Probing TeV gravity with extensive air-showers

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Abstract

Particle collisions with center-of-mass energy larger than the fundamental gravitational scale can generate non perturbative gravitational objects such as black holes and branes. In models with large extra dimensions, the fundamental gravitational scale may be around a TeV, making it possible for next generation particle colliders and ultra-high energy cosmic rays to produce such non perturbative gravitational objects. The decay of TeV gravitational objects is significantly different from standard model processes such that probes of these new ideas are within reach. We study the differences between standard model and TeV gravity interactions in extensive air showers (EAS) generated by ultra-high energy cosmic neutrinos. We show that discriminating TeV gravity from standard model interactions is generally difficult, but not impossible given a few unique signatures.

1. Introduction

In models with large extra dimensions (LEDs) [6-8], the fundamental scale of gravity may be $\sim$ TeV. In these models, particle collisions with center-of-mass (CM) energy larger than $\sim$ TeV may create non perturbative gravitational objects such as black holes (BH) [9] and branes [2,3]. Next generation particle colliders [11,13] and interactions of ultra-high energy cosmic rays (UHECRs) with the atmosphere [12,5,4] can reach TeV CM energies and, therefore, create these non perturbative gravitational objects (see [10] for a complete review).

The shower-to-shower fluctuations in EASs initiated by hadronic primaries combined with the small branching ratio to BH formation makes the study of TeV gravity with ultra-high energy protons hopeless [1]. Ultra-high energy neutrinos produced by the photo-pion production of ultra-high energy protons in the cosmic microwave background provide a cleaner beam to test departures from SM interactions [17]. Here, we discuss the characteristics of EASs initiated by cos-

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mogenic neutrinos that produce BHs in TeV gravity theories and contrast these with standard model (SM) interactions (based on a more detailed study reported in [1]). We find that due to the long interaction length of high energy neutrinos in the atmosphere and the large uncertainties in the BH formation cross section discriminating between the two scenarios is quite difficult. However, we also find that a few unique signatures involving tau leptons can help detect TeV BHs.

2. Black hole production in TeV gravity

The 4-dimensional Planck mass in natural units can be written as $M_{Pl} \equiv G_4^{-1/2}$, where G_4 is the 4-dimensional gravitational constant. In the presence of extra dimensions, the fundamental Planck mass is given by $M_\star = G_{n+4}^{-1/(n+2)}$, where n is the number of extra dimensions. The 4-dimensional and $(n+4)$-dimensional gravitational constants are related by $G_4 = G_{n+4}/V_n$, thus $M_{Pl}^2 = M_\star^{n+2}\, V_n$, where V_n is the volume of the extra dimensions. In models where V_n is large, $M_\star$ can be $\sim$ TeV. Depending on details of LED models (such as n, $M_\star$, and minimum BH formation mass, $M_{BH,min}$), the cross section for BH formation in neutrino-nucleon interactions can be either enhanced or suppressed with respect to SM cross section by several orders of magnitudes. Fig. 1 shows an example of the range in BH formation and SM cross sections, which include uncertainties in $M_{BH,min}$ and the parton distribution functions (PDFs) [14] (see [1] for other examples). If BHs form in TeV CM collisions, they evolve by shedding their hair first followed by Hawking evaporation, leading to the emission of SM particles such as quarks and gluons that subsequently hadronize into jets.

3. Extensive air-shower simulations

We simulated both SM showers and BH showers to compare their detectable characteristics. The most relevant SM process for the comparison is the ν_e charged current (CC) interaction which produces an electron shower that we modeled with AIRES [15]. For the BH production process, the secondary particles from BH evaporation are hadronized with PYTHIA [16] before producing a shower with AIRES. In Fig. 2, we show showers generated by neutrino primaries with energy $E_\nu = 10^7$ TeV and TeV gravity parameters n=6, $M_{BH,min} = 2M_\star = 2$ TeV. On the left panel, the first interaction point (X_0) is fixed to be 10 km above sea level with shower zenith angle of 70°, corresponding to a slant depth of 780 $g\,cm^{-2}$, for both BH and SM showers ($X_0^{CC} = X_0^{BH}$). ν_e-CC and BH showers are clearly different by ~ 200 g/cm^2. However, unlike the case of UHE protons, the interaction length for neutrinos in the atmosphere is large, thus, X_0^{CC} is not fixed. By shifting X_0 such that the shower maxima, X_m, for both cases match ($X_m^{CC} = X_m^{BH}$), the differences in shower development are much harder to distinguish as seen in the right panel of Fig. 2. Given a large number of neutrino

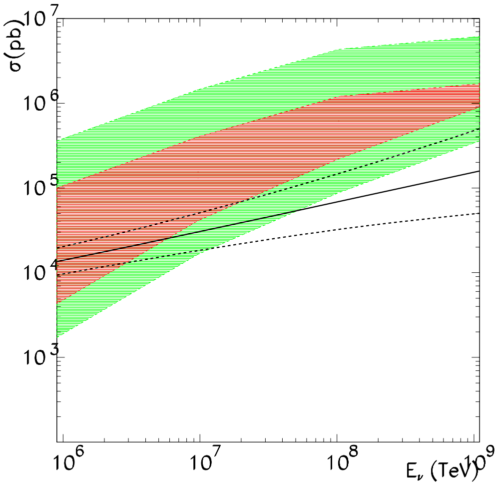

Fig. 1. BH cross section for $n = 6$ and $M_\star = 1$ TeV, with the $M_{BH,min}$ range in red and the uncertainties at the parton level and PDF in green. The solid lines give the SM cross section, with dashed lines showing PDF uncertainties for the SM case.

horizontal showers, one can distinguish the SM and the BH cases by studying the rise of the shower, $X_m - X_{0.1}$, where $X_{0.1}$ is the slant depth containing 10 % of particles of X_m. In addition, the muon content of BH showers is larger than the SM case, since BHs produce hadrons while CC showers do not. A deep horizontal shower accompanied by many muon secondaries is a sign of BH formation.

Detecting TeV BH formation with UHECR detectors may be possible through the decay of τ-leptons generated by ν_τ's that interact in the Earth or in mountain ranges close to the detectors. A secondary τ generated through the decay of a BH has much less energy than the SM τ secondary. In addition, BHs may produce multiple τ-leptons in their evaporation, a unique signature of TeV gravity. SM processes that generate multiple τ-leptons are highly unlikely, the detection of multiple τ's in earth-skimming and mountain crossing neutrinos will be a smoking gun for BH formation.

4. Conclusions

We showed that given the uncertainties in the ν-nucleon cross section for TeV gravity and the flux of cosmogenic neutrinos, distinguishing TeV LED models from the SM via the rate of neutrino induced EASs is unattainable. Although BH showers develop faster that the SM ones leading to a difference of 200 g/cm^2 in $X_m - X_0$, the variation in X_0 for neutrino showers make the distinction quite subtle. A large number of neutrino EASs with measured muon content and $X_m - X_{0.1}$ is necessary for a clear distinction of SM and BH formation. Finally, a few

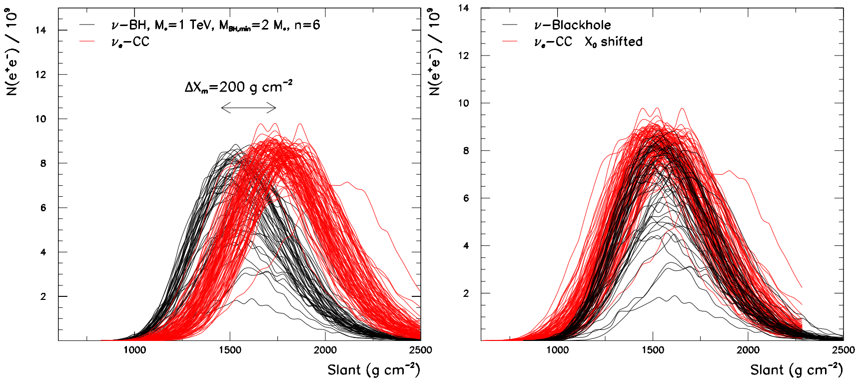

Fig. 2. e^+e^- pairs as a function of slant depth for $E_\nu = 10^7$ TeV. On the left, $X_0^{CC} = X_0^{BH}$, while on the right, X_0's are shifted s.t. $X_m^{CC} = X_m^{BH}$.

background free signatures such as multiple τ's and lower energy τ secondaries may more clearly signal the existence of TeV LED models. (We thank NSF and DOE for financial support.)

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