Particle Candidates of Ultrahigh Energy Cosmic Rays*

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Abstract

We discuss candidates for trans-GZK cosmic rays observed in a variety of detectors. Three types of primaries are represented among the abstracts submitted to this meeting: neutrinos causing a Z-burst, protons arising from the decay of ultra-heavy metastable particles and neutrinos within the framework of low scale string-like models of unification. We attempt to evaluate the relative merits of these schemes. No definite conclusion can be reached at this time. However, we point out that some schemes are more credible/predictive than others. Data to be gathered by the Pierre Auger observatories as well as orbiting detectors (OWL, Airwatch...) should be able to decide between the various schemes.

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1 Introduction

As soon as the cosmic microwave backround radiation (CMBR) was discovered, Greisen and Zatsepin and Kuzmin independently pointed out that there should exist a cutoff in the primary cosmic ray spectrum [1]. The physical basis of that cutoff is very well established. In fact, the physical process responsible for it was originally discovered by Enrico Fermi and his group in the fifties and has been extensively studied ever since. It is generally believed that the primary cosmic radiation at energies above, say, $10^{17.5}$eV or so, consists mostly of protons. The composition at these energies is discussed by Stecker in his excellent Erice lectures [2]. Protons interact with the CMBR, produce electron pairs, photoproduce pions and lose about 30% of their energy per interaction. (The production rate of more than one pion is negligibly small.) This means that, unless protons are produced in our "cosmic backyard", they cannot have energies exceeding some 10^{19}eV or so (the so-called *GZK cutoff*). Else, if produced far away with energies sufficiently high to allow them to arrive here above the GZK cutoff, their interaction with the CMBR would ultimately produce an unacceptably high photon background at lower energies, see Stecker, *loc. cit.* for a review.

At the time of this writing some 20+ events have been observed of energies exceeding the GZK cutoff and they have generated a flurry of theoretical papers exceeding the number of events observed by at least a factor of two or more. (The highest energy published event is still the one reported by Fly's Eye, see [3].[1]) Clearly, it is unsatisfactory to have a small number of events observed in the trans-GZK category. However, with the Pierre Auger observatories, OWL and Airwatch becoming operational within the near future, this situation will change drastically. **Should we get excited – if so, why?**

There is a variety of attitudes adopted in connection with the reported trans-GZK events. Here is a sample based on our informal evaluation of a variety of papers and conversations with some colleagues.

- *Denial.* OK, some trans-GZK events have been reported. However, it is known that the primary cosmic ray (CR) spectrum is rapidly falling at energies larger than, say, 10^{17}eV. In such a sit-

[1] Since the time this talk was given, another event of comparable or somewhat higher energy was reported. See M. Teshima, talk presented at the *Summer study on the future of Particle Physics, Snowmass, CO 2001*

uation it is easy to overestimate the primary energy. Maybe, the problem will just go away with more events observed.

- *Our backyard.* The GZK cutoff can be overcome if there is a sufficient number of local sources of UHECR. Blanton *etal.* [4] made the reasonable assumption that the distribution of sources follows the distribution of galaxies. They find a local overdensity of ≈ 2 and they conclude that for soft injection spectra this overdensity is insufficient to explain the observed flux around 10^{20}eV.

  Despite the original analysis of Elbert and Sommers [5], there may be *individual* sources of trans-GZK CR in our galactic neighborhood. In particular, CEN A has been conjectured as a possible source of such trans-GZK protons [6]. With a distance of about 3.5Mpc, CEN A "just barely makes it" as a potential source. In contrast to older calculations, the thorough analysis of Stanev *et al* [7] results in a much smaller radius of the GZK sphere (about 14 Mpc or so) rather than about 50 Mpc as believed previously[2].

  In order to illustrate what is involved in ref. [7], consider the following simple model. Roughly speaking, a proton executes a random walk in the chaotic magnetic fields. Let L denote the total path length necessary for the proton to lose a substantial fraction of its energy, *i.e.* the GZK length. Since the particle is ultrarelativistic, $t = L$ to a high degree of accuracy. The rms distance the proton travels in time t is therefore given by

  $$\sqrt{\langle \mathbf{x}^2 \rangle} \approx \sqrt{\lambda t} \approx \sqrt{\lambda L},$$

  where λ is the mfp of magnetic scattering; it is of the order of a few Mpc. Assuming, $\lambda \approx 5$Mpc, and $L = 50$Mpc, one gets $\sqrt{\langle \mathbf{x}^2 \rangle} \approx 16$Mpc. Considering the crudeness of all the approximations made here, this is in reasonable agreement with the result of ref. [7].

  At present, it is not clear whether CEN A can account for the observed trans-GZK events. Like previous similar proposals, the CEN A hypothesis has been criticized, see *e.g.* ref. [9]. In a sense, the controversy revolves around the question whether there are sufficiently strong random intergalactic magnetic fields to wash out the directionality of the UHECR arriving from a single source. An

[2]The GZK sphere is a somewhat fuzzy notion: roughly speaking, it is the radius of the sphere within which a source has to lie in order to provide us with protons of 10^{20}eV of energy. The work of Stanev *et al.* contains precise definitions. The difference between this work and previous ones lies in a careful accounting of intergalactic magnetic fields, which either were not treated or only in some sketchy way. A notable exception is ref. [8].

interesting test of the CEN A hypothesis was proposed by Anchordoqui *et al.*, ref. [10]. When the southern Auger Observatory will be operational, one should look for neutrons emitted by CEN A. At such energies, neutrons appear as stable particles. Being neutral, they are less affected by the magnetic fields on the way here than protons are.

Should the CEN A hypothesis (or some other similar one, *e.g.* M87 as a source) prove viable, the problem of trans-GZK cosmic rays will be resolved without invoking new particle physics or substantially new astrophysics.

- *New physics and/or astrophysics.* All works submitted to this meeting dealing with the problem of trans-GZK cosmic rays belong to this category. They represent approaches which, so far, have not been definitely eliminated either by accelerator based experiments (*e.g.* lower limits on the masses of superpartners) or by other physical or astrophysical arguments.

If the first two items mentioned above get somehow eliminated, then our answer is that *yes, we should get excited: the trans-GZK CR are messengers of some new particle physics or new astrophysics.* In the following sections, we discuss these works.

2 Z-bursts and Neutrino Clouds.

The original idea of Z-bursts was conceived by Fargion *etal.* and by Weiler, [11]. The basic idea is beautifully simple and it needs no particle physics beyond the well established Standard Model.

The authors argue that neutrinos can penetrate the CMBR, because they have a very small magnetic moment and in scattering on a CMBR photon, the CMS energy, $\sqrt{s}$ is about 100MeV or so. There may be a halo of neutrinos around our galaxy. If neutrinos are massive, of mass m_ν, an interaction between a neutrino coming from afar and a halo (anti) neutrino can excite the Z resonance. The neutrino energy needed for that is about $E = M_Z^2/2m_\nu$. The, Z, in turn, decays into nucleons, roughly 35% of the time and *voilá*, we have the trans-GZK cosmic rays. Strictly speaking, the neutrinos in the halo need not be massive. For massless neutrinos, just replace m_ν by $\approx kT$, with $T = 1.9^oK$. The trouble is that one needs inconceivably high neutrino energies if the neutrino mass is replaced by the thermal energy of a massless relic neutrino.

Waxman pointed out that the total energy carried by the high energy neutrino flux was dangerously close to the total luminosity of the Universe [12]. Clustering or a high lepton asymmetry [13] is needed in order to make the Z-burst scenario work. Unfortunately, a large lepton asymmetry leaves its imprint on the CMBR and the latest observations appear to be incompatible with the asymmetry postulated by Gelmini and Kusenko [14].

Now McKellar *etal.* [15] in a paper submitted to this meeting argue that clustering in the neutrino halo can be accomplished if one revives the idea of neutrino clouds [16]. The model is based on the assumption of a light scalar field weakly coupled to neutrinos. By performing a self consistent field calculation, the authors argue that the minimum of field energy is obtained if the neutrino beckground is not uniform, but clustered. This clustering phenomenon is somewhat similar to what is found in a realistic ferromagnet: the minimum of the free energy is obtained by forming domains instead of a completely homogeneously oriented spin array. This scenario has a chance to rescue the Z-burst model.

The authors consider a broad range of densities and cluster radii, within bounds imposed by the amount of dark matter in the solar system and upper bounds on the incident neutrino flux.

There are several questions to be answered, however, in this connection.

- Are there any other consequences? (For instance, imprint on the CMBR, cosmology, *etc.*) What is the cosmological density of the light scalar? Does it have an effect on nucleosynthesis?
- Several theoretical questions. Why a light scalar? Does it couple just to neutrinos (or just to ν_e)? Does such a light scalar fit into any reasonable unification scheme?
- Can the postulated light scalar be emitted during ordinary weak processes? In particular, does the emission of a light scalar lead to a measurable distortion of the spectra, apparent lack of energy-momentum conservation *etc.* Our guess is that the lack of distortion of β spectra and violation of energy–momentum conservation can pose a lower limit on the mass of the scalar and/or an upper limit on the strength of its coupling.

It is rather obvious at this point that further research is needed in order to determine the viability of the neutrino cloud model.

3 Topological Defects, X-particles, *etc.*: the Saga of Top-Down Models.

"Classic" (*i.e.* vintage $\simeq$ 1980's) grand unified theories (GUTs) contain quite a few candidates of particles of masses around the GUT scale, ranging between (approximately) 10^{11}GeV to 10^{16}GeV. Those are supposed to have been produced – in the form of leptoquarks, *etc.* – soon after the Big Bang, typically right after inflation. If sufficiently stable, they may be around us and decay, in part, into UHE protons, thus explaining the trans-GZK cosmic ray flux. This mechanism was originally conjectured by the Chicago group of astroparticle physicists (then including the late David Schramm) and the developments are summarized in the comprehensive review paper of Bhattacharjee and Sigl, [19]. For this reason, we can restrict ourselves to a very brief summary of the situation.

In essence, *if* — and that is an important *if* — X-particles of any kind can be made sufficiently stable to survive until the present epoch, their decay products can supply the highest energy protons responsible for the trans-GZK cosmic rays.[3] An interesting variation on this theme includes a recent article by Blasi *etal.* [20] , in which, besides decay, annihilation of superheavy particles is also considered. In essence, those authors conclude that an annihilation cross section of the order of the usual strong interaction cross sections (10 to a 100 mb) is needed in the annihilation scheme. Alternatively, a lifetime of $\simeq 10^{20}$yr is needed if the UHECR are to be produced through the decay of some X-particle. There is no known (weakly broken) symmetry to protect the X-particle from decaying rapidly. If this mechanism is to be a viable one, it is likely that the long decay lifetime is due to a higher dimensional operator as proposed in ref. [21]. A recent detailed account of this approach can be found in ref. [23] with appropriate references to earlier work.

The papers by Fodor and Katz [24] put an interesting twist on the X–particle saga. Instead of guessing on the basis of various theoretical considerations what the mass of the X-particle might be, they attempt to fit the available data by letting the mass of the X-particle float and be determined by the fitting procedure. In this way, they end up with a mass of $M_X \approx 10^{14.6}$GeV iun contrast to the value, $M_X \approx 10^{12}$GeV

[3] A model for (meta-)stabilizing superheavy particles has been proposed by Ellis *etal.* [21]. In that model metastability is accomplished because the superheavy particles decay *via* higher dimensional operators.

used in ref. [21]. Other hypotheses, for instance a heavy leptoquark decaying into a quark and lepton would further increase the fitted M_X. Fodor and Katz point out that their fitted mass value leads to no contradiction with the observed X-ray and soft gamma ray background. However, should they consider other X-particles (like the leptoquark just mentioned) they *may* run into trouble with the EGRET results. A careful discussion of this question is given in the review of Bhattarcharjee and Sigl already cited. Fodor and Katz also give χ^2 values for a variety of models including the standard model (SM) or minimal SUSY standard model (MSSM) by placing the X-particles into our own galaxy or making them extragalactic. Their best fit is either an extragalactic SM or MSSM X-particle. However, it may be prudent to await the arrival of some more data before such details can be extracted.

Another worry is based on the result of ref. [7]. As mentioned before, those authors find a geodesic GZK distance about a factor of 4 or so than previously believed. Hence, the density of X-particles has to be increased by a factor of about 45. *Does this not overclose the Universe?* However, Fodor and Katz assume a uniform distribution of X-particles. In reality, however, X-particles cluster around galaxies, due to the gravitational attraction of the latter. Hence, the danger of overclosing the Universe is, perhaps, avoided.

Fodor and Katz obtain an X particle mass which is, roughly, two orders of magnitude smaller than the "canonical" SUSY GUT mass, but it is about two orders of magnitude larger than a possible intermediate mass scale of the order of 10^{12}GeV, occurring in some SUGRA models. Normally, it is hard to maintain mass differences of this magnitude in a theory unless the small mass is protected by some symmetry. No such symmetry is known. It is unclear how the hierarchy problem raised by the result of Fodor and Katz can be avoided.

4 A String Inspired Model.

It has been realized a few years ago that, internal consistency of string theories requires that strings live in a multidimensional space (typically, d=10 for superstrings), the connection between a string scale and the Planck scale is less rigid than hitherto believed [25, 26, 27]. Although the original conjecture of TeV scale quantum gravity and millimeter size compactified extra dimensions is all but excluded now, it is useful to keep in mind such models as a paradigm from which useful features can be abstracted. At present, *there is no internally consistent, phenomenologically viable string model known in which even the basic features of the dynamics – including a mechanism of compactification – would be satisfactorily understood.*

Nevertheless, various string models have so many attractive properties that one is tempted to abstract their robust features and see whether some reasonable conjectures can be made once CMS energies of colliding particles reach the string scale. For the sake of argument, let us have a string scale of the order of a 100TeV in mind. This can be reached in UHE cosmic ray interactions: for instance, the "gold plated" Flye's Eye event has about 600TeV in the CMS.

Basically, two new phenomena are beginning to be observed around the string scale.

- A large number of excitations begins to show up with, presumably, increasing widths. As a consequence, at least some cross sections exhibit a rapid rise towards a value which saturates unitarity. The excitations are, in essence, of two types.
  1. *Kaluza-Klein (K-K) type excitations* if the extra dimensions are compactified. Similar excitations may take place if we live on a brane and the extra dimensions are not compactified, see [28]: there are brane fluctuations. The common feature of these excitations is that their level density grows like a power of the CMS energy; hence, at best, a cross section (for instance the νN cross section) can grow only as a power of the energy. This is inadequate for explaining the trans-GZK cosmic rays, see Kachelriess and Plümacher[29].
  2. *The string excitations.* It is widely known that the density of states in the excitation spectrum of strings grows asymptotically as $\exp(a\sqrt{s})$ for $s \gg M_s^2$, see, for instance, Polchinski's [30] book on string theory. It is less widely known that the low lying excitations exhibit a more rapid rise of the density of states, typically, $\propto \exp(bs)$, where b is some model dependent constant. (Unlike the constant a, related to the central charges of the underlying conformal field theory, at present we do not know how to interpret the constant b in terms of the specific conformal field theory considered.)
- There appears to be a unification of interactions. In fact, as far as one can tell, once the energy gets into the string regime (after the first few excitations), all couplings are the same. There remain

questions, of course, for instance, "*is the unification mass equal to the characteristic string mass, M_s?* Perhaps there are factors of order unity between the two scales. We assume that they are the same, for lack of a really good model.

From the point of view of guessing a useful phenomenology, one conjectures that, in essence, there are three regimes of the future theory.

1. *The low energy regime* characterized by the fact that coefficients of non renormalizable operators in an effective field theory, proportional to some positive power of s/M_s^2 are small.
2. *The transition regime*, in which K-K excitations drive the coupling constants towards a common value, as discussed, *e.g.* by Dienes, ref. [31]
3. *The string regime proper*, with all interactions unified and cross sections, in essence governed by their unitary limits.

It was pointed out some time ago [32] that neutrinos could be ideal primaries of the trans-GZK cosmic rays since they have an essentially infinite mean free path in the CMBR. If one can arrange for a stronger than SM interaction with air nuclei, one could perhaps solve the puzzle of the trans-GZK events. The scenario sketched above provides the appropriate mechanism. In collisions with a CMBR photon, a neutrino of, say $E = 10^{21}$eV, has typically $\sqrt{s} \approx 200$MeV or so: this is deep in the low energy regime even of the SM. By contrast, in interactions with a nucleon in an air nucleus, one has roughly $\sqrt{s} \approx 10^3$TeV. Thus, we might be in the regime of unified interactions and string excitations [33].

Unlike some other scenarios, this one is predictive. One can easily understand in qualitative terms one of the most robust predictions [34]. It is known that in typical GUT schemes (the GUT group always containing $SU(3)_{\rm c} \otimes SU(2)_{\rm L} \otimes U(1)_Y$), the dominant decay mode of the leptoquark excited in a ν nucleon interaction is a lepton and a quark. Therefore, the shower starts as if one had a lepton induced and a hadron induced shower running parallel to each other. In the unified regime the shower tends to be enriched in quarks, due to the fact that quarks carry 3 times as many degrees of freedom as leptons do. However, the energy gets spread over many particles early in the development of the shower and, consequently, most of the evolution is governed by SM physics. Due to the fact that the leptonic component develops by means of low multiplicity interactions[4], the fluctuations are larger in a neutrino induced

[4] Counting electrons and photons on the same footing, the average multiplicity in a lepton

"anomalous" shower than in a proton (or nucleus) induced one.

In order to obtain a quantitative handle on this, the ALPS[5] Monte Carlo algorithm [35] was run both for proton induced showers and for "anomalous" ones. The anomalous showers were modelled along the lines just sketched; more details can be found in ref. [34]. Figure 1 displays the average profiles of a few showers with different impact parameters as it is suitable for orbiting detectors. (Recall that the impact parameter is given by $b = R_{\oplus} + h$, where h stands for the height above the surface of the Earth.) In the example shown, $M_s = 30$TeV was chosen. Conservatively, we assumed a ν-nucleon cross section 1/2 of a hadronic one.

One could "tweak" the various parameters in order to bring the p-induced and "anomalous" profiles; here we chose not to do so. However, the qualitative properties are clear.

Most importantly, the shapes of the shower profiles are quite similar to each other. (This is good, otherwise we would already know that our scheme cannot explain the trans-GZK events.) The number of electrons at shower maximum appears to be smaller than in a proton induced shower. By adjusting some parameters, that difference can be made smaller. In any case, due to fluctuations, it is hard to tell on an event-by event basis what the number of electrons at X_{max} should be.

In Figure 2 we display the rms deviation of X_{max} for both proton induced and "anomalous" showers. The result of the simulation clearly displays the feature we just discussed in qualitative terms: "anomalous" showers have larger fluctuations in the electron number, hence, given sufficient statistics, a distinction can be made between proton induced showers (presumably, coming from nearby) and neutrino induced ones.

5 Discussion.

At present, the situation is delightfully confusing, to some measure due to the unhealthy ratio of theoretical papers to trans-GZK events observed. The situation will change drastically in the next few years. HiRes and AGASA will continue observing. The Pierre Auger observatory and the planned orbiting detectors will be functioning. Hence, the event rate of trans-GZK showers is expected to be in the thousands per year. From the theoretical point of view, all scenarios submitted

- nucleus interaction is very close to 2.

[5]Adaptive Longitudinal Profile Simulation

to this meeting (and others not submitted) have some advantages and disadvantages and various degrees of falsifiability (in Popper's sense). Perhaps the scheme discussed last represents the most radical departure from established Standard Model physics. At the same time, it has the highest degree of falsifiability. The obvious disadvantage of that scheme is that, at present, calculations are very difficult: as shown in an elegantly simple paper by Cornet *et al* [36], weakly coupled string theories in the tree approximation are unlikely to explain trans-GZK phenomena. Most probably, we'll have to learn how to handle strongly coupled string theories — or whatever will supercede them.

Let us end with an optimistic conclusion. We may have seen hints at physics beyond the Standard Model or at least, some interesting new astrophysics. The jury is still out on what the correct explanation is. In the meantime, we have a lot of work to do.

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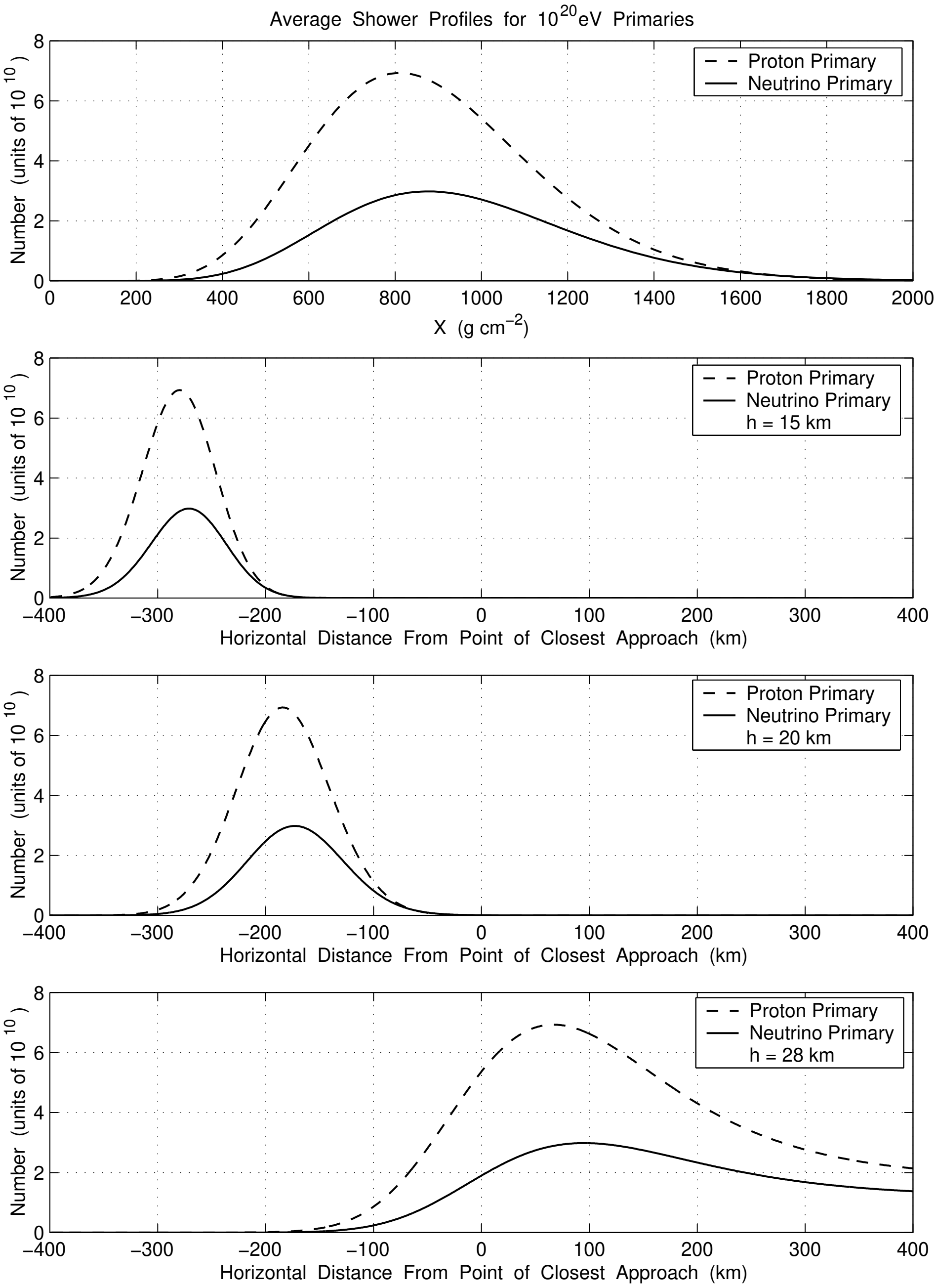

Figure 1: Comparison of average shower profiles for proton and neutrino induced showers as a function of column density and as a function of height above the Earth for a neutrino interaction cross section equal to half the proton value.

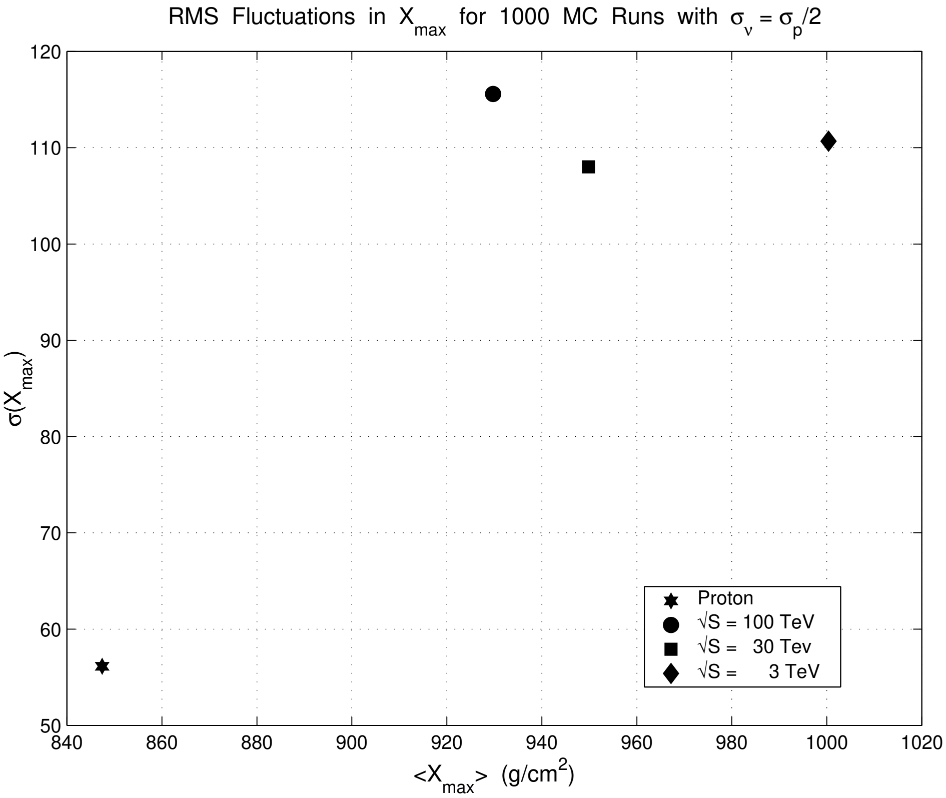

Figure 2: Standard deviations of the X_{max} distributions shown in Figure2 for proton and neutrino induced showers at various values of $\sqrt{S}$ and for a primary energy $E_0 = 10^{20}$ eV.