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QUANTUM BLACK HOLES EFFECTS ON THE SHAPE OF EXTENSIVE AIR SHOWERS

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Abstract. We investigate the possibility to find a characteristic TeV scale quantum black holes decay signature in the data recorded by cosmic rays experiments. TeV black holes can be produced *via* the collisions of ultra-high energetic protons ($E > 10^{18}$eV) with nucleons from the from atmosphere. We focus on the case when the BH decays specifically into two particles. These particles are then boosted in the Earth reference frame (back-to-back in the center of mass reference frame) and induce two overlapping showers. When reconstructing both the energy and the shape of the resultant air shower, there is a significant difference between showers induced only *via* standard model interactions and showers produced *via* the back-to-back decay of BH's as intermediate states.

Key words: Quantum Black Holes, UHECR's, Extensive Air Showers.

1. INTRODUCTION

Brane world models [1] or even four dimensional models with a large hidden sector of particles have been suggested when trying to explain the large hierarchy between the strength of the gravitational force and the standard model. In this context quantum gravity can become important anywhere between the standard Planck scale (*i.e.*, some 10^{16} TeV) and a few TeV. When the energy scale of gravity is in the lower end of this energy range (energies accessible for particle accelerators or in the center of mass of the collisions between ultra-high energy cosmic rays and nucleons from the atmosphere) particle collisions can result in the creation of TeV mass black holes (BH's). This is a threshold effect in the sense that BH creation turns on when the center of mass energy reaches the Planck scale. BH's formation *via* particle collisions has been studied since the 70's. The *Hoop conjecture* proposed by K. Thorne in 1972 states that a BH forms whenever the impact parameter b of two colliding objects (of negligible spatial extension) is shorter than the radius of the would-behorizon (roughly, the Schwarzschild radius, if angular momentum can be neglected) corresponding to the total energy M of the system $b \lesssim \frac{2 l_{Pl} M}{M_{Pl}}$. Because they are non-thermal, quantum black holes (qBH's) are expected to decay into a small number of particles, typically two. Such BH's are produced in the collisions between protons or neutrinos with energies above 10^{17} eV and nucleons from the atmosphere respectively water or ice. It needs to be pointed out that this signature, along with the ones proposed in Refs. [4, 5] are complementary to the TeV scale gravity searches performed by the various experimental groups from the Large Hadron Collider (LHC). In this article we study the possibility to distinguish the extensive air showers (EAS) induced by back-to-back BH decays from standard showers. Experiments such as Pierre Auger Observatory [2] can evaluate the shape of showers with their fluorescence detectors and the energy deposited by the shower in surface detectors. The findings of the present article are based on a set of EAS simulations made using CORSIKA 6.990 [6] for qBH's produced by protons with energies of 10^{18} eV which interact with nuclei in the atmosphere. The BH's decay immediately back-to-back into two particles, in the case we consider, a pair of pions. Two possibilities will be considered, $QBH \to \pi^+\pi^-$ and $QBH \to \pi^0\pi^0$ producing then two overlapping EAS.

2. BLACK HOLES PRODUCTION AND DECAY

The number of BH's expected to be produced within the volume of the atmosphere visible to a cosmic rays experiment, taking into account the experiment's dimensions and the duty cycle of the detectors, is given by

$$N = \int dE N_A \frac{d\Phi}{dE} \sigma(E) A(E) T \tag{1}$$

where $\sigma(E)$ is the production cross section, $\frac{d\Phi}{dE}$ is the flux of cosmic ray particles, $A(E)$ is the acceptance of the experiment measured in cm^2 sr yr, N_A is Avogadro's number and T is the running time of the detectors. The cross section p N $\to$ BH is given by:

$$\begin{aligned} \sigma^{pN}(s, x_{min}, n, M_D) &= \int_0^1 2z dz \int_{\frac{(x_{min} M_D)^2}{y(z)^2 s}}^1 du \int_u^1 \frac{dv}{v} F(n) \pi r_s^2(us, n, M_D) \\ &\quad \times \sum_{i,j} f_i(v, Q) f_j^N(u/v, Q) \end{aligned} \tag{2}$$

where M_D is the $4+n$ dimensional reduced Planck mass, $z = b/b_{max}$, $x_{min} = M_{BH,min}/M_D$, n is the number of extra-dimensions, $F(n)$ and $y(z)$ are the factors introduced by Eardley and Giddings and by Yoshino and Nambu. The virtuality scale Q is taken to be of the order of M_D. The $4+n$ dimensional Schwarzschild radius is given by $r_s(us, n, M_D) = k(n) M_D^{-1} [\sqrt{us}/M_D]^{1/(1+n)}$ where

$k(n) = \left[2^n \sqrt{\pi}^{n-3} \frac{\Gamma((3+n)/2)}{2+n}\right]^{1/(1+n)}$. Note that $s = 2xm_N E$, with m_N the nuclei mass and E the cosmic ray energy. The functions $f_i(x,Q)$ are the parton distribution functions.

Table 1

Number of qBH events per year expected at the Pierre Auger Observatory experiment for which the angle between the two decaying particles is $\theta_{CM} \in [75° - 105°]$.

No. of extra dimensions	M_{Pl} 5 TeV	M_{Pl} 6 TeV	M_{Pl} 7 TeV	M_{Pl} 8 TeV	M_{Pl} 9 TeV	M_{Pl} 10 TeV
0	29	14	7.5	4.5	2.8	1.8
1	1.9×10^2	1.1×10^2	0.71×10^2	0.48×10^2	0.34×10^2	0.25×10^2
4	1.1×10^3	7.6×10^2	5.2×10^2	3.8×10^2	2.9×10^2	2.2×10^2
5	1.6×10^3	1.0×10^3	7.0×10^2	5.2×10^2	4.0×10^2	3.1×10^2
6	2.0×10^3	1.3×10^3	9.2×10^2	6.7×10^2	5.2×10^2	4.0×10^2
7	2.4×10^3	1.6×10^3	1.1×10^3	8.3×10^2	6.4×10^2	5.0×10^2

In this article we analyze the signature of the events in which qBH's decay into a pair of pions, particles which then induce two overlapping showers. In the process of BH formation *via* particle collisions, some energy is radiated as gravitational radiation. When a proton having an energy of 10^{18} eV collides with a nucleon in the atmosphere, the resulting qBH mass can be up to the order of $M_{BH} \simeq 4 \times 10^{13}$ eV and can move relativistically with a gamma factor of $\gamma_{BH} \simeq 2 \times 10^4$. For our case of interest we select the interval of angles of the resulting particles in CM reference frame for which the two pions have energies between $4 \times 10^{17} - 6 \times 10^{17}$ eV. This happens for $75° \leq \theta_{CM} \leq 105°$. One can easily calculate that for 25.8% of the total number of qBH's produced the particles resulting from their back-to-back decay are emitted in this interval of angles. Using this range of angles, together with the acceptance for the Pierre Auger Observatory [2] and a fit for the cosmic ray flux in Eq. 1 one can estimate the number of events of this type that are expected to be seen in the Pierre Auger Observatory data. Table 1 shows the number of qBH's for which the energies of the two particles they decay into are between $4 \times 10^{17} - 6 \times 10^{17}$ eV when measured in the Earth reference frame as function of the number of extra-dimensions and the value of the Planck mass.

3. SIMULATIONS AND RESULTS

For the simulations we used the QGSJET 01C model for high energy hadronic interactions. Further, we wish to analyze if there is a distinctive signature for an EAS produced *via* the back-to-back decay into two particles of a qBH when compared with a standard air shower produced by protons. We consider two possible decay channels: $QBH \rightarrow \pi^+\pi^-$ and $QBH \rightarrow \pi^0\pi^0$. We consider the case when the two pions have roughly equal energies (on the order of 5×10^{17} eV) in the Earth reference frame. We

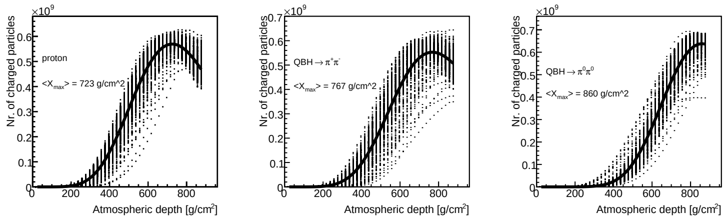

Fig. 1 – Longitudinal profiles of EAS's simulated with CORSIKA. Each plot contains 250 simulations. (*left*)shows standard model showers induced by protons with $E = 10^{18}$ eV. In these cases the primary particles were $E = 10^{18}$ eV protons which produced qBH's that decayed into $\pi^+\pi^-$ (*middle*), respectively $\pi^0\pi^0$ (*right*), with roughly equal energies in the laboratory reference frame. The black lines represent the fits with the Gaisser-Hillas function.

performed a set of 250 CORSIKA simulations for each case: the standard model type of proton induced showers and the two qBH decay channels. We found the following values: $< X^p_{max} >= 723$ g/cm^2 with the RMS = 42 g/cm^2 (in very good agreement with the QGSJET01C model), $< X^{QBH \to \pi^+\pi^-}_{max} >$ = 767 g/cm^2 with the RMS = 50 g/cm^2 and $< X^{QBH \to \pi^0\pi^0}_{max} >$ = 860 g/cm^2 with the RMS = 30 g/cm^2. Figure 1 shows a comparison between the $< X_{max} >$ values for these three cases. A shift of approximately 44 g/cm^2 is observed for the case $QBH \to \pi^+\pi^-$ and 137 g/cm^2 for the case $QBH \to \pi^0\pi^0$. The reconstruction of the primary energy takes into account the signal recorded by the ground detectors situated 1000 meters away (S(1000)) from the shower axis $E(EeV) = 0.12\left(\sqrt{1+11.8(sec\,\theta - 1)^2}\, S(1000)\right)^{1.05}$ where θ represents the zenith angle of the incoming primary particle. Figure 2 represents the lateral distribution function of charged particles at the observation level as a function of the distance from the shower axis. We observe that the density of charged particles is greater for the case of standard model showers in comparison with qBH induced showers. The right panel of Fig. 2 represents a zoom for the lateral distribution functions in the region from 950 to 1050 meters from the shower axis. The ratio of

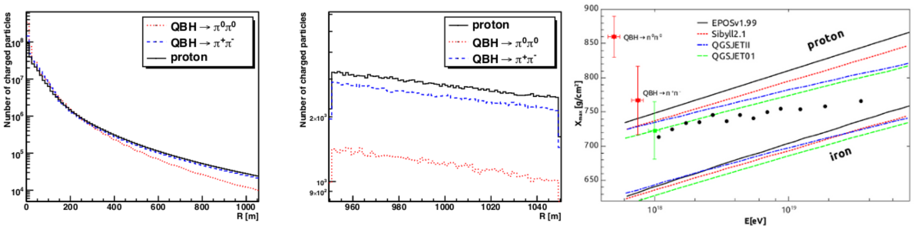

Fig. 2 – (Color online) Lateral distribution functions (number of charged particles *versus* the distance from shower axis) for the three cases: standard model type proton induced showers (black straight line), $QBH \to \pi^+\pi^-$ (blue dashed line) and $QBH \to \pi^0\pi^0$ (red dashed line) starting from the core of the shower (*left*), while the (*middle*) plot represents a zoom in the region around 1000 m. These are the average values calculated over 50 simulations per each case. The (*right*) plot represents the variation of the X_{max} as a function of the energy. The plot presents the Pierre Auger data [3] compared to air shower simulations for different hadronic models. In addition we include the cases of qBH's induced events for the simulations presented above.

the number of charged particles falling in this region in the case of the standard model proton induced showers to the number of particles falling in this region for the two types of qBH decays considered here is: $\frac{\rho^p_{ch}}{\rho^{qBH\to\pi^+\pi^-}_{ch}} \simeq 1.15$, $\frac{\rho^p_{ch}}{\rho^{qBH\to\pi^0\pi^0}_{ch}} \simeq 2.36$, with ρ^p_{ch} representing the number of charged particles for a standard model proton shower, while $\rho^{qBH\to\pi^+\pi^-}_{ch}$ and $\rho^{qBH\to\pi^0\pi^0}_{ch}$ represent the number of charged particle for the two qBH decay channels considered. These plots show that the surface detectors will underestimate the energies of the primary particles when the processes occur *via* intermediary qBH states. For the case of primary particles with energies of 10^{18} eV, the energies reconstructed in this way will appear to be 8.6×10^{17} for the case $qBH \to \pi^+\pi^-$ and 4.0×10^{17} for the case $qBH \to \pi^0\pi^0$. Figure 2 (*right*) shows the variation of X_{max} as a function of the energy. The plot presents the Pierre Auger data compared to air shower simulations for several hadronic models. It also includes the two data points representing the results of the simulations for EAS's produced *via* back-to-back qBH decays. We further analyze if this small number of qBH events can be separated from the proton induced standard model showers using the X_{max} distributions. In order to do that, we considered the flux of protons with energies above $10^{18} eV$ (which we claim to be the background) extrapolated from [2] with $< X^p_{max} >$ = 723 g/cm^2 and RMS = 55 g/cm^2 and the flux of qBH's (signal). The number of events is multiplied with a factor of 20 to obtain the statistics for 20 years and sprayed into Gaussian distributions with the associated $< X_{max} >$ and RMS values, as plotted in Fig. 3. We calculate the statistical significance $s/\sqrt{s+b}$ (where s stands for signal and b stands for background) in the interval of X_{max}[800 - 1100 g/cm^2]. We find it to be 0.07, 0.59, 3.23, 4.39, 5.35, 6.78 for n = 0, 1, 4, 5, 6 and 7 extra dimensions in the case $QBH \to \pi^+\pi^-$, respectively 0.20, 1.53, 8.97, 11.90, 14.83, 18.03 for n = 0, 1, 4, 5, 6 and 7 extra dimensions in the case $QBH \to \pi^0\pi^0$.

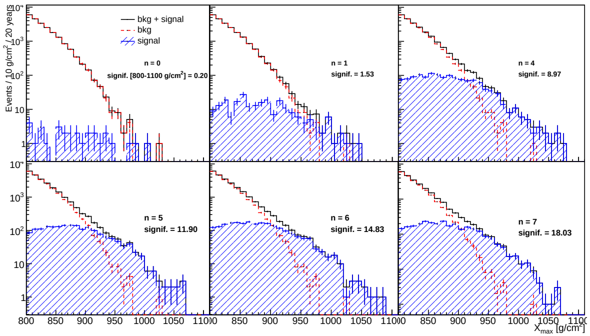

Fig. 3 – Signal (events which produced qBH's) and background (protons which interact without producing qBH's) estimates for the qBH events visible to the fluorescence detectors produced by $10^{18} \pm 10\%$ eV protons in 20 years of statistics at the Pierre Auger Observatory for the $QBH \to \pi^0\pi^0$ case and M_{Pl} = 5 TeV. The statistical significance is calculated for the range [800-1100 g/cm^2].

One can use Fig. 3 to look at the range of X_{max} values above 990 g/cm^2, range in which there is no standard model background.

4. CONCLUSIONS

UHECR's observatories provide a unique opportunity to test for the Planck scale one order of magnitude higher in energy than particle accelerators. The qBH induced showers have different profiles and X_{max} values when compared with similar showers generated *via* purely standard model processes. The shift in X_{max}, when considering 10^{18} eV primary ultra-high energy protons, is of approximately 44 g/cm^2 for showers generated by intermediary qBH's which decay into pairs of charged pions and it gets much larger, 137 g/cm^2 more exactly, for showers generated by qBH's which decay into pairs of neutral pions. On top of this, the primary particle energies can be underestimated by 14% in the first case and by 60% in the second case. The plots in Fig. 3 show that the signal significance is large enough for this signature to be detected at least in several of the cases under consideration. Therefore, we conclude that this signature is suitable to be used for performing qBH searches in the data recorded by cosmic ray observatories.

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REFERENCES

1. Nima Arkani-Hamed, Savas Dimopoulos, and G.R. Dvali. The Hierarchy problem and new dimensions at a millimeter. *Phys.Lett.*, B429:263–272, 1998.
2. J. Abraham, P. Abreu, M. Aglietta, C. Aguirre, D. Allard, I. Allekotte, J. Allen, P. Allison, J. Alvarez-Muñiz, M. Ambrosio *et al.*, Observation of the Suppression of the Flux of Cosmic Rays above 4×10^{19}eV. *Physical Review Letters*, 101(6):061101, August 2008.
3. S. Mariangela *et al.*, Latest results of the Pierre Auger Observatory. *Nucl.Phys.Proc.Suppl.*, 239:163-168, 2013.
4. Nicusor Arsene, Xavier Calmet, Laurentiu Ioan Caramete, and Octavian Micu. Back-to-Back Black Holes decay Signature at Neutrino Observatories. *Astropart.Phys.*, 54:132–138, 2014.
5. Xavier Calmet, Lauretiu Ioan Caramete, and Octavian Micu. Quantum Black Holes from Cosmic Rays. *JHEP*, 1211:104, 2012.
6. D. Heck and J. Knapp. Report **FZKA 6097** (1998), Forschungszentrum Karlsruhe; available from http://www-ik.fzk.de/˜heck/publications/. *Report* **FZKA 6097**, 1998.