

Ultra-high energy cosmic rays from super-heavy X particle decay

Cyrille Barbot

Physik Dept., TU München, James Franck Str., D-85748 Garching, Germany

Abstract

In this talk, I present the last and more precise results obtained in the computation of the final spectra of stable particles issued from the decay of super-heavy X particles ($M_X \sim 10^{21}$ to 10^{25} eV). Such very energetic decay products, carrying a fraction of the mass of the X particle, are believed to be a plausible explanation for the observed ultra-high energy cosmic rays (UHECR). Combining these results with X-particle models and with a code describing the propagation effects for UHECRs through the interstellar medium, it becomes possible to make some predictions on the fluxes expected on Earth, hopefully detectable in the next generation of experiments.

In the second part of the 20th century, the spectrum of cosmic rays (CRs) has been measured over more than 12 decades of energy. Even if our understanding of it has grown a lot in the last few decades, many enigma are remaining. One of them concerns the extremity of this spectrum, at the highest energies, where theorists were expecting a strong cut-off to occur at energies of the order of $5 \cdot 10^{19}$ eV : indeed, at these energies, CRs should be of extragalactic origin, and probably coming from distances further than the local cluster of galaxies, because we know no astrophysical object able to accelerate particles enough to give them this energy in our vicinity. But the point is that particles carrying energies above 10^{20} eV traveling over cosmological distances should loose their energy through propagation effects ; for example, a proton will interact with the cosmological microwave background (CMB) and photoproduce pions, with an interaction length of a few tens of Mpc, loosing around 20 % of its energy at each interaction. Similar processes occur with nuclei, photons or electrons. Thus particles with initial energy $\sim 10^{20}$ eV should reach the Earth with a maximal energy $\sim 5 \cdot 10^{19}$ eV, the so-called GZK cut-off [1, 2].* The fact is that events have been registered above this cut-off in very different experiments over the last few decades [3, 4, 5, 6]. Such an observation is almost impossible to reconcile with any model of acceleration of charged particles in any astrophysical object. Moreover, there is another strong indication against these models : UHECRs are expected to travel rather straight away in the universe, without being deviated by the (inter)galactic magnetic

*A notable exception are, of course, the neutrinos, which can travel over cosmological distances without loosing their energy. But the events observed on Earth cannot be attributed to primary neutrinos.

fields. Thus they should point to these sources within a few degrees. Yet, excepted the existence of a few doublets and triplets in the experimental data, the observations are compatible with an almost perfect isotropy [7][†].

These remarks lead to the development of another class of models for explaining the existence of UHECRs, namely the “top-down” theories, which are considering that the observed events could be generated through the decay of some mysterious super-heavy “X” particles. The existence of such X particles is predicted in number of GUT theories or in relation with topological defects collapsing or annihilating, and they can be created rather naturally at the end of the inflation [10, 11]. Among other more “model dependant” properties, top-down models require that these particles should have a mass bigger than the highest energies observed in UHECR events, $M_X > 10^{21}$ eV, and a lifetime of the order of (or greater than) the age of the universe. They could be trapped homogeneously in the galaxies[‡], explaining the isotropy of the data, and would constitute semi-local sources for UHECRs, avoiding the GZK problem. Moreover, if they are abundant enough and trapped in the galaxies, they could be a very good candidate for the dark matter problem [12].

Excellent reviews on the UHECRs can be found in the literature [13, 14, 15]. In this talk I will focus on the top-down theories, and give general results for the decay of ultra-heavy particles (first presented in [16]), independently of any particular model.

We first briefly describe the physical steps involved in the decay cascade of an ultra-heavy X particle in the framework of the MSSM, as they are illustrated on fig ?? . Our basic assumption is that the X particle decays in N very virtual particles of the MSSM*, each of them initiating a decay cascade, following the known physics at lower energy. At high virtuality, in the region of asymptotic freedom, each of the primaries will initiate a perturbative shower, splitting into two allowed particles of smaller virtuality, according to the Feynman laws [†]. These products will split at their turn too, and the process will continue until the virtuality has decreased enough, at a scale where both SUSY and $SU(2) \otimes U(1)$ will break (for simplicity we are considering a unique SUSY mass scale $M_{SUSY} \sim 1$ TeV for all sparticles). M_{SUSY} is symbolized by the first vertical dash-line in fig 1. All the on-shell massive sparticles produced at this stage will then decay into Standard Model (SM) particles and the only (eventually) stable sparticle, the so-called Lightest Supersymmetric Particle (LSP). The heavy SM particles, like the top quarks

[†]Nevertheless, it should be noted that there are still attempts to explain the UHECRs with these classical “bottom-up” theories, see for example [8, 9].

[‡]or possibly in some topological defects protecting them against decay, with distributions very different from matter distributions in the galaxies.

*The existence of an energy scale as high as M_X strongly suggests the existence of superparticles with masses not much above 1 TeV, in order to guarantee the perturbative stability of the hierarchy between M_X and the weak scale. We therefore usually allow superparticles as well as ordinary particles to be produced in X decays, as described by the minimal supersymmetric extension of the Standard Model (MSSM).

[†]In contrast to previous works [17, 18, 19, 20], we considered in our treatment all gauge interactions as well as third generation Yukawa interactions, rather than only SUSY-QCD; note that at energies above 10^{20} eV all gauge interactions are of comparable strength. The inclusion of electroweak gauge interactions in the shower gives rise to a significant flux of very energetic photons and leptons, which had not been identified in earlier studies.

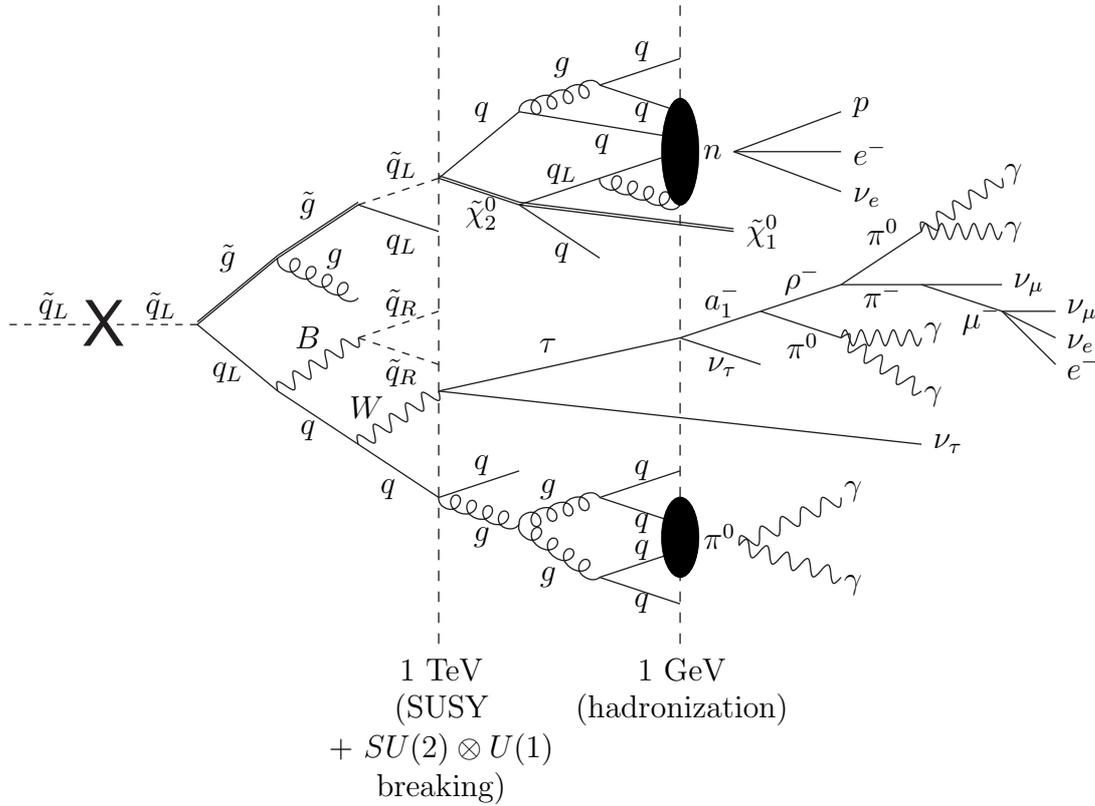


Figure 1: Schematic MSSM cascade for an initial squark with a virtuality $Q = M_X$. The full circles indicate decays of massive particles, in distinction to fragmentation vertices. See the text for further details.

and the massive bosons, will decay too, but the lighter quarks and gluons will continue a perturbative partonic shower until they have reached either their on-shell mass scale or the typical scale of hadronization (say 1 GeV), the second vertical dash-line of fig 1. At this stage, the color effects become too strong and the partons cannot propagate freely anymore, being forced to combine into colorless hadronic states. Finally, the unstable hadrons will also decay, and only the stable particles will remain and propagate in the intergalactic space, namely the protons, photons, electrons, the three species of neutrinos and the LSP (and their antiparticles).

The perturbative part of the shower is treated through the numerical resolution of DGLAP evolution equations [21] extended to the complete spectrum of the MSSM. These equations describe the evolution of the so-called “fragmentation functions” (FFs), which are describing the fragmentation of any fundamental particle into any other; the DGLAP evolution equations describe more specifically the impact of all 3-legs MSSM Feynman diagrams on these FFs, and their evolution with energy through the running of the associated coupling constants. We worked out all the FFs of the MSSM by solving these equations for all the unbroken fields between M_{SUSY} and M_X . At the breaking scale M_{SUSY} we applied the canonical unitary transformation to the FFs of the unbroken fields in order to obtain those of the broken ones, and computed the decay cascade of the supersymmetric

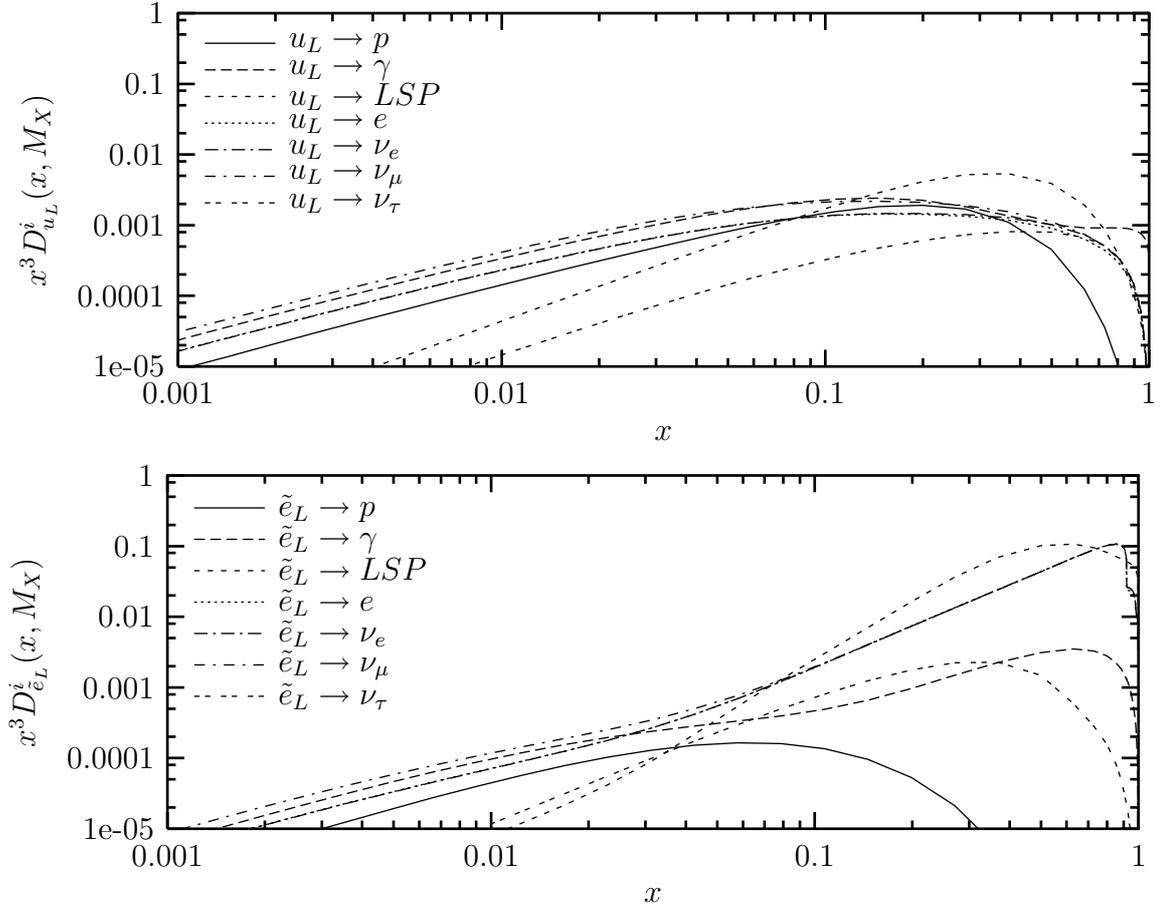


Figure 2: $x^3 \times$ Fragmentation functions of a first generation SU(2) doublet quark (top) and a slepton (bottom) into stable particles.

part of the spectrum. We used here the results of the public code Isasusy [22] to describe the allowed decays and their branching ratios, for a given set of SUSY parameters. If R-parity is conserved, we obtain the final spectrum of the stable LSP at this step, and the rest of the available energy is distributed between the SM particles. After a longer perturbative cascade down to $Q \sim \max(m_{quark}, 1\text{GeV})$, as stated before, the quarks and gluons will hadronize. We used the results of [23] as input functions for describing the hadronization and convoluted them with our previous results for the FFs of quarks and gluons (according to the factorization theorem of QCD, see for example [24]). During the complete cascade, we paid a special attention to the conservation of energy (what was not doable in previous studies, because of the incomplete treatment of the cascade). We are able to follow the energy conservation on the complete evolution up to a few per thousand.

As a result of the code we have written, we can obtain the spectrum of any stable particle (protons, photons, electrons, neutrinos, LSPs)[‡] at the end of the cascade, for *any*

[‡]We summed over particles and antiparticles.

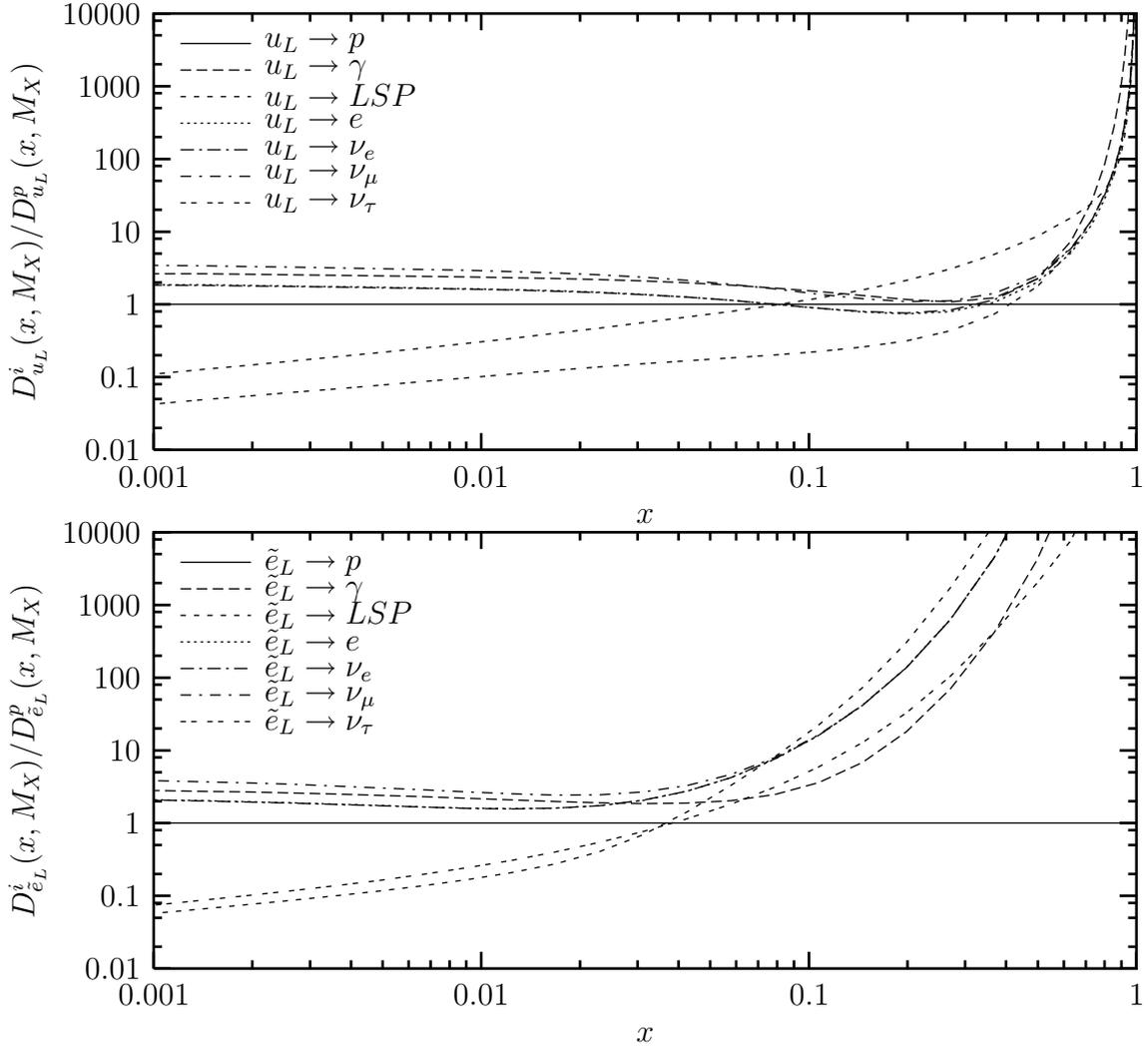


Figure 3: Ratios of FFs D_I^h/D_I^p for different stable particles h , for an initial first or second generation $SU(2)$ doublet quark, $I = q_L$, (top) or slepton, $I = \tilde{e}_L$, (bottom).

given N-body decay mode of the X particle into particles of the MSSM[§]. We choose to show here the results obtained for two initial $SU(2)$ doublets of the first generation, a quark and a slepton. Fig 2 shows the FFs themselves and fig 3 the ratios of the different FFs on the proton flux. Among the new general features appearing on these spectra, I would like to describe here a few points of particular interest :

1. The spectra at small and large x are quite different ; especially, as can be seen on fig 3, the small x physics is to a strong extent independant on the nature of the primaries, and the ratios between the different stable particles always remain the same. It allows us to order the fluxes from the strongest to the lowest one in the small x region : ν_μ , γ , ν_e , electrons, and protons, within one order of magnitude; the

[§]To describe any N body decay from the FFs of the decay products of X, we just need one more convolution between these FFs and the phase space of the decay.

two smallest fluxes, LSP and finally ν_τ , can be one order of magnitude lower than the proton flux at small x . We see that at large x , the fluxes are much more model dependent and change with the nature of the X decay products, but that LSP and γ are generally the strongest ones.

2. Due to the strength of the electroweak couplings at very high energy, the photon and neutrino spectra are even stronger than what was expected before ; these primaries have to be added to the flux of secondaries expected from propagation effects (especially through decay of pions after pion photo-production over the CMB). It is a puzzling result, because there are already strong indications that no photon event has been observed in the extremity of the CR spectrum (see for example [25]).

In this talk, I have shown the type of results that can be obtained with the code “SHdecay”, which allows to compute the final spectra of stable particles for any N-body decay mode of an initial super-heavy X particle, in the framework of the MSSM. This code will be soon made available. Combined with a model describing the nature, the cosmic distribution, and the decaying properties of an X particle, on one hand, and with a propagation code describing the losses of energy of the stable particles traveling through the interstellar medium, on the other hand, it allows to study many particular scenarios and to make quantitative predictions for the fluxes to be observed on Earth for each of these scenarios. We already developed a partial approach of these issues, in collaboration with F. Halzen and D. Hooper, for computing the expected fluxes of neutrinos [26] and neutralinos [27] on Earth for different models, in the next generation of experiments.

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