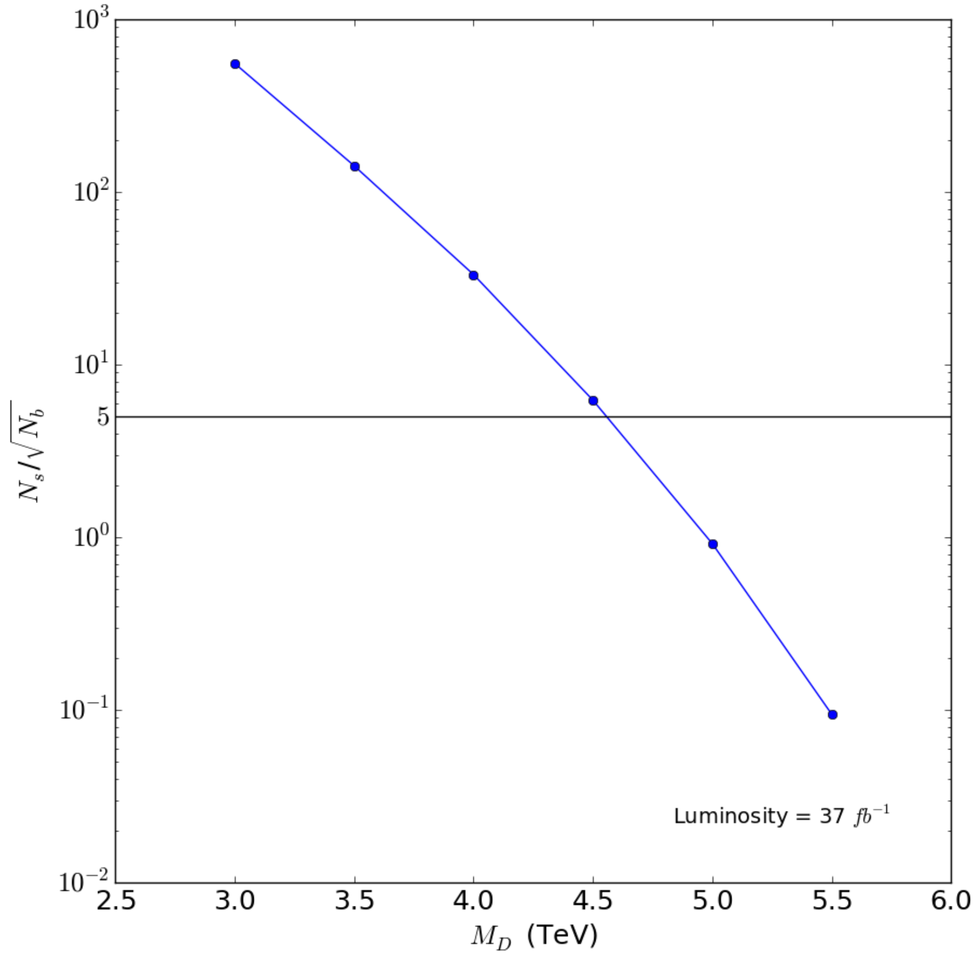

Figure 5: Plot of the $N_s/\sqrt{N_b}$ significance value for the signal generated with varying Planck scale, M_D.

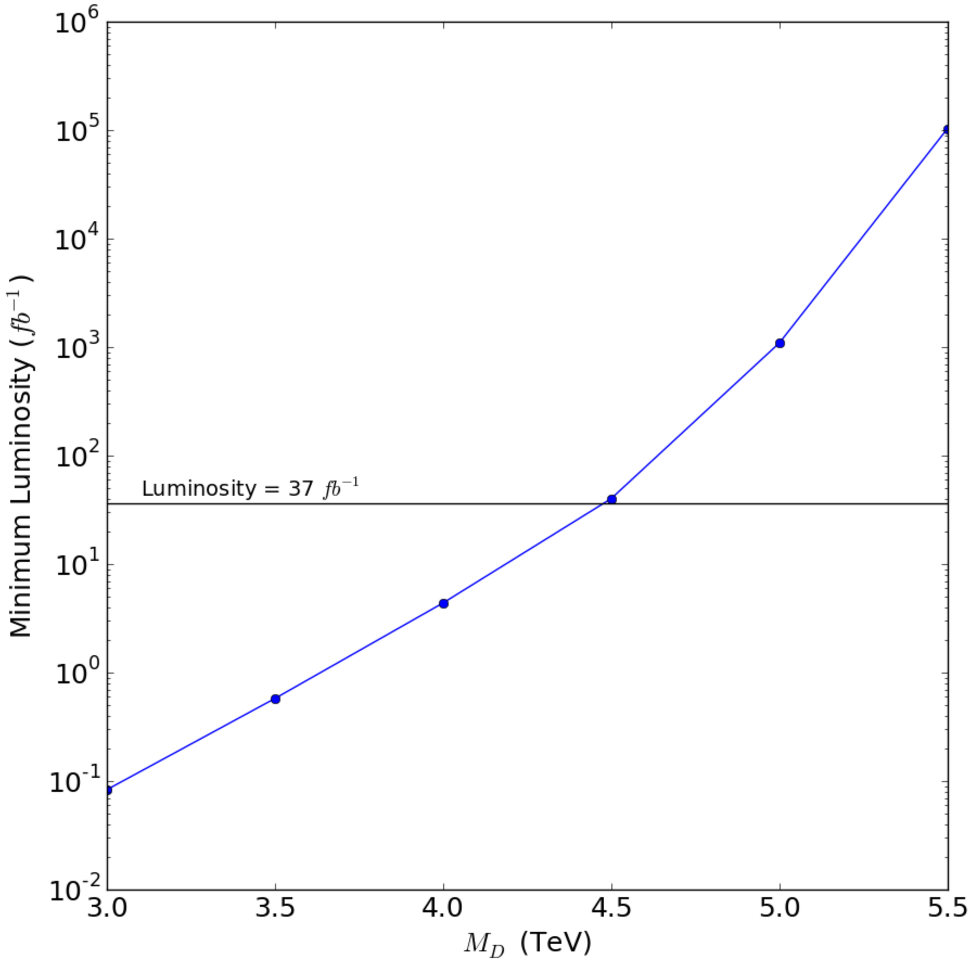

Figure 6: The plot of the minimum luminosity required for signal to be significant when generated with Planck scale, M_D.

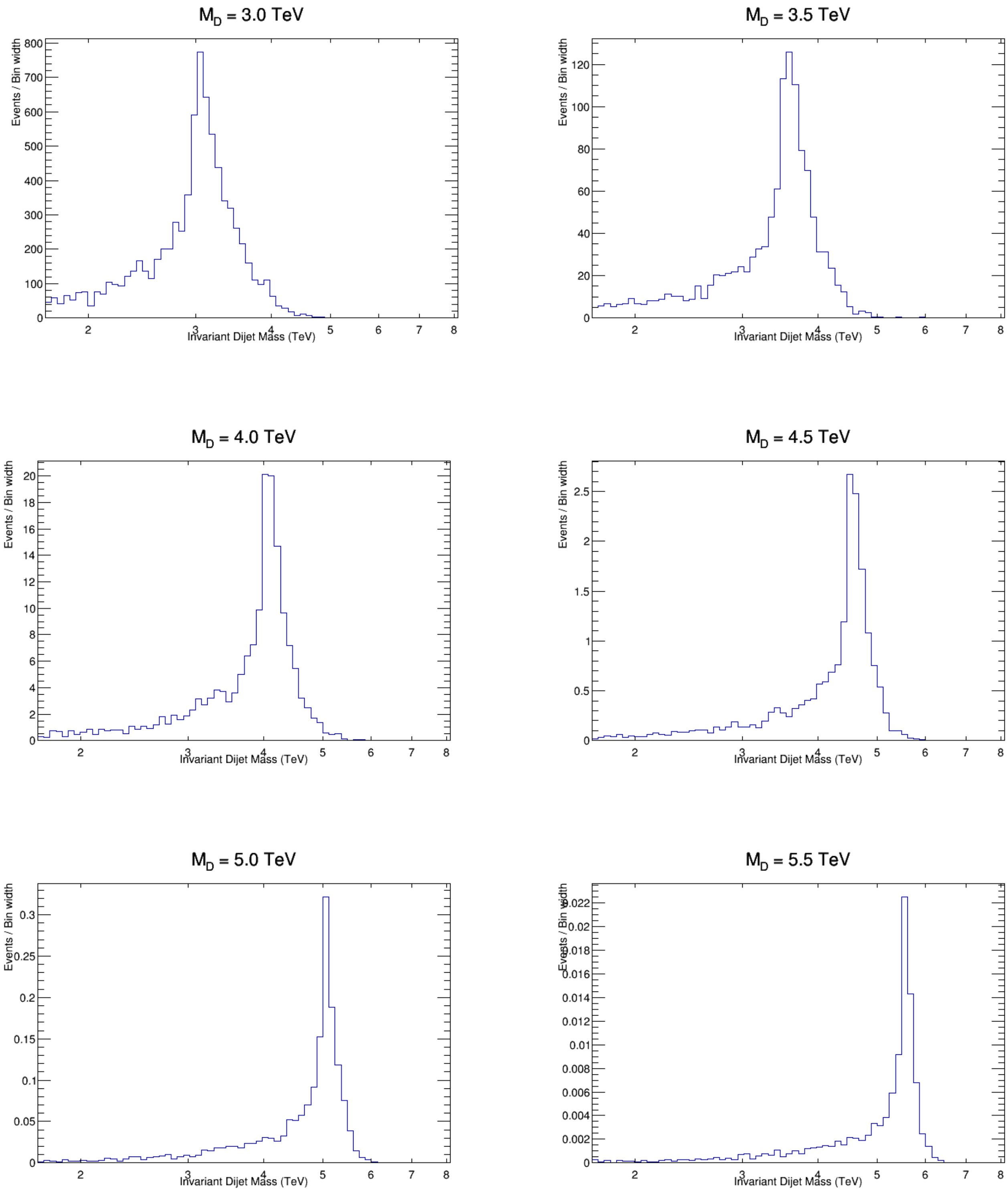

Figure 7: Histograms of the invariant dijet mass for QBH events generated with varying M_D. They are normalized to a luminosity of 37 fb^{-1} at LHC energy of 13 TeV.

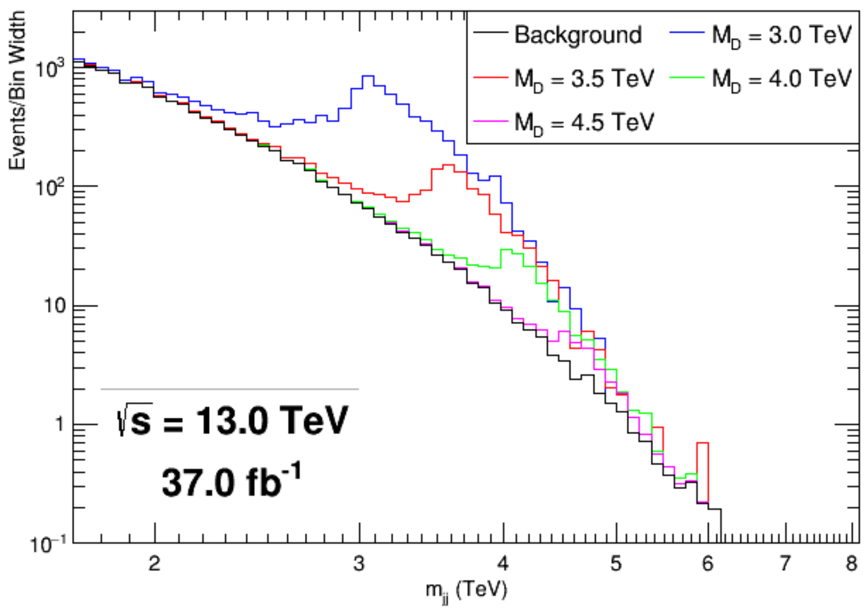

Figure 8: Comparison between the dijet background m_{jj} distribution and those with the signal included for four possible values of M_D. The histograms are normalized to a luminosity of 37 fb^{-1}