Cosmic-ray knee and flux of secondaries from interactions of cosmic rays with dark matter

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Abstract

We discuss possible implications of a large interaction cross section between cosmic rays and dark matter particles due to new physics at the TeV scale. In particular, in models with extra dimensions and a low fundamental scale of gravity the cross section grows very fast at transplanckian energies. We argue that the knee observed in the cosmic ray flux could be caused by such interactions. We show that this hypothesis implies a well defined flux of secondary gamma rays that seems consistent with MILAGRO observations.
1 New physics at the TeV scale

We know from collider experiments that there are three basic interactions between elementary particles. These interactions are understood in terms of a $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry, and have been confirmed by all data during the past decades: the standard model is basically correct up to energies around 200 GeV. On the other hand, we also observe gravitational interactions. Their strength is set by Newton’s constant, which in natural units defines the Planck mass, $M_P = G_N^{-1/2}$. Gravity is much weaker than gauge interactions and not detectable at colliders. It has been tested only at macroscopic distances, in processes involving the exchange of quanta of up to $10^{-13}$ GeV.

What do we expect at higher energies? If we extrapolate what we know in a straightforward way, we find that the three gauge couplings have log corrections that point towards a grand unification scale at $M_X \approx 10^{16}$ GeV. Gravity is different, it grows quadratically with the energy and becomes of order one at the Planck scale, $M_P \approx 10^{19}$ GeV. Below $M_P$ one needs a consistent framework for the four interactions, and string theory is the only available candidate. The LHC is going to explore energies of up to 1 TeV. It could find, for example, supersymmetry, a discovery for the next decades that would provide consistency to the whole picture. But such discovery would leave us still very far from the fundamental scale. String theory and quantum gravity are in this framework non-reachable, almost non-physical.

However, this is not the only possibility. In a different framework that has been discussed a lot recently the fundamental scale of gravity ($M_D$) is pushed down to the TeV. This can be done, for example, with flat extra dimensions that accelerate the running of $G_N$, or with a warped metric, the popular Randall-Sumdrum models[1]. In any case, within this framework the LHC could see exciting physics, maybe even a hint of the string scale itself. The transplanckian regime ($s \gg M_D^2$) would probably be not accessible there, but it would be clearly at the reach of very energetic cosmic rays. Collisions in this regime are really different from what we have seen so far in colliders. In particular, the spin 2 of the graviton implies that gravity becomes strong and dominates over gauge interactions at distances that increase with $\sqrt{s}$.

The range of energies that cosmic rays provide is very wide, exceeding the 14 TeV to be reached at the LHC. In the collision of a cosmic proton with a dark matter particle $\chi$ in our galactic halo we have

$$\sqrt{s} = \sqrt{2m_\chi E} \approx 10^7 \text{ GeV}.$$  \hspace{1cm} (1)

One would obtain even higher energies, up to $10^{11}$ GeV, in the head on collision of two cosmic rays[3]: these are the most energetic elementary processes that we know are occurring in
nature, and would be clearly transplanckian within the TeV gravity picture. Here we will focus on the first type of processes.

2 Transplanckian collisions

Can one calculate a cross section at $\sqrt{s} \gg M_D$ without knowing the details about the fundamental theory? The answer is yes as far as the fundamental theory does not change the long distance properties of gravity at these transplanckian energies. It is the case, for example, in string theory, where the Regge behaviour implies that at $s \gg M_s^2$ only the low $t$ (forward) contributions of the massless string modes survive. And due to the spin 2 of the graviton, in this regime gauge contributions are negligible, only gravity matters.

In a collision at transplanckian energies we expect two basic processes[2]. At small impact parameters we expect capture, the collapse of the two particles into a mini black hole of mass $M \approx \sqrt{s}$ and radius

$$R \approx \left(\frac{M}{M_D}\right)^{\frac{1}{n+1}} \frac{1}{M_D}.$$  \hspace{1cm} (2)

At larger impact parameters we expect processes where the incident particle transfers a small fraction $y$ of its energy and keeps going. These elastic processes can be calculated in the eikonal approximation, that provides a resummation of ladder and cross-ladder contributions.

An important observation is that these are long-distance processes, the typical distance is larger than $1/M_D$ and grows with the energy. To see quantum gravity, string theory or even a Z boson the incident particle needs to go to short distances (of order $1/M_{Z,S,D}$) inside the black hole horizon, so all these details become irrelevant. The higher the energy in the collision, the more reliable is the estimate based on classical gravity (strongly coupled but tree level).

Another important point is that, although the typical distance is longer than $1/M_D$, it is still shorter than the proton radius and the exchanged gravitons see the partons inside the proton. A parton carrying a fraction $x$ of the proton momentum hits $\chi$ and, as a result, the proton breaks into a scattering parton or a black hole plus the proton remnant. From the analysis of these jets using HERWIG we obtain

$(i)$ The scattering parton and the proton remnant define jets giving a very similar spectrum of stable particles. This spectrum is only mildly sensitive to the fact that the parton may be a quark or a gluon.

$(ii)$ In the center of mass frame of the two jets the final spectrum of stable particles
is dominated by energies around 1 GeV, almost independently of the energy of the parton starting the shower.

(iii) The stable species (particle plus antiparticles) are produced with a frequency $f_i$ that is mostly independent of the energy or the nature of the two jets. We obtain an approximate 55% of neutrinos, a 20% of photons, a 20% of electrons, and a 5% of protons.

(iv) The spectrum of stable particles resulting from a mini BH in its rest frame is very similar to the one obtained from the quark and gluon jets.

A parametrization of the final spectra of stable particles from quark and gluon jets and from black hole evaporation can be found in [4].

3 Secondaries from collisions of cosmic rays with dark matter

Let us now discuss if there is any observable effects from these processes. When an ultrahigh energy cosmic ray reaches the Earth coming from outside the galaxy, it has crossed a certain dark matter column density $x$. The probability of interaction is just

$$p(x) \approx \frac{\sigma x}{m_\chi}.$$  \hspace{1cm} (3)

Since the depth $x$ from the border of the galaxy can vary in a factor of ten, more cosmic rays will interact from deeper directions, which could imply an anisotropy in the flux of extragalactic cosmic ray that has not been observed. We find, however, that for cross sections up to the mbarn and for the expected dark matter densities the probability of interaction is too small to produce an observable effect.

The effect on lower energy cosmic rays, however, could be more relevant. The crucial difference is that cosmic rays of energy below $10^8$ GeV are trapped inside the galaxy by random magnetic fields of order $\mu$G. Their trajectory from the source to the Earth is not a straight line, it is more similar to a random walk. The depth that they face grows with time, and a fraction of them could interact with a dark matter particle before reaching the Earth. Now, in these models the cross section grows very fast at center of mass energies above $M_D$, so there could be a critical energy giving a cross section large enough for cosmic rays to interact. At larger energies the interaction would break them and produce an effect that could explain the knee (the change in the spectral index from $-2.7$ to $-3$) observed in the cosmic ray spectrum.
Figure 1: Secondary fluxes from $p-\chi$ gravitational collisions for $n = 6$, $M_D = 5$ TeV and $m_\chi = 200$ GeV. The point at 15 TeV indicates the gamma-ray flux measured by MILAGRO.

If gravitational interactions were responsible for this change, then there would be a flux of secondary particles that could be readily estimated. Let us assume that, on absence of gravitational interactions, the flux $\propto E^{-2.7}$ would have extended up to $10^8$ GeV. This means that the flux

$$\Phi_N \approx \int_{10^6 GeV}^{10^8 GeV} dE \ 1.8 \ (E^{-2.7} - 10^{1.8} E^{-3}) \ \text{nucleons cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

had been processed by these interactions into secondary particles of less energy. In Fig. 1 we plot the fluxes of secondary protons and gamma rays together with the flux of dark matter particles boosted by eikonal scatterings. The flux of $e = e^+ + e^-$ is similar to the photon flux, although the propagation effects (synchrotron emission, etc.) that may distort the spectrum have not been included. Recent data from PAMELA\[5\] signals an excess in the positron flux above 10 GeV, although the contribution that we find seems well below these data. We add in the plot the diffuse gamma-ray flux measured by MILAGRO\[6\] at energies around 15 TeV, which seems to indicate an excess versus the expected values from some regions in the galactic plane. The contribution that we find could explain anomalies in the gamma-ray flux above 10 GeV or in the positron and antiproton fluxes above 1 TeV. The diffuse photon flux that we obtain is always around MILAGRO data and proportional to $E^{-2}$ at energies between 100 and $10^6$ GeV for any values of the dark matter mass and the number of extra
dimensions.

4 Summary

Strong gravity at the TeV scale would affect the propagation of the most energetic cosmic rays. In particular, cosmic protons could interact with the WIMP \( \chi \) that constitutes the dark matter of our universe. These interactions could break the incident proton and produce a deflection in the flux (the cosmic ray knee), together with a flux of secondary antiparticles and gamma rays. The analysis of the cross sections and dark matter densities required for this hypothesis to work will be presented elsewhere[7]. In any case, it is puzzling that the change in the spectral index in the flux appears at center of mass energies \( \sqrt{2m_\chi E_{\text{knee}}} \approx 10 \) TeV, where the new physics is expected.

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References

[1] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429 (1998) 263; L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370.

[2] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B 630 (2002) 293; J. I. Illana, M. Masip and D. Meloni, Phys. Rev. D 72 (2005) 024003;

[3] P. Draggiotis, M. Masip and I. Mastromatteo, JCAP 0807 (2008) 014.

[4] M. Masip and I. Mastromatteo, JCAP 0812 (2008) 003.

[5] O. Adriani et al., “Observation of an anomalous positron abundance in the cosmic radiation,” arXiv:0810.4995 [astro-ph].

[6] A. A. Abdo et al., Astrophys. J. 688 (2008) 1078.

[7] R. Barcelo, M. Masip and I. Mastromatteo, “Cosmic ray knee and new physics at the TeV scale,” arXiv:0903.5247 [hep-ph].