

New gamma ray signal from gravitationally boosted neutralinos at the Galactic CenterM. Cannoni,^{1,*} M. E. Gómez,^{1,†} M. A. Pérez-García,^{2,‡} and J. D. Vergados^{3,§}¹*Departamento de Física Aplicada, Facultad de Ciencias Experimentales, Universidad de Huelva, 21071 Huelva, Spain*²*Departamento de Física Fundamental and IUFFyM, Universidad de Salamanca, Plaza de la Merced s/n 37008, Salamanca, Spain*³*Theoretical Physics Division, University of Ioannina, Ioannina, Gr 451 10, Greece*

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We discuss the possibility that colliding dark matter particles in the form of neutralinos may be gravitationally boosted near the supermassive black hole at the Galactic center so that they can have enough collision energy to annihilate into a stau pair. Since in some phenomenologically favored supersymmetric models the mass splitting between the neutralino and the lightest stau, one of the two scalar superpartners of the tau lepton, is a few GeV, this channel may be allowed. In addition, staus can decay only into a tau lepton and another neutralino. We calculate the gamma ray spectrum and flux generated by the tau pair discussing the observability of the obtained features.

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Dark matter (DM) accounts for more than 80% of the mass of the Universe, but its nature is still one of the open problems in physics. In a widely accepted theoretical scenario, DM is formed by a weakly interacting massive particle that has been in thermal equilibrium with standard model (SM) matter in the early Universe, leaving, after decoupling, the DM relic density as inferred by WMAP [1]. In this light, supersymmetric extensions of the SM provide a natural weakly interacting massive particle candidate. In the minimal supersymmetric standard model, R -parity conservation assures that if the lightest supersymmetric particle is the lightest of the four neutralino states—indicated as χ in the following—this particle is absolutely stable. In a phenomenologically favored scenario of the constrained minimal supersymmetric standard model (CMSSM), the stau coannihilation region ($\tilde{\tau}_{\text{CR}}$) [2], the lightest stau $\tilde{\tau}_1$, one of the scalar superpartners of the tau lepton, is close in mass to the neutralino. In the $\tilde{\tau}_{\text{CR}}$ parameter space, the cross section for nonrelativistic annihilation into fermions of the SM, $\chi\chi \rightarrow f\bar{f}$, is typically small and results in a too large relic density. However, including the so-called coannihilation processes [3], as, for example, $\chi\tilde{\tau}_1$, $\tilde{\tau}_1\tilde{\tau}_1$ collisions, when the mass splittings of the involved particles are small, one can efficiently enhance the thermally averaged cross section $\langle\sigma v\rangle$ and, consequently, diminish the relic density to the measured value.

The standard cosmological model predicts that nonrelativistic cold DM particles ($v/c \sim 10^{-3}$) cluster into halos [4] that contain baryonic matter. Since DM in the halo follows a certain mass distribution, the two-body annihilation processes can happen at a rate that is proportional to the DM mass density squared. Therefore, the highest

chances to detect an observable indirect signal of their existence are attained in a region with high DM density, in particular, in the Galactic center (GC). Among the various signatures from DM annihilation, gamma ray signals have received much attention. A continuum spectrum of secondary photons may arise from hadronization and decay of the annihilation products [5] and from radiation from final state charged particles [6]. Direct annihilation into photons is also possible but only at the loop level [7].

The gravitational potential in the GC is dominated by a supermassive black hole (BH) with mass $M_{\text{BH}} = 4 \times 10^6 M_{\odot}$ and Schwarzschild radius $R_{\text{S}} = 2GM_{\text{BH}}/c^2 = 4 \times 10^{-7}$ pc [8]. Recently, the idea that a BH can act as a particle accelerator has been proposed [9]. The highest center of mass frame (CMF) energies are obtained when the colliding particles approach the horizon on falling geodesics with opposite angular momentum per unit mass $L/m_{\chi} \leq L_c = 4GM_{\text{BH}}/c$, in the case of the Schwarzschild metric. The maximum possible value is $\sqrt{s} = 2\sqrt{5}m_{\chi}$ [9,10] for a nonrotating BH, while it can be arbitrarily large for the Kerr BH [9]. In principle, due to this general relativity effect, new annihilation channels into heavier states, kinematically forbidden for nonrelativistic particles, could be accessible. Additionally, a realistic calculation of an indirect DM signal in this scenario would also be determined by the particle escape function at distances close to the BH. For the horizon proximity, this has been calculated in Ref. [11] under the restrictive assumptions of annihilation into two massless particles with isotropic angular distribution.

In this work, we show that if DM is formed by neutralinos with the characteristics of the $\tilde{\tau}_{\text{CR}}$, a new dominant annihilation channel may be opened already for subrelativistic neutralinos [12] boosted in the inner regions of the GC.

Near the BH, the DM density is described by a power law $\rho(r) \propto r^{-\gamma}$, as we will discuss later. From the

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Newtonian approximation given by the Jeans equation, the root mean squared velocity is $v(r) \approx (GM_{\text{BH}}/r)^{1/2}$ [13–15], or in terms of the Schwarzschild radius, $v(r)/c \approx (R_S/2r)^{1/2}$. Since a Keplerian orbit with L_c would cross the horizon if the pericenter distance is less than $r_{\text{min}} = 4R_S$, hence we will consider safely $r > 4R_S$. In this way, for example, at $r = 10R_S$ we have $v/c \approx 1/\sqrt{20} \approx 0.22$. Requiring that the neutralino has the relic density inferred by WMAP, the relative mass splitting with the $\tilde{\tau}_1$, $\delta = (m_{\tilde{\tau}} - m_\chi)/m_\chi$, is typically less than 5%. In the CMF the energy threshold for stau pair production is $\sqrt{s} = 2E_\chi \geq 2m_{\tilde{\tau}}$ that implies $v/c \geq [1 - 1/(1 + \delta)^2]^{1/2}$. With $\delta = 2\%$, $v/c \geq 0.197$; there exists thus a range of radii where the kinetic energy is high enough to reach the threshold of the process $\chi\chi \rightarrow \tilde{\tau}^-\tilde{\tau}^+$. The maximum radius is given by $r_{\text{max}} = 1/2[1 - (m_\chi/m_{\tilde{\tau}})^2]R_S$.

If the mass splitting $\Delta m = m_{\tilde{\tau}} - m_\chi$ is larger than the tau mass $m_\tau = 1.777$ GeV, the staus can decay only into the two-body final state $\chi\tau$; see diagrams in Fig. 1. The neutralino is binolike; thus, the vertices's $\chi - \chi - Z$ and $\chi - \chi - (h, H)$ are suppressed, while the vertex $\chi - \tilde{\tau}_1 - \tau$ is not suppressed by mixing. In fact, it is proportional to $Z_{11}U_{12}$, the product of the relevant neutralino and stau mixing matrix elements that are both close to 1. The dominant diagrams in Fig. 1 are thus the ones with t, u channel exchange of the tau. At energies near the threshold, the produced staus are slow; thus, the propagator $1/(p_\chi^2 - p_{\tilde{\tau}}^2 - m_\tau^2) = 1/(m_\tau^2 + m_\chi^2 - 2E_\chi E_{\tilde{\tau}} + 2\mathbf{p}_\tau \cdot \mathbf{p}_\chi - m_\tau^2)$ is approximately $1/[(m_\tau - m_\chi)^2 - m_\tau^2]$. The cross section, proportional to the square of this quantity is, thus, enhanced for mass splittings approaching the tau mass.

We illustrate the above features in Fig. 2, where we show the relevant cross sections as a function of \sqrt{s} (left panels) for four points of the $\tilde{\tau}_{\text{CR}}$ that are allowed by present phenomenological constraints. The values of the universal scalar mass m_0 , gaugino mass $m_{1/2}$, trilinear scalar coupling A_0 , and the ratio of the two Higgs expectation values $\tan\beta$ that define the CMSSM parameter space are given in Table I. The numerical computation was done by using the

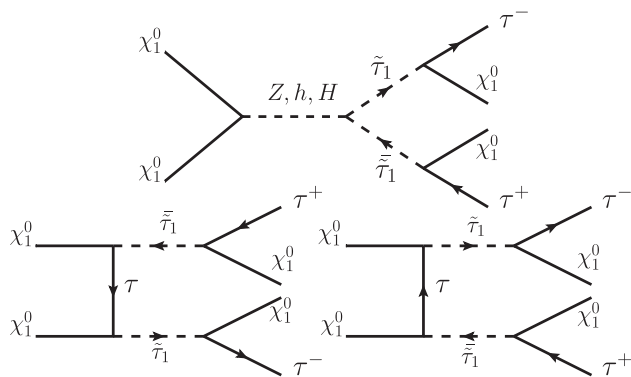


FIG. 1. Diagrams for stau pair production and decay in neutralino annihilation.

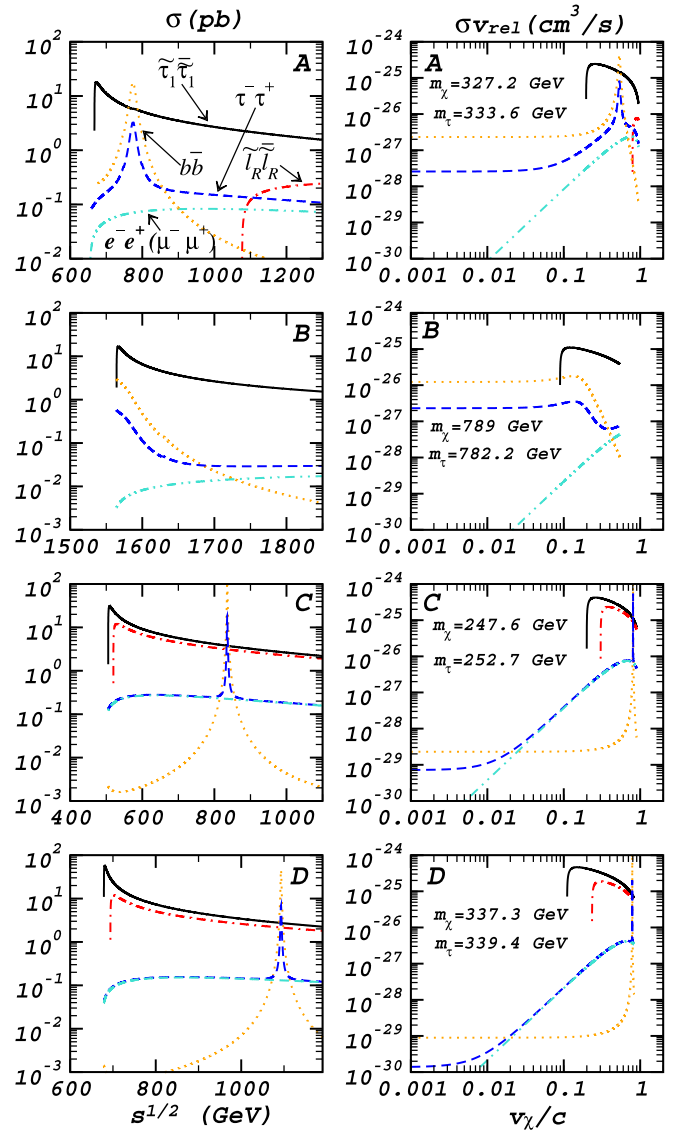


FIG. 2 (color online). Annihilation cross sections in picobarns as a function of the CMF energy (left panels) and annihilation cross section times the relative velocity in cm^3/s as a function of the colliding neutralino velocity (right panels). The CMSSM points are specified in Table I, and the annihilation channels are labeled in the upper left panel.

interfaced codes MICROMEGAS [16], CALCHEP [17], and SOFTSUSY [18]. Point A is similar to the best-fit point found in Ref. [19], that predicts a light Higgs around 119 GeV. Next we take three cases with $A_0 = 0$, as usual for setting upper limits with LHC searches. In point B the Higgs is slightly heavier. Points C and D have low $\tan\beta$, and the Higgs is around 115 GeV. In all cases, the cross section for stau pair production clearly dominates by 1 or 2 orders of magnitude the cross sections for annihilation into fermions except when \sqrt{s} corresponds to the heavy Higgs A, H masses where the s -channel propagators are resonant. In the right panels in Fig. 2, we show the annihilation cross

TABLE I. CMSSM points used in this work. The sign of μ is positive. The neutralino and stau masses are also reported.

	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	$m_{\tilde{\chi}}$ (GeV)	$m_{\tilde{\tau}_1}$ (GeV)
A	452	780	1110	41	327.2	333.6
B	858	1780	0	45	789.0	782.2
C	122	600	0	10	247.6	252.7
D	166	805	0	10	337.3	339.4

section times the particle relative velocity, as a function of the CMF velocity of colliding neutralinos; this is the quantity that enters in the calculation of indirect detection signals of the processes considered. Note that σv_{rel} for annihilation in staus, near the threshold, is at least an order of magnitude bigger than the freeze-out value $3 \times 10^{-26} \text{ cm}^3/\text{s}$ and that these values correspond to $v/c \sim 0.1\text{--}0.2$ that are just the ones that can be obtained with the gravitational boost discussed above. At low $\tan\beta$, cases C and D, the ‘‘right’’ selectron and smuon ($\tilde{\ell}_R$) tend to become degenerate in mass with $\tilde{\tau}_1$, and the cross section for annihilation into pairs of these scalars is much larger than in cases A and B. Although the masses of the particles in point B are much heavier than in the other cases, the mass splitting is around 3 GeV and σv is of the same magnitude. The same effect can be seen by comparing case D with C.

A possible signal of the opening of the new channel is given by the gamma rays produced by the tau pair. The extension of the source is set by r_{max} . This is too small to be resolved by present telescopes; thus, we treat it as a point source at the GC at a distance from us of $D = 8 \text{ kpc}$. To evaluate the flux we first note that, applying the small width approximation to the stau propagators, and given that $\text{BR}(\tilde{\tau}_1^\pm \rightarrow \tau^\pm \chi) = 1$, we have $\sigma(\chi\chi \rightarrow \tau^- \tau^+ \chi\chi) \simeq \sigma(\chi\chi \rightarrow \tilde{\tau}_1 \tilde{\tau}_1) \text{BR}^2(\tilde{\tau}_1 \rightarrow \tau\chi) \simeq \sigma(\chi\chi \rightarrow \tilde{\tau}_1 \tilde{\tau}_1) \equiv \sigma_{\tilde{\tau}\tilde{\tau}}$. We can thus evaluate the differential photon flux as

$$\frac{d\Phi}{dE_\gamma} = \frac{R_S^3}{D^2} \int_{r_{\text{min}}}^{r_{\text{max}}} dr r^2 \sigma_{\tilde{\tau}\tilde{\tau}}(r) v_{\text{rel}}(r) \frac{\rho^2(r)}{m_\chi^2} \frac{dN}{dE_\gamma}(r). \quad (1)$$

In the integral we treat the distances in units of the Schwarzschild radius; thus, r is dimensionless and a factor R_S^3 appears explicitly. We note some differences with the standard almost-static $\chi\chi \rightarrow \tau^+ \tau^-$ annihilation: (i) There is no factorization into a particle physics and astrophysics factor, because all the factors in the integrand depend on r through the velocity dependence. An integration over the CMF scattering angle is implied in $\sigma_{\tilde{\tau}\tilde{\tau}}(r)$ that is evaluated by taking the exact spin averaged squared matrix elements from CALCHEP; (ii) we do not divide by 2, because the final state necessarily contains two neutralinos; (iii) the taus are not monochromatic and the spectrum changes with the collision energy \sqrt{s} and ultimately with the distance, while in the static case the taus have an energy equal to the

neutralino mass and the radiated photon spectrum is limited by $E_\gamma^{\text{max}} = E_\tau = m_\chi$.

Before proceeding further, we will discuss this last point. The tau energy spectrum can be easily obtained by applying a Lorentz transformation with parameters $\beta = (1 - 4m_\tau^2/s)^{1/2}$ and $\gamma = \sqrt{s}/2m_\tau$ to the spectrum calculated in the rest frame of the stau. In this frame it has fixed energy and momentum: $E_\tau^* = (m_\tau^2 - m_\chi^2 + m_\tau^2)/2m_\tau$ and $p_\tau^* = (E_\tau^{*2} - m_\tau^2)^{1/2}$. The resulting energy distribution is flat and limited: $dN(\tilde{\tau}_1 \rightarrow \chi\tau)/dE_\tau = 1/\Delta E$, $\Delta E = E_\tau^{\text{max}} - E_\tau^{\text{min}}$, with $E_\tau^{\text{min}} = \gamma(E_\tau^* - \beta p_\tau^*) \leq E_\tau \leq E_\tau^{\text{max}} = \gamma(E_\tau^* + \beta p_\tau^*)$. The number of photons with energy E_γ produced by a tau with energy E_τ is given by $dN_\gamma/dx = 1/2f(x)$ with $x = E_\gamma/E_\tau$ and $f(x) = x^{-3/2} \exp[g(x)] + q \log[p(1-x)](x^2 - 2x + 2)/x$. This formula was obtained in Ref. [20], to which we refer the reader for details, by fitting the photon yield from taus obtained with Monte Carlo simulations of the nonrelativistic process $\chi\chi \rightarrow \tau^+ \tau^-$. In this case the taus have equal energy; hence, we use a factor 1/2 for the yield of one particle. The gamma spectrum at distance r is then obtained by integrating over the tau energy distribution:

$$\frac{dN}{dE_\gamma}(r) = \frac{1}{\Delta E(r)} \int_{E_\tau^{\text{min}}(r)}^{E_\tau^{\text{max}}(r)} \frac{dE_\tau}{E_\tau} f\left(\frac{E_\gamma}{E_\tau}\right) \theta(E_\tau - E_\gamma). \quad (2)$$

We have multiplied by 2 to obtain the yield of the pair. The Heaviside function takes into account that for fixed E_γ the integrand is zero if $E_\gamma > E_\tau$. For this reason the photon energy cutoff is E_τ^{min} for each \sqrt{s} . The absolute cutoff when integrating over \sqrt{s} will be at $\gamma(r_{\text{max}})E_\tau^*$. In fact, as $r \rightarrow r_{\text{max}}$, $\beta \rightarrow 0$ and $E_\tau^{\text{min}} \rightarrow \gamma(r_{\text{max}})E_\tau^*$. Note that $\gamma(r_{\text{max}}) \sim 1$ and $E_\tau^* \leq (m_\tau - m_\chi)$; thus, the cutoff is indicative of the mass splitting between the neutralino and the stau.

The last ingredient that we need to evaluate in Eq. (1) is the DM density profile. In Ref. [21], it was shown that the adiabatic growth of the BH at the center of the halo causes a steepening, called a spike, of the initial halo profile toward the GC. Successive studies [14,15,22–28] showed that considering physical effects such as scattering of DM particles off stars, capture by the BH, self-annihilation, and capture within stars during the evolution of the DM distribution results in a shallower profile: $\rho_{\text{sp}}(r) \propto r^{-3/2}$. For the supersymmetric models A–D, and generally for all the $\tilde{\tau}_{\text{CR}}$ parameter space, the spin-independent and spin-dependent elastic neutralino-nucleon cross sections are in the range $10^{-11}\text{--}10^{-9}$ and $10^{-8}\text{--}10^{-7}$ pb [29], respectively; thus, the energy lost by elastic collisions with baryonic matter is not likely to be important. At a certain distance from the GC, the density reaches a value such that self-annihilation itself acts to stop further rising. It has been shown [27,28] that this latter effect does not set the density to a constant value, usually called the annihilation plateau or core, but results in a mild spike (MS) with $\rho_{\text{ms}}(r) \propto r^{-1/2}$. In addition, the

adiabatic compression of the gravitational potential caused by the baryons already in the bulge of the Galaxy [30] should also be taken into account.

We hence model the profile considering that at the radius $r_{\text{sp}} \approx 0.2r_h$, with $r_h = 1.67$ pc the influence radius of the BH, DM density is given by a compressed Einasto profile, $\rho_{\text{sp}} = 5 \times 10^6$ GeV/cm³ as in Ref. [22]. From here the profile is given by $\rho(r) = \rho_{\text{sp}}(r/r_{\text{sp}})^{-\gamma_{\text{sp}}}$, $\gamma_{\text{sp}} = 3/2$, up to the radius r_a where the density reaches the value $\rho_a = m_\chi/(\sigma v)_0 t_f$. $(\sigma v)_0$ is the annihilation cross section, and $t_f = 10$ Gyr [22,23] is the elapsed time since the formation of the spike. Finally, the inner MS is $\rho_a(r/r_a)^{-\gamma_a}$, $\gamma_a = 1/2$, up to the limit $4R_S$. The radius r_a is found by matching the two power laws: $r_a = r_{\text{sp}}(\rho_a/\rho_{\text{sp}})^{-1/\gamma_{\text{sp}}}$. The values of ρ_a are between 10^{11} and 10^{12} GeV/cm³, and r_a are of the order 10^{-4} pc for the CMSSM points A–D. In cases C and D, σv in the nonrelativistic limit is around 10^{-29} cm³/s that would result in ρ_a a factor of 10^2 larger than in A and B. Anyway, as was already noted in Ref. [12], the cross section for annihilation into leptons is strongly velocity-dependent as can be seen in Fig. 2: It rises rapidly reaching values around 10^{-27} cm³/s at $v/c \sim 0.1$ – 0.2 ; thus, ρ_a is of the same order as in A and B.

In the top panel of Fig. 3, we show the differential flux multiplied by E_γ^2 to exhibit the behavior at the highest energies near the cutoff. In the bottom panel, the differential photon flux is given by the dots. We find that the spectral shape of the flux is well fitted with the sum of two exponentials, as shown by the dashed lines in the bottom panel. The functional form is $F(x) = F_0 + F_1 \exp(-E_\gamma/E_1) + F_2 \exp(-E_\gamma/E_2)$ with F_0 , $F_{1,2}$, and $E_{1,2}$ fit parameters.

The peculiar characteristics of the signal are (i) its origin is in the innermost region around the BH where the DM distribution is given by the MS density; (ii) the differential flux presents a nearly exponential shape with a hard cutoff that is determined by the mass splitting between the neutralino and the stau; and (iii) the signal shows up at energies below 10 GeV. Interestingly, in this few GeV energy region there are some unexplained excesses over the known backgrounds [31,32]. However, our predicted signal is too feeble to account for them. It is expected that, after 5 years operation, the Fermi-LAT satellite reaches sensitivities of 10^{-10} – 0.5×10^{-11} photons cm⁻² s⁻¹ for energies between 0.5 and 10 GeV [33]. The proposed signal can be one of the components observed by the collaboration. Furthermore, it might be discriminated by the new proposed experiment Gamma-Light [33] that should achieve a better energy and angular resolution than Fermi-LAT in the interval (10 MeV–1 GeV).

In summary, we have shown that if DM is formed by neutralinos as described in the stau coannihilation region of the CMSSM, stau pair production may be the dominant annihilation channel in the innermost region of the GC near the BH. We have further shown that the gamma ray

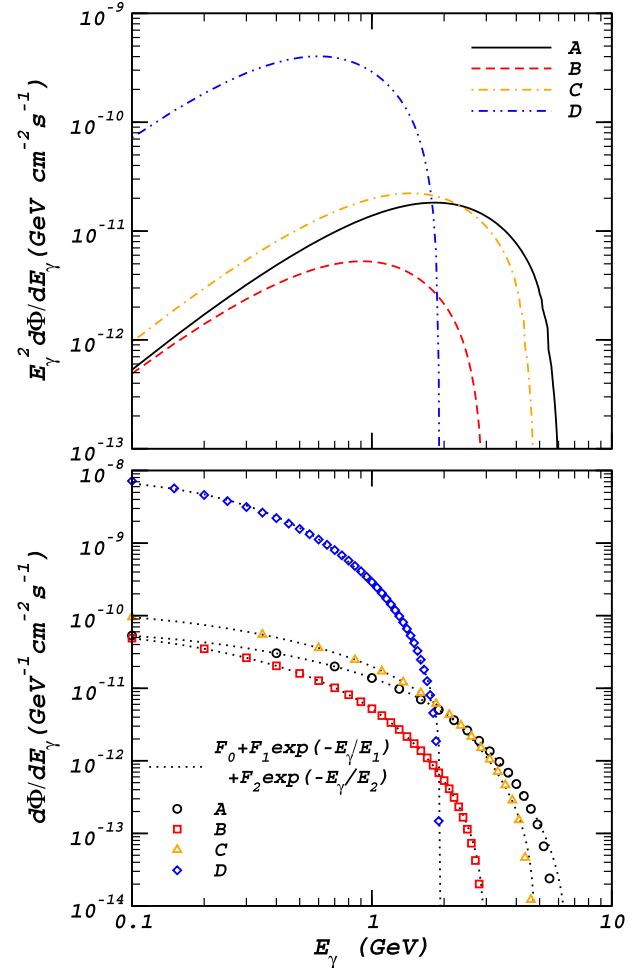


FIG. 3 (color online). Top panel: Differential flux multiplied by E_γ^2 . Bottom panel: Differential flux (dots) and fit (dashed lines) with $F(x) = F_0 + F_1 \exp(-E_\gamma/E_1) + F_2 \exp(-E_\gamma/E_2)$. F_0 , $F_{1,2}$, and $E_{1,2}$ are fit parameters.

spectrum produced by the $\tau\tau$ pair coming from the decay of the staus presents peculiar features. This may further motivate the exploration of the GC by the Fermi-LAT satellite to achieve a better understanding of backgrounds and to look for a possible new indirect signal of the presence of a DM component.

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