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Effects of massive photons from the dark sector on the muon content in extensive air showers

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ABSTRACT

Inspired by recent astrophysical observations of leptonic excesses measured by satellite experiments, we consider the impact of some general models of the dark sector on the muon production in extensive air showers. We present a compact approximative expression for the bremsstrahlung of a massive photon from an electron and use it within Monte Carlo simulations to estimate the amount of weakly interacting photon-like massive particles that could be produced in an extensive air shower. We find that the resulting muon production is by many orders of magnitude below the average muon count in a shower and thus unobservable.

1. Motivation

The relatively recent observations of excess lepton fluxes from space, as measured by PAMELA [1] and ATIC [2] have motivated large interest in models of dark matter annihilation that could explain these data, while staying in agreement with other existing astrophysical evidence. For the ultra-high-energy cosmic ray (UHECR) experiments, neither these low-energy fluxes, nor their hypothetical parent particles are directly observable. But the common feature of such models is that they need to add new physics to increase the production of leptons with respect to hadrons in the current Universe. While this production is mainly targeted at electrons and positrons, many of such processes also lead to extra production of muons.

Some evidence of disagreement in muon production in extensive air showers initiated by high-energy cosmic rays with the predictions of Monte Carlo simulations has been given already by the DELPHI [3], ALEPH [4] and L3 [5] experiments at LEP and it has been repeatedly reported by the Pierre Auger Observatory [6]. In both cases, the data indicate that the current interaction models may significantly underestimate the number of muons produced.

It is then only natural to ask, whether some of these extra muons could be accounted for if some of the above-mentioned new physics is incorporated into the Monte Carlo simulations. Instead of considering every single model of the dark sector that has ever been proposed (for a very recent review of models with specific references, see Ch. 4 of [7]), we turn to the work [8], which is rather general. There it is argued that, considering not only the above-mentioned excess, but also general cosmological observations and direct dark matter searches, it is not unreasonable to expect the TeV-scale dark matter to be accompanied by a relatively light particle with mass around 250 MeV and some weak coupling to ordinary matter. This idea is further corroborated in [9] for the special case of such a particle being essentially a massive photon that couples to ordinary matter via kinetic mixing suppressed by a small factor of the order of $\epsilon \approx 10^{-2}$–10^{-3}. We call this particle a “dark photon” for brevity as the factor ϵ effectively appears in any vertex that includes both a Standard Model particle and a dark photon, thus making it difficult to detect by electromagnetic interactions. This scheme is not only backed by a compelling theoretical motivation, but also relatively simple to implement as a first look into the topic, yet reasonably general; thus we focus on it in the rest of the Letter.

In the following article [10] the authors show that this model leads to the prediction of specific collider signatures in the form of “lepton jets” stemming from the prediction of the TeV-scale particles in hadronic collisions. These events are too rare to have any effect on extensive air showers, as there are only hundreds of sufficiently high-energy hadronic interactions in a single air shower, which itself is a rather rare event — the total luminosity in UHECRs

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is simply too small for even Standard Model electroweak effects to have any impact on observable data, even more so for exotics. Nevertheless, this model is still interesting because the dark photon, being coupled to ordinary electric charge, albeit weakly, can be produced via bremsstrahlung from electrons. The amount of electromagnetic interactions of photons and leptons in each shower is by many orders of magnitude larger than that of hadronic interactions and so it is not immediately obvious what size of cross-section for the dark photon bremsstrahlung (investigated in the next section) is needed to produce observable effects.

The attractive feature of a massive photon is that it can decay into a pair of a charged particle and its antiparticle. Additionally, the dark photon is "dark", that is, it has limited interactions with ordinary matter. Thus, dark photons in the relevant range of masses will almost always decay instead of producing a pair in the electromagnetic field of an atom in the air. In the case of pair production, almost all produced pairs are electron–positron as the cross-section falls with the fourth power of the lepton mass, whereas the decay of the dark photon proceeds democratically into every kinematically possible final state, save for threshold effects. Thus, for mass of the dark photon $m_\gamma \in (212, 280)$ MeV, for every dark photon produced, there is on average one muon added to the shower. For higher masses, pion final states are possible, but muon production is still sizeable.

2. Dark photon bremsstrahlung

The problem of bremsstrahlung of a massless photon from a lepton interacting with an atomic target in quantum electrodynamics is a well-known one and, to the leading order, it is exhaustively described in [11]. Interestingly, we did not find an expression for the bremsstrahlung of a massive photon in any literature, so we had to derive one ourself. Elementary as it may seem, the calculation is actually quite tedious. Thus, even though it is technically possible to just add a photon mass into the equations in [11] and proceed, this would be a major task and prone to errors. Instead we note the work [12] where it is shown that similar results can be derived using the computationally much simpler Weizsäcker–Williams approximation, where the $2 \to 3$ problem is reduced to a $2 \to 2$ Compton scattering times a factor determined by kinematics and the scattering target. Schematically

$$\frac{d\sigma(2\to 3)}{d(P_1\cdot k)\,d(P_i\cdot k)} = \left.\frac{d\sigma(2\to 2)}{d(P_1\cdot k)}\right|_{t=t_{\min}} \frac{\alpha}{\pi}\frac{\chi}{P_2\cdot P_i}, \tag{1}$$

where P_i is the initial four-momentum of the target, P_1 and P_2 are the initial and final four-momenta of the lepton, k is the four-momentum of the produced (massive or not) photon, $\alpha = e^2/4\pi$ is the fine structure constant and χ is a factor that involves the form-factors of the target, which is independent of the $2 \to 2$ process. The subscript $t = t_{\min}$ denotes that the $2 \to 2$ process is evaluated using a particular kinematic set up.

In [13], this approximation is used for the bremsstrahlung of a massive axion. While the resulting formula is not directly applicable to the production of a massive photon, most of the work is actually done. The difference is only in the matrix element for the $2 \to 2$ process, which is a well-known function. The difficult part, which is the kinematics, is exactly the same for any massive particle, while being vastly different from the case of a massless photon. From Eq. (7) of [13] we observe that the kinematics for the $2 \to 2$ process can be worked out so that

$$\left.\frac{d\sigma(2\to 2)}{d(P_1\cdot k)}\right|_{t=t_{\min}} = \frac{1}{16\pi(P_2\cdot k)^2}|\overline{\mathcal{M}}|^2, \tag{2}$$

where $|\overline{\mathcal{M}}|$ is the absolute value of the invariant matrix element for the $2 \to 2$ process averaged over initial state polarisations and summed over final state polarisations. For massive photons,

$$|\overline{\mathcal{M}}|^2 = -16\pi^2\alpha^2 \times \frac{2(m_\gamma^4 + 2m_\gamma^2(P_2\cdot k - P_1\cdot k) + 2((P_1\cdot k)^2 + (P_2\cdot k)^2))}{(m_\gamma^2 - 2P_1\cdot k)(m_\gamma^2 + 2P_2\cdot k)}, \tag{3}$$

where we can safely neglect the electron mass if we are interested in dark photons capable of decaying into two muons. This approximation was numerically checked against the full result and the agreement is better than a fraction of a per cent for $m_\gamma = 250$ MeV in almost the whole range of x, while the length of the formula is significantly reduced. Using Eq. (1) and kinematics, we deduce that the bremsstrahlung cross-section is

$$\frac{d\sigma}{dx\,d\Omega} = \frac{\alpha^3 E_1 x(x^2 - 2x + 2)\chi}{\pi(m_e^2 x(1 + (\frac{E_1}{m_e})^2\theta^2) + m_\gamma^2(\frac{1}{x} - 1))^2}, \tag{4}$$

where x is the fraction of E_1 carried by the produced dark photon and θ is its production angle with respect to the incoming electron in the laboratory frame. Here we must keep the electron mass non-zero not only because of the behaviour for $x \to 1$ but also because the γ-factor of the electron can be huge.

To proceed with the angular integration we must specify the χ-factor. Again, we take it from [13]. In the "complete screening" limit it can be written as

$$\chi = 2\left[Z\ln\left(\frac{1194}{Z^{2/3}}\right) + Z^2\ln\left(\frac{184}{Z^{1/3}}\right) + (Z + Z^2)\left(\ln\left(1 + \left(\frac{E_1}{m_e}\right)^2\theta^2\right) - 1\right)\right], \tag{5}$$

where Z is the atomic number of the target. "Complete screening" refers to an approximation valid when

$$184\,\mathrm{e}^{-1/2}\frac{Z^{-1/3}}{m_e}t_{\min} \ll 1, \qquad 1194\,\mathrm{e}^{-1/2}\frac{Z^{-2/3}}{m_e}t_{\min} \ll 1 \tag{6}$$

– an explicit numerical calculation again shows, that it is well justified. To make the production of a 250 MeV dark photon even possible, the γ-factor squared of the electron has to be in the order of at least 10^5 and thus the scattering is strongly suppressed for large angles. The suppression is in fact strong enough that we can extend the integral in θ to infinity, yielding a much more compact analytical result, namely

$$\frac{d\sigma}{dx} = \frac{4\alpha^3 x((x-2)x+2)}{E_1} \times \left[\frac{Z + Z^2 - Z\ln(\frac{1194}{Z^{2/3}}) - Z^2\ln(\frac{184}{Z^{1/3}})}{m_\gamma^2(x-1) - m_e^2 x^2} + \frac{(Z+Z^2)\log(\frac{m_e^2 x^2}{m_\gamma^2(1-x) + m_e^2 x^2})}{m_\gamma^2(x-1)}\right]. \tag{7}$$

Here we keep only the electron masses that cannot be neglected by any means. Our ultimate goal is to compare this expression with the well-known formula for massless photon bremsstrahlung, that is