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Gravi-Burst: Super-GZK Cosmic Rays from Localized Gravity [*]

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Abstract

The flux of cosmic rays beyond the GZK cutoff ($\sim 10^{20}$ eV) may be explained through their production by ultra high energy cosmic neutrinos, annihilating on the relic neutrino background, in the vicinity of our galaxy. This process is mediated through the production of a Z boson at resonance, and is generally known as the Z-Burst mechanism. We show that a similar mechanism can also contribute to the super-GZK spectrum at even higher, ultra-GZK energies, where the particles produced at resonance are the Kaluza-Klein gravitons of weak scale mass and coupling from the Randall-Sundrum (RS) hierarchy model of localized gravity model. We call this mechanism Gravi-Burst. We discuss the parameter space of relevance to Gravi-Bursts, and comment on the possibility of its contribution to the present and future super-GZK cosmic ray data and place bounds on the RS model parameters. Under certain

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assumptions about the energy spectrum of the primary neutrinos we find that cosmic ray data could be potentially as powerful as the LHC in probing the RS model.

1 Introduction

About 25 years ago, Greisen, Zatsepin, and Kuzmin (GZK) noted that the observed spectrum of proton, photon, and nucleus cosmic rays must virtually end at energies above $\sim 10^{20}$ eV, the GZK cutoff [1]. Their key observation was that Ultra High Energy Cosmic Rays (UHECR's) deplete their energy through various interactions with the 2.7° K Cosmic Microwave Background Radiation (CMBR), over distances of order $10 - 100$ Mpc. Above 10^{19} eV, nuclei are photo-dissociated by interactions with the CMBR, and a 10^{20} eV proton loses most of its energy over a distance of ~ 50 Mpc. The analogous distance for a photon of the same energy is ~ 10 Mpc, due to e^+e^- pair production on the radio background [2].

However, over the past three decades, different experiments have observed a total of about 20 events at or above this 10^{20} eV bound[3]. Since there seem to be no feasible candidates for the sources of these cosmic rays, such as Active Galactic Nuclei, within a GZK distance ~ 50 Mpc of the earth, the observation of these events poses a dilemma. A number of proposals have been made to resolve this puzzle [4]. One such proposal for the origin of the super-GZK events, due to Weiler, is based on the observation that UHECR neutrinos can travel over cosmological distances, with negligible energy loss[5, 6]. Therefore, if these neutrinos are present in the universe they could in principle produce Z bosons on resonance through annihilation on the relic neutrino background, within a GZK distance of the earth. The highly boosted subsequent decay products of the Z will then be observed as primaries at super-GZK energies, since they do not have to travel cosmological distances to reach us. This mechanism for producing super-GZK cosmic rays is referred to as Z-Burst.

The Z-burst mechanism has the advantage that it does not assume physics beyond the Standard Model (SM) and is, therefore, minimalistic. However, any extension of the SM that provides a particle X which couples to $\nu\bar{\nu}$ and decays into the usual primaries can in principle contribute to the super-GZK spectrum beyond the range presently observed. Assuming a mass $m_\nu \sim 10^{-2} - 10^{-1}$ eV for neutrinos as suggested by atmospheric oscillation data, the particle X must have a mass of order the weak scale (~ 1 TeV) to be relevant to the spectrum near the GZK cutoff. In this paper, we will show that the massive Kaluza-Klein (KK) tower of gravitons in the Randall-Sundrum (RS) localized gravity model[7] are viable candidates for particle X.

The RS model is based on a truncated five-dimensional Anti-deSitter(AdS_5) spacetime, with two 4-d Minkowski boundaries. Our visible 4-d universe and all fields associated with the SM are assumed to be confined on one of these boundaries, referred to as the TeV brane, with the other 'Planck' brane boundary separated from us by a fixed distance $r_c \sim 10\,\overline{M}_{Pl}^{-1}$, the compactification scale along the 5^{th} dimension; $\overline{M}_{Pl}$ is the reduced Planck mass. The RS geometry is such that the induced metric on the visible TeV brane generates the weak scale from a 5-d scale $M_5 \sim \overline{M}_{Pl}$, without fine-tuning, through an exponentiation. The interested reader is referred to Refs. [7, 8] for the details of the RS model and its numerous phenomenological implications. However, here we mention that a distinct feature of this model is that it predicts the existence of a tower of spin-2 KK gravitons, $G^{(n)}$ $(n = 1, 2, 3, \ldots)$, starting at the weak scale, and with weak scale mass splittings and couplings.

Phenomenological studies [8, 9] suggest that the lowest lying KK graviton $G^{(1)}$ can be as light as ~ 400 GeV. The $G^{(n)}$ have couplings to all particles, due to their gravitational origin and can be produced by $\nu\bar{\nu}$ annihilation, eventually decaying into $q\bar{q}, gg, \gamma\gamma, \ldots$. Thus, the $G^{(n)}$ can in principle contribute to the super-GZK spectrum in a way that is similar to the Z-burst contribution. We call this graviton mediated process Gravi-Burst.

Since the Z and $G^{(n)}$ have different couplings and branching fractions to the observed primary particles, we expect that experiments may be able to distinguish between Z-burst and gravi-burst initiated primaries. Also, depending on the behavior of the flux of neutrinos at super-GZK energies, more than one member of the KK graviton tower could contribute to gravi-burst. In this case, the RS model predicts a characteristic multi-peaked behavior for future data at super-GZK energies and beyond. However, collider experiments may be a better place to directly search for the graviton tower, with cosmic ray data providing complementary information as we will discuss in detail later.

In the next section, we present the necessary formulae for estimating the super-GZK flux in the Z-burst model. We adapt this approach to gravi-burst and give the corresponding rate estimates in this scenario. Section 3 contains our results for a range of RS model parameters and a comparison with the Z-burst predictions. We will show that if the neutrino spectrum falls sufficiently slowly with energy we can use GZK data to greatly restrict the parameter space of the RS model. Our conclusions are given in section 4.

2 The Burst Mechanism

The burst mechanism relies on several well-motivated assumptions given the successes of the SM, Big Bang Nucleosynthesis and the observation of neutrino oscillations due to the existence of finite neutrino masses. This scenario is most easily demonstrated in terms of the conventional Z-burst. This model proposes that a high energy flux of neutrinos (and anti-neutrinos) are produced by some as yet unknown astrophysical source and collide with the relic background neutrinos in the galactic neighborhood. The origin of this flux is unspecified but constraints on its magnitude and energy dependence exist from Fly's Eye data[10]. If the flux at the Z-pole is sufficient to explain the super-GZK excess then the Fly's Eye data tells us that the fall off with energy of the neutrino flux at somewhat lowers energies goes at least as fast at $E^{-0.9}$. A similar energy behavior may be expected above the Z-pole.

Due to the finiteness of neutrino masses one would expect that the local density of neutrinos will most likely be enhanced over the uniform cosmological background due to their gravitational clustering around the galaxy[6]. Massive neutrinos within a few Z widths of the right energy

$$E_\nu^{R_Z} = M_Z^2/2m_\nu = 4(0.1\ \mathrm{eV}/m_\nu) \times 10^{22}\ \mathrm{eV}\,, \tag{1}$$

will then resonantly annihilate into hadrons with the local anti-neutrinos (and vice versa) at the Z-pole with the large cross section

$$< \sigma_{ann} >^Z = \int \frac{ds}{M_Z^2} \sigma_{ann}(s) = \frac{4\pi G_F B_h^Z}{\sqrt{2}} \simeq 28\mathrm{nb}\,, \tag{2}$$

where $B_h^Z \simeq 0.70$ is the hadronic branching fraction of the Z. We assume that only left-handed neutrinos exist and employ the narrow width approximation. Given a neutrino mass hierarchy and the Super-Kamiokande atmospheric oscillation results[11] we expect one of the neutrinos to have a mass near $\simeq 0.05 - 0.06$ eV. (This follows from using the latest two parameter fit to the Super-K data which yields a value for Δm^2 of 3.2×10^{-3} eV^2 and by supposing that one of the neutrino masses is at least a few times larger than the second.) The locally produced 30 or so hadrons from the decay of the Z are then the effective primaries for the super-GZK events that are observed with energies in excess of $\sim 10^{20}$ eV. (In principle, there being three neutrinos, we should consider three different cases depending on their masses. This is a straightforward extension of the present discussion.) If the source of the initial neutrinos is randomly distributed in space then, as shown by Weiler[6], we can calculate the total rate of super-GZK events induced by $\nu - \bar{\nu}$ annihilation at the Z pole within a distance D of the Earth as

$$F_Z \simeq E_\nu^{R_Z} F_\nu(E^{R_Z}) < \sigma_{ann} >^Z \int_0^D dx\ n(x)\,, \tag{3}$$

where the narrow width approximation has again been employed, $F_\nu(E^{R_Z})$ is the incident neutrino flux evaluated at the resonant energy, and $n(x)$ is the column number density of neutrinos. In deriving this expression it is assumed that the product $< \sigma_{ann} >^Z \int_0^D \, dx \, n(x) << 1$ as is the case for the Z in the SM and in the RS model we consider below. In practice we are interested in rather close annihilation, *i.e.*, values of D of order the GZK limit for protons which is ~ 50 Mpc.

Weiler has shown that for reasonable ranges of the parameters the resulting value of the flux F_Z can indeed explain the $\simeq 20$ events beyond the GZK bound observed over the last few decades. We note that the model in its present form predicts that all of the super-GZK events are relatively well clustered in energy just beyond $\sim 10^{20}$ eV and that essentially no events should exist beyond those induced near the Z pole. Obviously, if such 'ultra'-GZK events were observed then there must be new processes which can also lead to enhanced annihilation cross sections beyond those arising in the SM.

In the RS model with the SM gauge and matter fields lying on the TeV brane there exist a Kaluza-Klein tower of massive, weak scale gravitons, $G^{(n)}$, with essentially electroweak couplings. There are basically two parameters in this model: the ratio $c = k/\overline{M}_{Pl}$, with k a mass parameter with a magnitude comparable to the five-dimensional Planck scale, and the mass of the lowest lying graviton state. The masses of the tower KK states relative to the first non-zero mode are given by the ratio of roots of the Bessel function J_1 and c is expected to lie in the range $\sim 0.01 - 1$[7, 8, 9]. Specifically, while the zero mode graviton couples with a strength $\overline{M}_{Pl}^{-1}$, all of the remaining KK tower states couple as Λ_π^{-1} where $\Lambda_\pi = \overline{M}_{Pl} \, e^{-\pi k r_c}$. For values of kr_c in the range 11-12, the RS model provides a solution to the hierarchy problem. The masses of the KK states, $G^{(n)}$, are then given by $m_n = kx_n \, e^{-\pi k r_c}$ with x_n being the n^{th} roots of J_1. This implies that the tower mass spectrum is completely determined once the mass of the lowest lying excitation is known and is given by $m_n = m_1 x_n/x_1$. Thus we see that the parameters $c = k/\overline{M}_{Pl}$ and m_1 determine all of the other quantities within the RS model.

Both phenomenological and theoretical constraints can be used to restrict this two dimensional model parameter space as has been discussed in our previous works[8, 9]. As an initial numerical example of the Gravi-burst mechanism let us consider the specific case where $m_1 = 600$ GeV and $k/\overline{M}_{Pl} = 0.1$ which is a point in parameter space that is allowed by all of the current constraints; it is then straightforward to consider the more general case. For these specific values of the parameters we can calculate the cross section for $\nu\bar{\nu}$ annihilation into hadrons. This cross section now has a number of distinct contributions besides those arising from $q\bar{q}$ final states as in the decay of the Z in the SM. (Even in the SM, above threshold, neutrinos can annihilate into pairs of W's, Z's and top quarks which can subsequently hydronically decay.) In the RS case, the gravitons not only lead to $q\bar{q}$, $t\bar{t}$, W^+W^- and ZZ final states but also to pairs of gluons and Higgs bosons, gg, hh. Gluons fragment directly into hadrons while the SM Higgs bosons decay mostly to $b\bar{b}$. (Here we assume for numerical purposes that the mass of the Higgs is 120 GeV.) By combining all of these individual process cross sections, including interference with SM Z exchanges, we can calculate the full energy dependence of the total $\nu\bar{\nu} \to$ hadrons cross section. This allows us to determine the *ratio* of expected cosmic ray rates for super- and ultra-GZK events in units of the Z-pole induced rate F_Z computed above. It is important to note that in forming this ratio almost all of the astrophysical uncertainties cancel except for the energy dependence of the neutrino flux. We find

$$R(\sqrt{s}) = \frac{F_{SM+GRAV}(\sqrt{s})}{F_Z} = \frac{2\sqrt{s}\ \sigma_{ann}^{SM+GRAV}(\sqrt{s})\ (M_Z/\sqrt{s})^\lambda}{M_Z^2 < \sigma_{ann} >^Z}\,, \tag{4}$$

where we have assumed that the neutrino spectrum above the the resonant Z pole energy falls in a power-like manner as $\sim E_\nu^{-\lambda/2}$. We denote by F_{SM} the complete energy dependent flux anticipated in the SM beyond that obtained through the use of the narrow-width approximation alone. (In what follows it will be sufficient to assume that this power-like fall off adequately describes the neutrino spectrum for a few orders of magnitude in energy above $E_\nu^{R_Z}$.) Integration of R over a range of $\sqrt{s}$ values then tells us the relative rate of events expected in the RS model to those originating from Z-bursts.

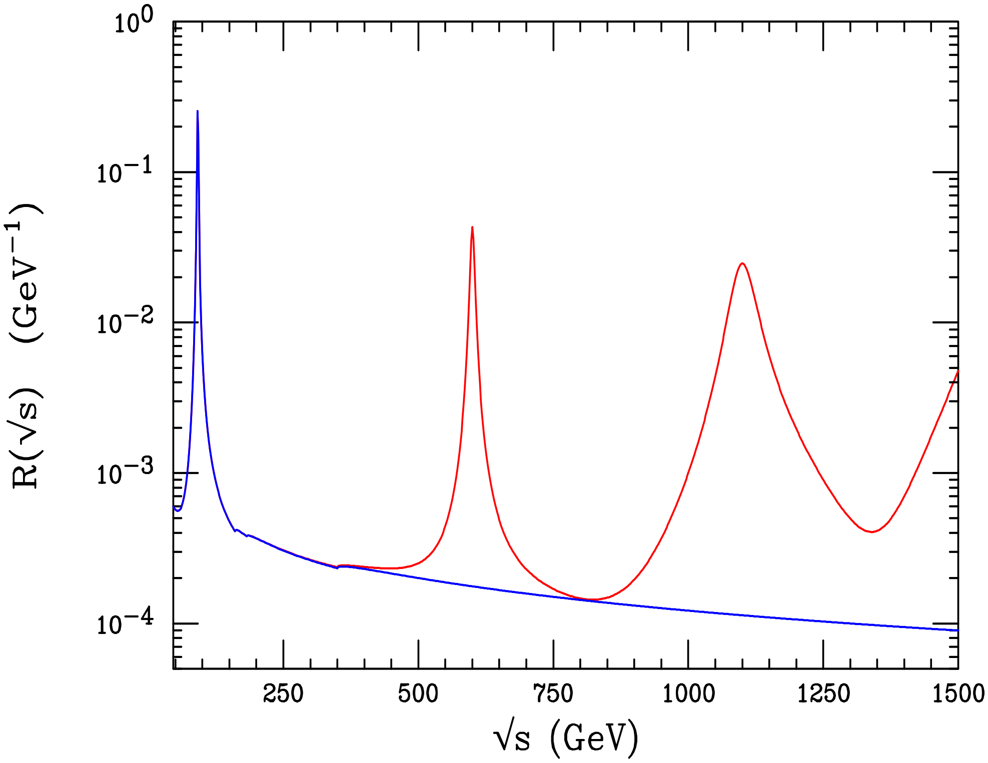

Figure 1: Energy weighted total cross section for hadron production in units of that for the Z pole in the Weiler Z-burst model for $\lambda = 0$ as a function of center of mass energy for the SM(the relatively flat lower blue curve) and in the RS model(the upper red curve) with $c = k/\overline{M}_{Pl} = 0.1$ and $m_1 = 600$ GeV. The small irregularities in the curves are due to WW, ZZ, hh and $t\bar{t}$ thresholds.

To get an idea of what this ratio looks like as a function of energy we show the simplest specific case where $\lambda = 0$ in Fig. 1. Note that the integral of R under the Z pole gives the value unity as it should to reproduce the Weiler results. We are also reminded by the figure that even in the SM there exists a long high-energy tail to this ratio. In the RS scenario, the Z peak is followed by a number of ever widening graviton peaks which also yield reasonably large cross sections. From the figure, one can see that if the neutrino flux falls off slowly enough with energy we should expect events at even higher energies than those observed at present assuming that the Z accounts for the 'usual' super-GZK events. We will make this assumption in what follows, *i.e.*, that the Z-burst scenario explains the observed super-GZK events. Given that hadronic multiplicities grow only very slowly with $\sqrt{s}$, as is observed in e^+e^- annihilation data, we would interpret events induced by Gravi-bursting on the first graviton resonance to result in hadronic effective primaries that have energies approaching 10^{22} eV. As of yet no such events have been recorded which places bounds on the allowed parameters of the RS model for different values of the neutrino energy spectrum described by the parameter λ.

3 Analysis

As we found in the last section, under the assumption that Z-bursts explain the super-GZK events the existence of even higher energy ultra-GZK events is a rather generic prediction of the RS model. Let us restrict ourselves to the region $\sqrt{s} \geq 300$ GeV which corresponds to effective primary energies in excess of 10^{21} eV of which none have been yet observed. Integrating R above this lower bound, even in the SM, can yield some 'background' events; the use of the narrow width approximation is not strictly correct in that some rare events can arise from values of $\sqrt{s}$ away from the Z pole. In the RS case, we integrate R over the region from 300 GeV up to $\sqrt{s} = 4m_1$ beyond which perturbation theory fails. † This yields a conservative lower bound on the total number of ultra-GZK events that are predicted in

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†We note that the RS model as described in four dimensions is a non-renormalizable theory. In addition, once the value of $\sqrt{s}$ significantly exceeds Λ_π the theory also becomes non-perturbative and only qualitative statements can be made about the behavior of the cross section[8].

the RS model since most certainly more events can arise from even larger values of $\sqrt{s}$. Integrating R in the SM over the above ranges and assuming that the 20 super-GZK events are from the Z-pole region, we find that for $\lambda = 1(2,3)$ we would expect to have already seen $\simeq 0.24(0.04, 0.008)$ ultra-GZK background events from the tail of the Z pole, which is quite acceptable. (As discussed above we might expect that $\lambda \geq 1.8$ is allowed by Fly's Eye data if the energy dependence of the neutrino spectrum below and above the Z-pole are similar.) Performing the same calculation in the RS model for a fixed set of values of m_1 and λ it will be clear that for some range of $k/\overline{M}_{Pl}$ the cross sections will be too large to have avoided the present non-observation of ultra-GZK events. In the usual manner this means that we can place a 95% CL bound on $k/\overline{M}_{Pl}$ as a function of m_1 for different assumed values of λ, using the existing data.

The dashed curves in Fig. 2 show the results of this analysis using the existing data for various values of λ; other constraints obtained on the $(k/\overline{M}_{Pl})$-m_1 parameter space from our earlier work[9] are also shown. We see immediately that the effectiveness of the bound is quite strongly dependent on the value of λ. For $\lambda \geq 3$ at most only a tiny region beyond that excluded by existing Tevatron Run I data is now ruled out. As λ decreases the size of the region presently excluded by cosmic ray data grows rapidly. For $\lambda = 2$ a substantial region allowed by the present Tevatron data becomes excluded. Furthermore, a sizeable region *beyond* that accessible at Run II with a luminosity of 30 fb^{-1} is also excluded. Using accelerators alone this region would be inaccessible until after the LHC turns on but here we see that it would be excluded by cosmic ray data provided $\lambda \leq 2$. For $\lambda \leq 1$ the bound is extremely powerful and at most only a tiny sliver of the RS model parameter space would remain viable.

In the region below the dashed curves, which is not excluded by existing cosmic

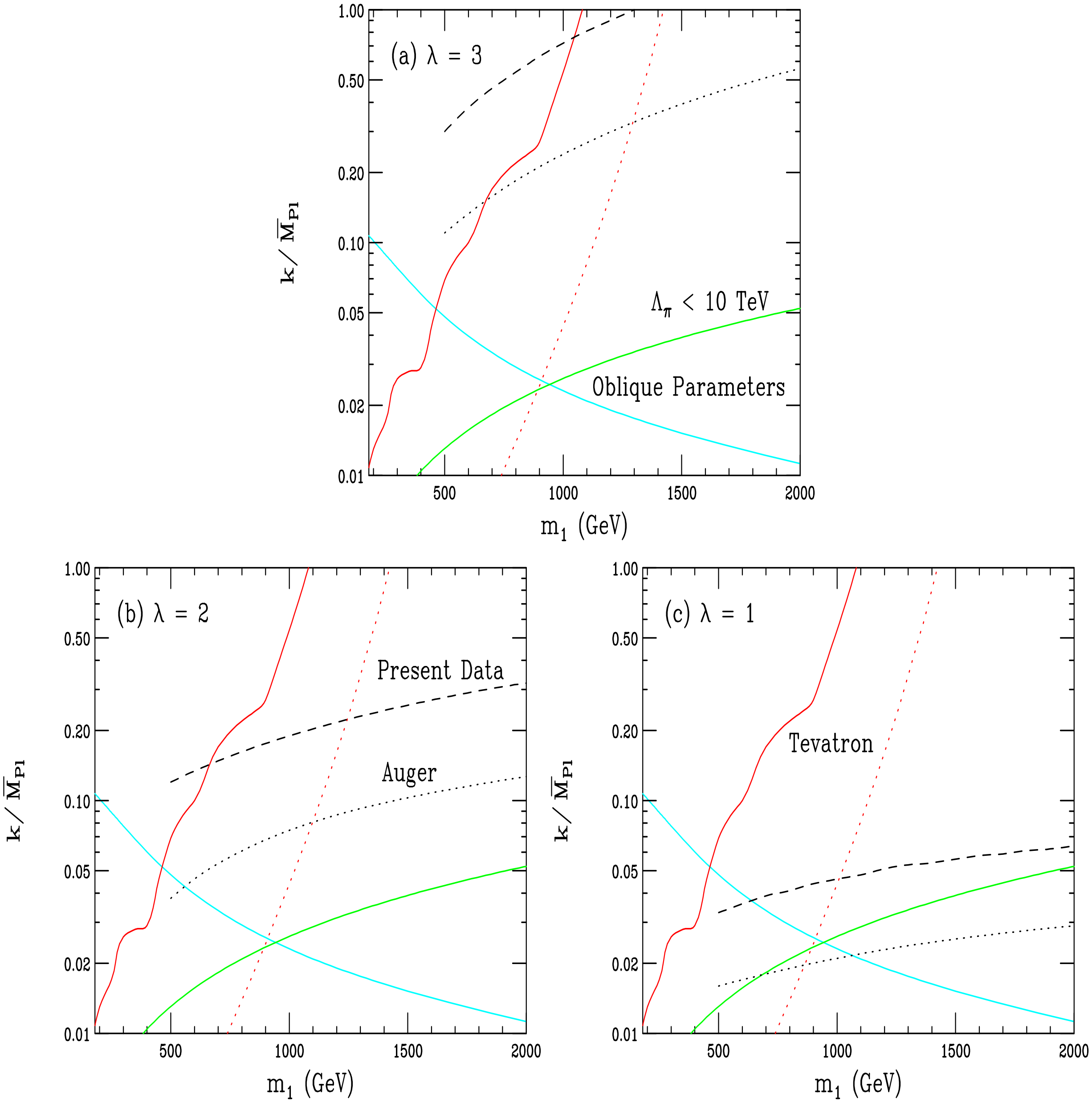

Figure 2: Allowed region in the $(k/\overline{M}_{Pl})$-m_1 plane. The solid(dotted) diagonal red curve excludes the region above and to the left from direct searches for graviton resonances at the Run I(II, 30 fb^{-1}) Tevatron. The light blue(green) curve is an indirect bound from the oblique parameter analysis (based on the hierarchy requirement that $\Lambda_\pi < 10$ TeV) and excludes the region below it. The black dashed(dotted) curves excluding the regions above them at 95% CL based on present (anticipated future Auger) cosmic ray data. The top(bottom left, bottom right) panel corresponds to $\lambda = 3(2,1)$ which describes the fall with energy of the neutrino flux as $E^{-\lambda/2}$.

ray data, we might expect ultra-GZK events to show up in future experiments at reasonable rates. If this does not happen it's clear that the present bounds discussed above will improve drastically especially with the new cosmic ray observatories such as Auger[12] coming on line. Within a 5 year period of data taking at Auger one would expect ~ 1000 super-GZK events[13] induced by Z-Bursts with correspondingly higher sensitivity to the ultra-GZK region. If no events above the SM background from the Z pole tail are observed at Auger during this period we can repeat the analysis above to obtain strong constraints on the RS parameter space as shown by the dotted curves in Fig. 2. We find the SM background expectations in this case for $\lambda = 1(2,3)$ to be $\simeq 12.5(2.05, 0.422)$ events. Here we see that for $\lambda = 2,3$ the size of the presently allowed region is quite significantly reduced. Particularly note the case $\lambda \leq 1$ where we find that the non-observation of any ultra-GZK events at Auger would completely *exclude* the RS model with the SM gauge and matter fields on the wall. This is a very powerful result.

If events above background are observed at Auger due to gravi-bursts they will have two distinctive characteristics. First, due to the resonance structure predicted by the RS model the energies of the effective hadronic primaries will show peaking at a set of fixed energies provided the energy resolution of the detectors is sufficiently good. Second, in addition to the rather 'soft' photons arising from conventional fragmentation π^0's, much harder photons can arise from the direct decays of the gravitons in the KK tower. As shown in our earlier work, gravitons in the mass range of interest can decay with a reasonable branching fraction, $\simeq 4-5\%$, into photons. Since they carry half of the energy of the resonance mass these photons will have energies an order of magnitude or more larger than those arising from π^0 decays. Of course with this rather small branching fraction a reasonable number of more 'ordinary' ultra-GZK events should be observed before one induced by these very hard photons.

So far we have only discussed the case of a single massive neutrino; data based on oscillation solutions to the solar neutrino problem[11] suggest a second massive state exists near 3×10^{-3} eV, about a factor 20 or so in mass below the 0.06 eV case discussed above. This second neutrino can also induce a Z-burst but only if the energy of the corresponding incident neutrino is $\simeq 20$ times larger, $\simeq 1.4 \times 10^{24}$ eV. In comparison to that for the case of the higher mass neutrino the flux of these lighter neutrinos would be $\simeq (20)^{\lambda/2}$ times smaller. This assumed neutrino mass ratio, strongly suggests that $\lambda \geq 2$ to avoid ultra-GZK events from the second Z resonance. To eliminate any additional background generated by this new Z contribution, we would need to raise lower bound on our $\sqrt{s}$ integration, which is actually an integral over the neutrino energy. (The $\sqrt{s} = 300$ GeV lower bound translates into a minimum neutrino energy of $\simeq 8 \times 10^{23}$ eV and thus would now include additional background events from the second Z peak.) Raising the minimum neutrino energy by a factor of two would remove the second Z contribution while still staying comfortably below the excitation energies of any of the gravitons. In this case we would expect at most only slight alterations in the bounds presented above.

Before we conclude we briefly discuss a generalization of the RS model where the SM gauge and matter fields are taken off the TeV brane[9] and how this would influence our results above. In this case not only can graviton towers be exchanged in the $\nu\bar{\nu} \rightarrow$ hadrons process but now there are also Z boson towers whose members are generally interspaced in mass with the gravitons. If these additional contributions are also present it is quite possible that the neutrino cross section can be significantly enhanced leading to even stronger limits than those obtained above using current data. One might also expected that with increased cross sections it might be possible to probe cases where the slope of the neutrino energy spectrum is even steeper than what we have considered here. Unfortunately, to determine how much our previous results are modified in a quantitative manner requires a detailed analysis which is far beyond the scope of this paper.

4 Conclusions

In this paper we have examined the possible contribution to the spectrum of cosmic rays beyond the GZK cutoff due to new physics arising in the Randall-Sundrum model of localized gravity. Our analysis is based on the assumptions (i) that the events observed immediately above the GZK bound can be explained by the Z-Burst mechanism and (ii) the neutrino spectrum needed for Z-Bursts extends s few orders of magnitude further in neutrino energy with a reasonably slow fall-off. If these conditions hold then the existence of a series of s-channel Kaluza-Klein graviton resonances in the $\nu\bar{\nu} \to$ hadrons channel, which is predicted in the RS model, can lead to events with even higher energies, ultra-GZK, due to Gravi-Bursts. The rate for these bursts are generally at or near the present level of observability for a wide range of RS model parameters. The fact that such events are not as yet observed can be used to constrain the parameter space of the RS model once a specific form of the neutrino energy spectrum is assumed. These bounds can be more restrictive than those that can be obtained from the lack of graviton resonance production at the Tevatron during Run II (30 fb^{-1}) if the fall-off with energy of the UHECR neutrino flux is linear or less steep. If ultra-GZK events are not observed by future experiments such as the Auger Array, then the resulting bounds on the RS model can be complementary to those obtainable at the LHC. If such events are observed at future experiments, the RS resonance structure may be observable given both sufficient statistics and good hadronic energy resolution. In addition to hadronic modes, the RS graviton KK tower states can directly decay to photon pairs which will have more than an order of magnitude greater energies that those that can arise due to ordinary fragmentation into π^0's which subsequently decay into two photons. If photon and hadron induced showers can be distinguished at such energies this will provide a unique signature for the RS model as the origin of the ultra-GZK events.

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