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Muon pairs at TeVs-PeVs energy decaying in flight, airshowering inside LHAASO lunar and solar shadows

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Skimming Cosmic Rays on the external Solar atmosphere can be showering in gamma, electron and energetic muon pairs. Such secondaries of TeV or higher energy could reach Earth along a thin frontal solar ring. The skimming gamma and electron rays are abundant, but originated in a very thin layer of the solar atmosphere, disturbed and obstacled in their propagation by solar corona fields and plasma scattering. On the contrary, secondary TeVs-PeVs muons are much rare, but are much more penetrating : they may escape from deeper solar edges along large cord distances, forming a thicker solar ring areas, shining brighter towards our Earth. Being muons of opposite charges, their trajectories are splitted in a twin ring of muons signals that should finally exit the Sun, decays in flight, reaching array detectors on Earth. These muons and their decay in electron pairs, even partially deflected up a few TeVs, must lead to rare gamma-like, air-showers, in LHAASO array detector, falling inside or around the same solar shadows. These rare gamma-like airshowers must be soon disentangled and observable within an energy range of a few up to tens TeV energy.

A more rare, more exciting, signal must also occur from the entire lunar surface or disk, by upward escaping TeVs muons toward the Earth, made by tens TeV muon astrophysical neutrinos , interacting in a few kilometer lunar crust depth, shining around a $6-60$ TeV energy windows, as above, as detectable electron air-shower. Such a lunar mass volume, as a calorimeter for astrophysical neutrinos, is at least a million times larger than the IceCube one, but their arrival solid angle is extremely small. Therefore this lunar disk area signals will be hardly observable in present LHAASO, even within several years or decades. However future larger area, LHAASO like arrays, might be opening the road to a guaranteed lunar induced neutrino muon Astronomy. The first expected solar (and lunar) air-shower rate and geometry in their LHAASO shadows are described.

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1. Introduction: Muons and their electrons, in solar and in lunar shadows

While Cosmic Rays, CR, as shown below, are effective source of secondary muons from the Sun, the same muons induced by neutrinos on our Moon are (rare) sources of detectable signals, in LHAASO like array. Indeed, Cosmic Rays , CR, might be skymming the outer Solar atmosphere. There, CR will be sources of a solar "atmosphere showering" in electron pairs, gamma and muon pairs. Such prompt skimming electron pairs and gamma secondaries originated at GeVs-TeVs energies, can reach the Earth from a very thin (below or around a few tens meters depth of solar photo-sphere surface), diluted in extremely thin solar atmosphere rings. Therefore such direct gamma skimming rays arise only from a negligible thin solar rings and area facing the Earth. Anyway these GeVs secondaries electron pairs, while spiraling on the solar atmosphere might be able to shine to us, by brehmstrallung and by ICS, (Inverse Compton Scattering), a large fraction of their own energy. Therefore Sun is found to be a remarkable GeVs gamma source, converting CR into gamma up to few hundreds GeV, above solar expeceted model. Finally above this 200 GeV energy there are, up to now, only upper bounds.

We are here considering the very amplified role of high (TeVs-PeVs) energy muons, secondaries of higher hundred TeVs, or PeVs, CR solar skimming to Earth. These muons are at horizons pointing to us. Their escape from deeper (thousands or hundreds kms) inside a solar corona depth, surviving a long flight cord . Their flight may held several tens of thousand kilometers, finally emerging and , escaping from a wider solar rings. Soon these TeVs (or tens TeVs) muon pairs are , decaying into electron pairs. Being charged inside magnetic fields, these energetic electrons are partially split while deflected toward the Earth. These TeVs or ten TeV electrons, reaching our atmosphere, are able to airshower in large area, as LHAASO one, with abundant secondaries traces. Contrary from tens PeVs muons, (that did not decay in flight from Sun), these TeVs (few-hundred ones) muons and later, electron airshowers behave in a comparable way as gamma ones. Therefore they behave very differently from hadronic ones. A recent Km size, LHAASO, are able to disentangle such final electromagnetic TeVs or tens-hundred TeVs airshowers, from hadronic ones, even with great accurancy (a part over ten thousands). Therefore , in principle, a well observable signal. We show how to estimate here their first approximated rates of such ring pairs, in LHAASO. These proposal are not new: we started to elaborate them since a few years , [1], [2]. However here, since the active LHAASO detector existence, we should be able, within one or just a few years, to disclosure such new meaningful "muon" signals along the Solar shadows [3]. Opening a new road to a Muon Solar Astronomy view.

On the other side, the Moon has a valuable albedo (made by prompt pion by CR at tens-hundred MeV); indeed the lunar hard surface has as an additional ideal role to reveal eventual anti-meteorites hit on lunar soil into (unobserved up to now) sharp micro-gamma burst [4]. (This arguments led us to inferr severe bounds on antimatter in our galaxy). However lunar rock surface cannot show any twin ring signal, as Sun, by skimming CR,because of the very soft spectra in the secondaries along the lunar rock soil. On the contrary there is a much rare (but more exciting) neutrino astronomy , made mainly by induced tens "astrophysical" TeVs muons, inside the lunar skin crust, a half sphere side, or a disk area, facing the Earth. However the Moon has not any atmosphere. Then there are not any lunar "atmospheric" neutrinos noises. If our Moon was inside a dense atmosphere, as the Titan one, there will be both a strong signal of atmospheric muons along a wide ring (like the solar one), as well a detectable flux of induced (atmospheric) muon neutrinos. Therefore, being our Moon with no atmosphere, there are not the same (abundant) atmospheric muon neutrinos signals as we do observe here on Earth, or around our Sun. On the contrary its hard rock lunar soil, cannot induce any atmospheric neutrino noise, but just a rare astrophysical neutrino signal. Because we already know that at TeVs muon neutrinos are, on Earth, over-crowded by our atmospheric ones, we cannot foresee a soon, rich, astrophysical signal escaping from our Moon to us. At tens TeV or hundred TeVs energy the expected muon neutrinos will be too rare to be observable in LHAASO. A good and a bad news at once. These signals, anyway, should be reaching us from a lunar disk (not a ring one as for Sun),by a wider solid angle, as made by electron pairs, at a very low rate, lower respect the solar ring signals, see 2. Only much larger (future tens-hundreds km size) LHAASO like array, could be able to observe such a revolutionary, new, filtered, neutrino muon astronomy from the Moon. These muon lepton decay from Moon horizons has a similar tau airshower signal expected from Earth horizons or soil : Tau airshowers that are (often) referred as "skimming neutrinos", [5]. They are searched by ground array detectores (AUGER and TA array) and by Jem-EUSO balloons detectors in space, looking for upward tau escaping from the Earth [6].

1.1 Secondaries electron pairs shining on Sun into GeVs gamma by Inverse Compton

Gamma and electron rays in air shower are abundant, but they are a originated in a thin layer of the solar atmosphere. They are somehow bent by magnetic fields and blurred, spread in their propagation along the solar corona fields and while scattering with solar plasma. Inverse Compton Scattering (ICS) [7] may play as an amplifier tool of gamma rays at GeVs: their observed signals seem indeed overabundant. Therefore one will expect only a very limited GeV gamma flux from such skimming CR on the solar surface. They (GeVs-hundred GeV) should shine only inside a thin gamma ring. Nevertheless , surprisingly, the GeVs gamma observed from the Sun is larger (an order of magnitude) than what one would expect.The overproduction of GeV gamma ejected from our Sun with growing energy reaches a maximum at 40 GeV: later on the flux decreases (in an unexplained dip); at hundred GeV the flux is growing in a remarkable fluence reaching a maximum at 200 GeV. A following TeVs energy edges had not yet been revealed in the solar gamma spectra. As we shall see , this signal is beyond the LHAASO detection threshold. Vedi Fig.4. The 40 GeV spectra dip in solar gamma spectra: how can we explain this solar unexpected dip? It is not our present goal to face and try to solve here that problem. Here we just suggest the role of skimming CR at high altitude, in a very diluted solar atmosphere: they are mostly bent by hundred Gauss magnetic fields , leading, on the Sun, to long life spirals of a characteristic radius $R_{Larmor} = 13.2 \cdot km \cdot (E/40GeV) \cdot (B/100Gauss)^{-1}$. Their hit on the solar light photons bath may increase, by ICS, [7] , the hard (tens GeV) gamma energy edges. Also their brehmstrallung on the very diluted solar atmosphere may shine GeVs gamma photons. However at hundreds GeV the wider Larmor spirals may free the electrons avoiding their additional gamma over-productions. Therefore at two hundreds GeV up to TeVs or tens TeVs the new muon component, a more penetrating one in solar atmosphere, may start to play a role. In particular because their decayed electrons offer a brighter gamma-like imprint in LHAASO array. This is the main subject in present article: these ten TeVs muon-electron signals are at the LHAASO edge of detection. Just beyond the corner, See Fig.4.

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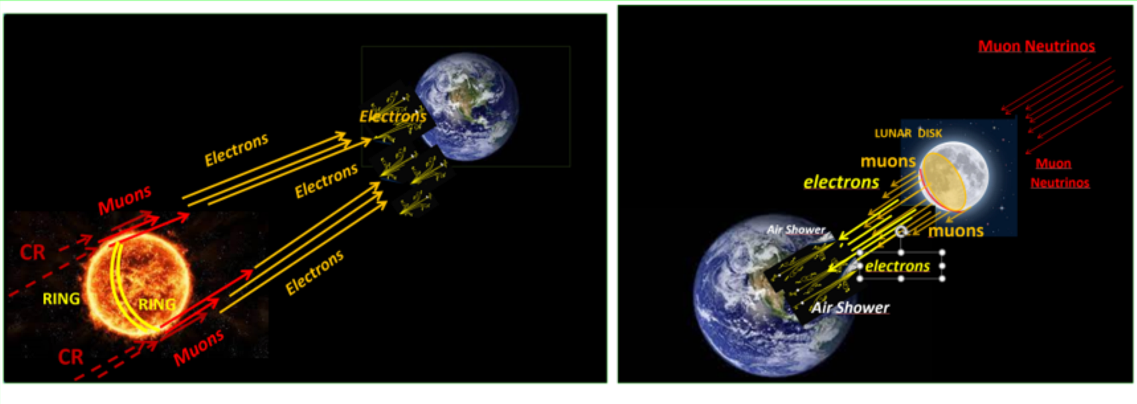

Figure 1: A solar and moon picture showing their eventual muon origination. The solar ring, made by skimming CR, and later on by their muon secondaries pointing to the Earth, are decaying into electrons in flight. A similar induced muon formed by a spherical-disk of thin lunar soil, induced by muon and antimuon neutrinos , sending tens TeV muon and later electrons to the Earth.

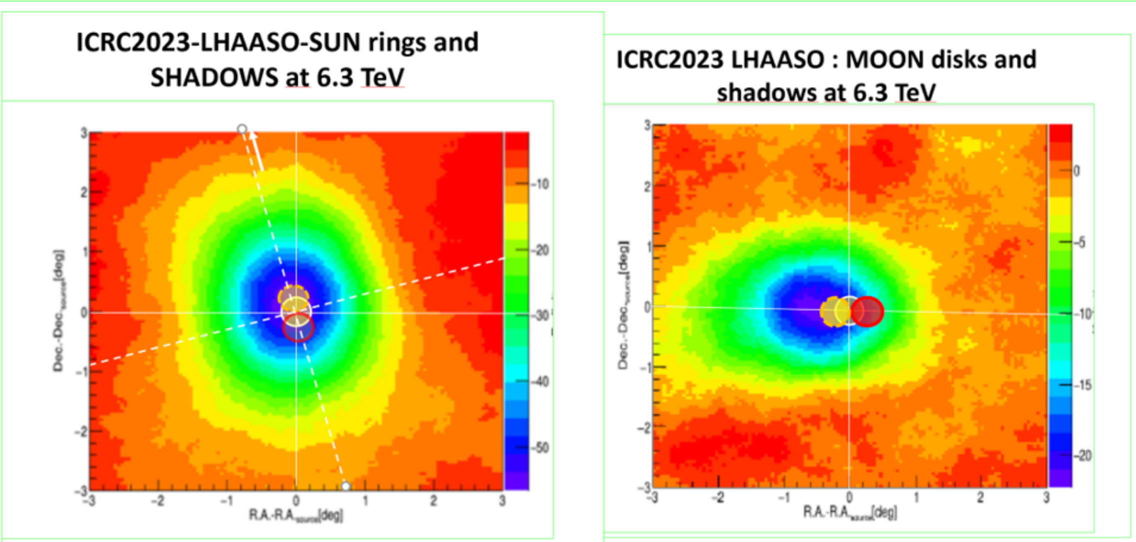

Figure 2: As above about a solar and moon picture showing the expected muon origination and their bending at 6.3 TeV energy, falling around their (LHAASO, observed), hadronic, solar and lunar shadows [3]. Note the different bending elongation for Moon and Sun , because of their little different magnetic field morphology . The solar ring, made by skimming CR, and later on by muons are pointing to the Earth are decaying into electrons in flight. A similar induced muon formed on a spherical-disk of lunar soil, are originated by muon and antimuon neutrinos at tens-hundreds TeV , sending final tens TeV muons, and later, electrons, to the Earth. The size of the LHAASO shadows, around 4 TeV energy , are enlarged by the Helium (and heavier) bent nuclei, with more charges and bending angles.

2. Secondaries muon signature

Secondary TeVs-PeVs, (or even EeVs muons), are much rarer than electron pairs, but they are much more penetrating. This occur because the muon cross section and energy losses are , in a first approximation, tens of thousands times smaller than electron ones: as small as the square of the electron over the muon mass. The muon pairs therefore may flight tens of thousands kilometers and escape,after such a long cord flight inside the solar corona, from deeper solar edges, forming a thicker ring area,shining brighter to our Earth. This phenomena depends also on the solar atmosphere density , see Fig. 3, and the muon range at those gas density. Their rings area are therefore thicker (by three or four order of magnitude larger) than primary skimming gamma rings, greatly increasing a signal respect to the first skimming primary gamma and electron ones.

2.1 Expected Solar TeVs Gamma-like signals in LHAASO

These rare gamma-like airshowers (originated by TeVs muon decay ones) must be observable in LHAASO in the very near future, within the energy range of few or ten TeV by a careful data acquisition [1, 8, 9]. These muons arrival themselves on Earth is very hardly observable. But at TeVs-PeVs energies, luckly, they decay from Sun. Their decay secondaries (the electron pairs) are able to arrive (even by a tiny bending), and they are better showering than muons, on terrestrial atmosphere. Such final air-shower signals, like gamma ones, shine in wide areas and by a rich rain of secondaries, in well observable way. Present largest area detector array as LHAASO, could be able to record such few TeVs (up to one or few tens TeV) signal along and inside the Sun shadows.

2.2 The muon cord flight on solar atmosphere

The succesful muon flight at TeVs energies across the deep solar corona cords must overcome three obstacles: 1) the muon life time, 2) the slanth depth along the cord for the average muon survival distance in the dilutes solar atmosphere and 3) the corresponding cord lenght maximal distance for each maximal depth (negative height h) to be considered. Naturally the higher the muon enrgy, the better its penetration and the wider the ring thikness, (as well as the wider the solar ring illumination). However the muon (as well the CR) spectra is rapidly decreasing with the energy increase. But the same LHAASO detection threshold is better above several TeVs energy. Therefore the optimal energy range is not obvious at all. We tested different solar muon spectras and depth finding their corresponding (tuned) , largest, event rates. We here only remind the key expressions needed to achieve these results: 1) The Sun and Lunar bending angle $\theta = (1.6)^o \cdot (E_\mu/TeV)$; therefore at 6.4 TeV the bending is,at least half, inside the inner shadows disk, see 2. 2) The muon cord, at a negative depth h below the solar photo-sphere layer: $D = 2 \cdot (2 \cdot h \cdot R_{Sun})^{0.5} = 2360 \cdot (h/km)^{0.5} km$. . The solar ring area A is $A = 2\pi \cdot R_{Sun} \cdot h$. The solar solid angle is well known, comparable to the lunar one. See Fig.3. The consequent probability of detection is given by the ratio $A/(\pi \cdot R_{Sun}{}^2)$ times the horizontal muon flux times detection LHAASO area, times the fraction of solar ring views, and the integral times and area in LHAASO. 3) The muon relativistic flight distance: $L_\mu = 6600 \cdot (E_\mu/TeV) km$. 4) The muon range $L_{\mu_{range}}$ inside any matter, water, gas or in any1 an energy windows (from a TeV to a hundred TeV energy), the windows of interest, could be approximated by a simple law:

$$L_{\mu_{range}} = ((4 \cdot log(E/GeV) - 9.5)/(\rho)) km$$

. Where ρ is in gr/cm^3 unity. For instance, at $h = 0.5\% \cdot R_{Sun}$ for $(\rho) = 10^{-4} \cdot gr/cm^3$, the 10 TeV muon will cross a range of nearly 66.000 kilometers. However the inner cord will be nearly twice much longer, and these 10 TeVs events might reach us only from a more outer, external and shorter cord layers. To tune a few energy cases and values, we considered each correlated ideal cord (and depth h) able to coexist with the same muon lifetime distance (and range in that density values). This iterative operation is not described here in detail. We just report our results, in number of event expected $\Delta N_{event/year}$ in the inner $100.000 \cdot m^2$ LHAASO water array array, assuming a half a day detectability for a whole year. We used the experimental, observed horizontal muon flux on Earth that it is (very probably) an underestimated value for the solar, a much more diluted, horizontal atmosphere. We multiplied the expected fluxes by solar solid angle. We obtained, for these peculiar energy values of interest, $E_\mu/TeV = 3, 6, 10, 20, 25$ the following optimized parameters leading to a larger detection rate:

$$E_\mu = 3TeV; h = 10^{-4} \cdot R_{Sun}; D = 19695km.; L_\mu = 19800km << L_{\mu_{range}}.\Delta N_{event/year} = 2.4$$
$$E_\mu = 6TeV; h = 4 \cdot 10^{-4} \cdot R_{Sun}; D = 39384km.; L_\mu = 39600km << L_{\mu_{range}}.\Delta N_{event/year} = 1.87.$$
$$E_\mu = 10TeV; h = 10^{-3} \cdot R_{Sun}; D = 62282km.; L_\mu = 66.000km << L_{\mu_{range}}.\Delta N_{event/year} = 1.42.$$
$$E_\mu = 20TeV; h = 5 \cdot 10^{-3} \cdot R_{Sun}; D = 139.268km.; L_\mu = 132.000km << L_{\mu_{range}}.\Delta N_{event/year} = 1.19.$$
$$E_\mu = 25TeV; h = (1/2)^{-1} \cdot 10^{-2} \cdot R_{Sun}; D = 139.268km.; L_\mu = 165.000km << L_{\mu_{range}}.\Delta N_{event/year} = 0.93$$

These values are somehow reported in the following Fig.4 , marked by some green ellipses.

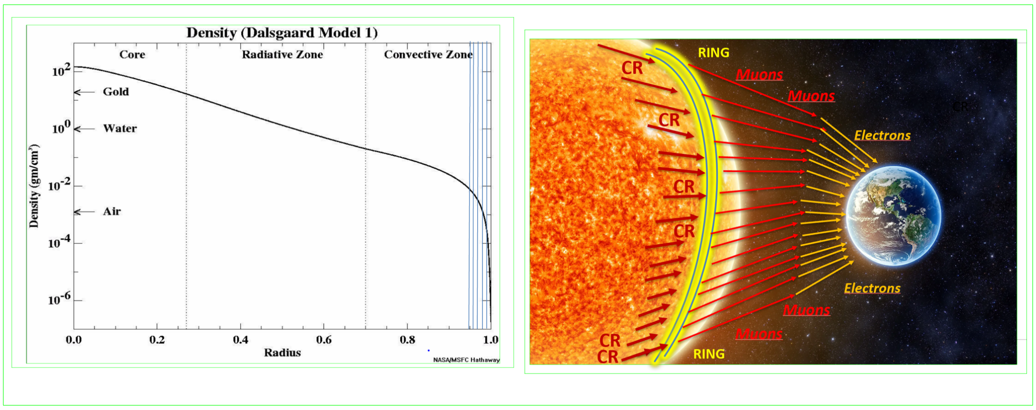

Figure 3: On the left side:he solar density profile considered, following a NASA model. The extreme 5% radius columns of internal Sun atmosphere are shown. Only within the last, 1% of the Sun radius, a few Tens (30 TeV) muons are able to penetrate and survive along the nearly 200.000 km cords. Because most TeVs muons life time is much shorter, we considered mainly a smaller depth of only 0.5%, or less, as 0.1% and below, of the solar radius. Therefore their cords are shorter. In the right side figure a more detailed scheme describing the muon ring ejecting toward the Earth, by secondaries electron pair ring signals. There are tens of thousand of such rings pointing everywhere. But the observable one, from the Earth, is the one described by figure above

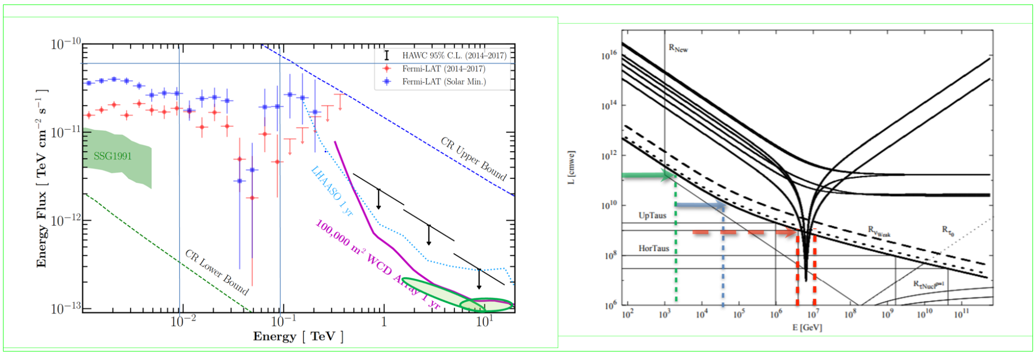

Figure 4: On the left side, the expected signals of muons-electron air-showers in side the recent flux energy-energy diagram [9]. The thin green ellipses area are somehow summirizing our foreseen signals by skimming muons along the Sun. On the right side, the neutrino opacity in solar,terrestrial and lunar scattering. The Sun, green, Earth, blue, and Moon, red lines, show the UHE neutrinos opacity. Tau ones on Earth are foundamental tool to a guaranteed neutrino astronomy. Terrestrial muons neutrino, is under the dominant atmospheric noises, the lunar ones are surviving opacity, up to a tens PeV energy windows. The Glashow resonance, (the reversed peak tuned energy at 6.3 PeV), might produce also PeVs-TeVs muons (by a 11% channel), able to add escaping muons at hundreds or tens TeV energy.

3. Muons by UHE muon neutrinos interacting, escaping from a thin Moon crust

A rarer signal, but a more significant phenomenon (similar to the solar one described above) occurs with a few TeVs up to PeV astrophysical muon neutrinos passing across and through the Moon, on their way to the Earth, interacting (rarely) in a thin lunar layer, a few kilometer depth, a facing surface (an effective volume of tens of millions of cubic kilometers, in a thin solid angle). Also an additional Glashow resonance by anti-electron neutrino at few PeVs might also play a role. Indeed W decay may feed also 11% decay channel in PeVs muons escaping from the Moon. Indeed the lunar beam dump role to produce, by 6.3 PeVs of anti neutrino-electron scattering over electron, in lunar crust, a W boson resonance remind an analogy: speculative proposal to explain UHECR puzzling origins, where ZeV neutrinos are scattering onto relic cosmic neutrinos with eV mass, (a dark Mpc beam dump halo) forming a Z boson resonace [10], [11], [12]. The narrow solid angle due to Earth-Moon distance, the weak interaction cross-sections, makes the volume and its corresponding narrow view detection a rather limited effective detection target. But future larger areas of LHAASO like hundreds or thousands square kilometer size might in a far future, observe this muon neutrino Astronomy.

4. Conclusions

Taus [5, 6] and muons [1, 8] are mostly ignored as astrophysical signal carriers.
Nonetheless, skimming TeVs-PeVs hadron CR produce secondaries on solar atmosphere that might be solar-like «air»-showering muon pairs, whose decay in their flight to Earth leads to much better detectable electron pairs, observable as gamma airshowers. These TeVs-PeVs electrons can interact (almost as gamma) in our atmosphere leading to extensive air showers well detectable by square kilometer arrays such as LHAASO. See Fig. 4. Similar, but rarer, hundreds or tens TeVs

astrophysical neutrinos passing through the Moon can interact in the outer thin crust layer facing us, leading to TeVs muons whose decay in flight can shine as a gamma airshower in LHAASO. See Fig. 4. This signature will be a totally new additional roadmap for neutrino astronomy [5, 6], mainly because the Moon devoid of any atmosphere: it has no "atmospheric muon noises" as our terrestrial ones. At present these signals are expected to be rare, but in a future , (few in decades), larger LHAASO areas could achieve the goal [1, 8].

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References

[1] D. Fargion, P. Oliva, P.G. De Sanctis Lucentini and M.Y. Khlopov, *Signals of he atmospheric μ decay in flight around the sun's albedo versus astrophysical ν_μ and ν_τ traces in the moon shadow*, *International Journal of Modern Physics D* **27** (2018) 1841002.

[2] D. Fargion, P.G. De Sanctis Lucentini and M. Khlopov, *Neutrino signals by Upward Tau airshowering at Earth horizons and by Muon airshowering at Moon shadows*, *PoS* **ICRC2021** (2021) 1208.

[3] M.-Y. Cui, *Observations of cosmic-ray Sun shadow with LHAASO-WCDA*, *PoS* **ICRC2023** (2023) 270.

[4] D. Fargion and M. Khlopov, *Antimatter bounds from antiasteroid annihilation in collisions with planets and sun*, *Astroparticle Physics* **19** (2003) 441.

[5] D. Fargion, *Discovering ultra-high-energy neutrinos through horizontal and upward τ air showers: evidence in terrestrial gamma flashes?*, *The Astrophysical Journal* **570** (2002) 909.

[6] D. Fargion, P.G. De Sanctis Lucentini, M. De Santis and M. Grossi, *Tau air showers from earth*, *The Astrophysical Journal* **613** (2004) 1285.

[7] D. Fargion and A. Salis, *Inverse compton scattering off black body radiation in high energy physics and gamma (mev–tev) astrophysics*, *Physics-Uspekhi* **41** (1998) 823.

[8] D. Fargion, P.G. De Sanctis Lucentini and M.Y. Khlopov, *Neutrino signals by upward tau airshowering at earth horizons and by muon airshowering at moon shadows*, .

[9] M. Nisa, J. Beacom, S. BenZvi, R. Leane, K. Ng, A. Peter et al., *The sun at gev–tev energies: A new laboratory for astroparticle physics*, *arXiv preprint arXiv:1903.06349* (2019) .

[10] D. Fargion, B. Mele and A. Salis, *Ultra-high-energy neutrino scattering onto relic light neutrinos in the galactic halo as a possible source of the highest energy extragalactic cosmic rays*, *The Astrophysical Journal* **517** (1999) 725.

[11] D. Fargion, P.G. De Sanctis Lucentini, M. Grossi, M. De Santis and B. Mele, *Ultra high energy cosmic ray and uhe $\nu - \nu_r - z$ showering in dark*, *Memorie della Societa Astronomica Italiana* **73** (2002) 848.

[12] D. Fargion, M. Grossi, P.G. De Sanctis Lucentini, C. Di Troia and R.V. Konoplich, *Shadows of relic neutrino masses and spectra on highest energy gzk cosmic rays*, in *Dark Matter in Astro- and Particle Physics*, H.V. Klapdor-Kleingrothaus, ed., (Berlin, Heidelberg), pp. 455–468, Springer Berlin Heidelberg, 2001, DOI.