

TeV Solar Gamma Rays as a Probe for the Solar Internetwork Magnetic Fields

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Recently, solar gamma rays produced by cosmic rays interacting with the solar atmosphere have been detected in the GeV to TeV energy range, revealing that cosmic rays are significantly affected by magnetic fields in the solar atmosphere. However, much of the observations remain unexplained by existing physical models. Using a semianalytic model, we demonstrate that magnetic fields at and below the photosphere with a large horizontal component could account for the approximately 1 TeV solar gamma rays observed by HAWC. This suggests that high-energy solar gamma rays could serve as a novel probe for magnetic fields beneath the photosphere, which in the future could help improve the understanding of solar magnetism, the key driver of space weather.

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Introduction—It has long been theorized that cosmic rays impacting the Sun would produce high-energy gamma rays through hadronic interactions [1]. The pioneering work, Ref. [1], proposed that magnetic flux tubes could significantly enhance the gamma-ray flux production by cosmic-ray reflection. These solar atmospheric gamma rays were first detected by EGRET [2]. Subsequently with Fermi, Ref. [3] showed that the flux is much higher than predicted [1] in 0.1 – 10 GeV. Later, Refs. [4–7] confirmed this up to 100 GeV. Furthermore, solar gamma rays were found to exhibit a hard spectrum, large time variation that anticorrelates with solar activity [4,5,7], a dip in the energy spectrum [5], and time-dependent morphologies [7,8]. Recently, solar gamma rays were detected for the first time by HAWC [9] in the TeV range with a soft spectral index of -3.6 .

In terms of modeling efforts, Refs. [10,11] implemented the PFSS [12–15] corona magnetic field model in particle simulation suites to compute the solar gamma-ray flux. While both calculations showed that corona magnetic fields can significantly boost gamma-ray production and could plausibly explain the ~ 10 GeV flux, the flux above 100 GeV remains unexplained. References [16,17]

connected the Sun shadow data with solar emissions. Reference [18] hypothesized that the Sun could be a TeVatron to explain the high-energy emission. Using 3D Magnetohydrodynamic simulations, Ref. [19] suggested a pressure-magnetic field relation for computing the cosmic-ray interactions in the solar atmosphere. Most recently, Refs. [20,21] considered magnetic flux tubes and flux sheets, showing an impressive agreement in flux and spectral shape with data above ~ 10 GeV, though the flux at TeV falls short by a factor of a few under the chosen parameters. References [22,23] showed that cross-field diffusion in closed magnetic loops could also enhance the gamma-ray flux production.

Despite these efforts, there is a lack of concrete understanding on solar gamma rays. Given the complexity of solar magnetic fields and the vast energy scale involved, a complete description of solar gamma-ray production may seem daunting without expensive and detailed simulations. However, as we argue in this work, given a set of reasonable assumptions, we can identify the dominant effect responsible for the gamma-ray production at the high-energy limit. In particular, we show that horizontal subphotospheric internetwork magnetic fields are likely responsible for the observed $\sim$ TeV solar gamma rays.

The need for strong fields—In this work we exclusively discuss steady solar gamma-ray emission; transient emission, such as that associated with solar flares [24–28], has only been observed up to a few GeV [29]. There are also leptonic components, such as inverse Compton [2,30–35] and synchrotron [36,37] emission, which have completely different morphology and could be distinguished from the disk component with sufficient angular resolution.

Solar atmospheric gamma rays (disk component) are produced mainly through hadronic channels, when

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secondary particles (e.g., pions) decay into gamma rays. Typically, the produced gamma rays carry about 10% of the primary cosmic-ray energy, $E_\gamma \sim 0.1E_p$. The fact that HAWC observed TeV solar gamma rays implies that cosmic rays up to 10 TeV are strongly affected by magnetic fields. Considering the Larmor radius (L),

$$\frac{E}{20 \text{ TeV}} \simeq \frac{L}{R_\odot} \frac{B}{G} \simeq \frac{L}{10^3 \text{ km}} \frac{B}{\text{kG}}, \quad (1)$$

at least 1 kG field strength is needed to affect ~ 10 TeV cosmic rays with a physical scale of 10^3 km.

For the context of the 10^3 km scale, we can look at the density distribution of the Sun [38,39]. (shown in Fig. 3) Assuming spherical symmetry, we set our frame origin at the north pole of the Sun. We define the quantity *depth* (d), zero at the photosphere, to be $-z$ in the Cartesian coordinate of this frame. One can then estimate the gamma-ray production efficiency by considering the vertical optical depth toward the solar center $\tau_v = \int (\rho/m_p) \sigma d(d)$, where ρ and m_p are the matter density and proton mass, respectively. In this work, we take the hadronic cross section, σ , to be 31 mb [40], and we ignore the modest increase of the cross section versus energy. As depth increases, it is increasingly more difficult for the gamma rays to escape the Sun. We can estimate the combined gamma-ray production and escape efficiency with $\tau_v e^{-\tau_v}$ (see also the subsection “Orbit simulation and interaction efficiency” and Fig. 3), and the peak of the efficiency can be found at around 10^2 – 10^3 km depth. Incidentally, this is also approximately the size of a granule, the convective cell at the solar surface.

Sunspots are possible locations for the 1 kG fields. However, sunspots only occupy a small fraction of the solar surface, and are thus unlikely to account for most of the solar gamma-ray production. Vertical kG fields can also form in the quiet Sun in intergranular lanes and flux tubes, which was investigated in Refs. [20,21]. By assuming that cosmic rays follow the field lines to enter these structures and are then reflected by the magnetic bottle effect, their calculation could reasonably match the low-energy data, though it falls below TeV data by a factor of a few, given their chosen parameters. This indicates that network fields could be important for the gamma-ray production over a wide energy range.

In this work, we look at a completely different potential source of kG fields: *horizontal* internetwork fields below the photosphere.

The role of solar internetwork magnetic fields—The atmosphere of the Sun (photosphere, chromosphere, and Corona) shows a diverse range of magnetic phenomena [41–43]. In the photosphere, it can be divided into active and *quiet* regions. Active regions host strong magnetic features such as Sunspots. The quiet regions, once thought to be nonmagnetic, are now known to be fully magnetic

[44], and could even dominate the magnetic energy of the Sun [45].

The magnetic fields in the quiet regions come from network and internetwork regions (see Refs. [46,47] for reviews). The network regions outline the shape of the granular and supergranular cells, while the internetwork regions represent the cell interiors. The internetwork fields, which have typical field strength of $\mathcal{O}(100)$ G at the solar surface, have a large horizontal component [45,46,48–50] and are suggested to be caused by the local dynamo from the ubiquitous convective motion [47,51–53]. Given the large coverage of the internetwork regions and that the convective motions below the surface could produce similar horizontal fields, we consider their role in gamma-ray production.

As we limit our attention to TeV gamma rays, we can safely ignore the processes that affect mostly lower energy cosmic rays. In particular, we neglect cosmic-ray propagation in interplanetary magnetic fields [3,54,55] and corona magnetic fields [10,11,15].

A toy model of horizontal internetwork fields: We consider a simplified horizontal internetwork fields model. At the solar surface, the typical $\mathcal{O}(100)$ G horizontal field strength [45,46,48–50] is comparable to the kinetic energy density of the fluid. For reference, with density 3×10^{-7} g/cm³ and flow speed 3 km/s, the equipartition field is around 580 G. We model the horizontal field strength below the photosphere following this assumption, $|\vec{B}(d)| = f \sqrt{4\pi\rho(d)|\vec{v}(d)|^2}$, where $|\vec{v}|$ is the flow speed and f is a free parameter with f^2 being the fraction of the magnetic energy over the kinetic energy. Though we consider $f \leq 1$ as a physically reasonable representation of the field strengths obtainable by local dynamo action (its value was found to be approximately constant with depth, e.g., see Ref. [56]), we also investigate some larger values to mimic the rise of the magnetic field from lower depths of the convection zone to inject field into the subphotospheric region. Observations of the photosphere suggest the strength of the quiet sun magnetic field are largely independent of solar cycle (e.g., Refs. [57,58]), implying f may not have a temporal variation, though the surface fraction of the quiet Sun could vary over a cycle.

The flow speed can be estimated by convection models [59–61], inferred from simulations [62], or indirectly probed through surface observation and helioseismology [63]. For our toy magnetic field model, we obtain the flow speed as a function of depth from Unno, Kondo, and Xiong [59], which is consistent with that from global and local simulations (see Fig. 4 and Fig. 4 of Ref. [64]).

Above the photosphere, the magnetic fields get weaker and become more complicated. In the spirit of this Letter, we consider two cases to estimate the uncertainties associated with magnetic fields above the photosphere. One is that we extrapolate the field strength linearly to 1 G at -1250 km depth and cut to zero beyond that while keeping

the field direction (labeled as $|B(-1250)| = 1$ G, dashed lines in Fig. 4); these values are chosen to roughly estimate the effect of coronal fields and have no particular significance. The second case is that we set the field to be zero above the photosphere (labeled as $|B(< 0)| = 0$). These two models roughly bracket the two extreme effects of magnetic fields above the photosphere: one suppresses cosmic rays from reaching the photosphere and one has no effect on that.

Orbit simulation and interaction efficiency: With the specified magnetic field model, we solve for trajectories of particles that go into the Sun to calculate the interaction probabilities, with the following assumptions: (1) The horizontal fields are coherent within the convection cell, and the cell is always large enough to contain our cosmic-ray particles; (2) particle trajectories are not affected by interactions; and (3) the cosmic rays are made of protons only. (The effect of nuclei on the flux is estimated below.)

The protons are injected at 1250 km above the photosphere, and is assumed to be isotropic. This is justified as Refs. [10,11] showed that corona fields have a small effect on TeV solar gamma rays. At the injection point, a set of downgoing trajectories are simulated. Only the hemisphere towards the Sun is needed, as the other half will simply escape. The anisotropy induced by the corona field may affect the gamma-ray production when coupled to the subphotospheric fields, however. We defer this to future studies. With these assumptions, the particle trajectories are obtained by solving the equation of motion $(d\vec{p}/dt) = q[(\vec{v}/c) \times \vec{B}]$, where $\vec{p}$ is the particle momentum, $(\vec{v}/c)$ is the particle velocity in unit of speed of light, and q is the particle charge. In total, we consider 51 energy bins in equal log space between 10^2 and 10^7 GeV.

Under the above assumptions, the trajectories only depend on the proton energy E_p and the incident direction, labeled by Ω . They are used to compute the optical depth by integrating along the track length (ℓ), hence, $\tau(E_p, \Omega) = \int (\rho/m_p) \sigma d\ell$. Both the primary proton and the produced gamma rays get attenuated as they propagate. For the track of the produced photon, we assume they take the path that the primary proton would have if there were no interaction. We define the efficiency factor as $\mathcal{T}(E_p, \Omega) = \tau e^{-\tau}$. (See Appendix C for more details about the efficiency factor.) As the most important photons produced are those that point at the direction of the cosmic rays after interaction, therefore the most important parts of the path length are those after the cosmic rays have been reflected; only these outgoing photons have a chance of escaping the Sun. In this case, for the optically thin tracks, the first half of the tracks (down-pointing) is not useful. For optically thick cases, interactions would more likely to occur when the tracks are pointing down, which would not contribute to observable gamma rays; the exponential part of the efficiency factor already heavily suppresses these cases. Therefore, including the downgoing tracks could have slightly overestimated

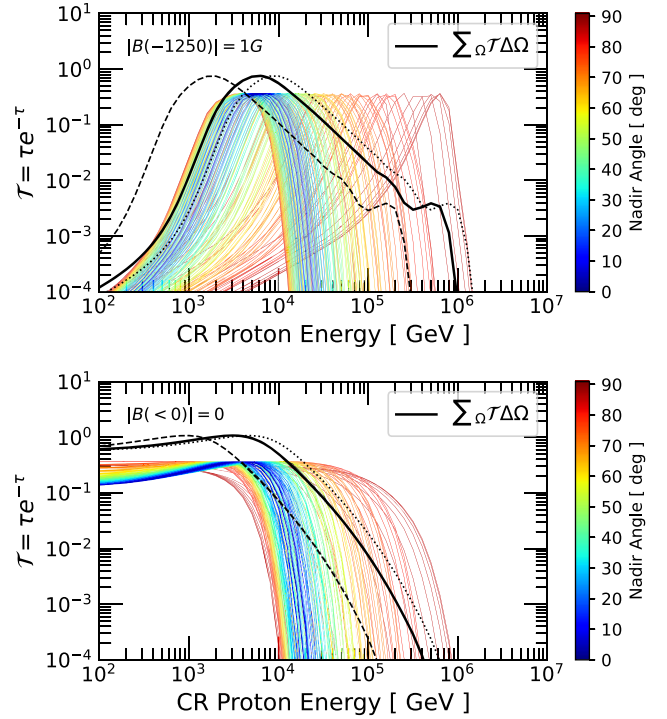


FIG. 1. The efficiency factor $\mathcal{T} = \tau e^{-\tau}$ for downgoing trajectories, color coded according to the nadir angles, for the $f = 1$ case. Each line represents the efficiency from the discrete set of proton energies, obtained from integrating along the entire orbit in our simulation volume. The black (dashed, solid, dotted) lines are the nadir-weighted sums of the efficiencies $\sum_{\Omega} \cos \theta \mathcal{T} \Delta\Omega$, for $f = (0.3, 1, 1.5)$. The top and bottom panels correspond to the two magnetic field cases in this work.

the gamma-ray flux. Furthermore, there are several factors that our model does not take into account, such as multiple interactions, changes of orbits due to energy loss, and different photon escape efficiencies depending on their direction at production, etc. These effects can be more precisely determined with a numerical setup in the future.

For the orbit simulation, a total of 368 down-going trajectories are solved for each energy bin, prescribed using the HEALPY package [65,66] with $N_{\text{side}} = 8$. This corresponds to 368 equal-solid angle sky areas, each of which covers a sky area of about $\Delta\Omega = (7.3 \text{ deg})^2$. A sample of the simulated tracks are shown in Appendix C (Figs. 5–7).

Figure 1 shows the gamma-ray efficiency factor for both cases, color coded according to their *nadir* angles, θ at the injection point, defined as the angle between the $-\hat{z}$ unit vector and the particle momentum unit vector. The black lines are the nadir-weighted solid angle sums $\sum \cos \theta \mathcal{T} \Delta\Omega$, which are used below in Eq. (3). We can see that the chosen number of trajectories is sufficient to accurately compute the weighted sums, especially around the most relevant energy at 10^4 GeV. Here we can see the main differences between the two magnetic field models. For the $|B(-1250)| = 1$ G case, the efficiency is suppressed at

low energies as cosmic rays can be reflected off the Sun before reaching sufficient column density to interact. This suppression is especially significant for particles with large nadir angles.

The efficiency also drops off at high energies due to the $e^{-\tau}$ factor. The efficiency peak ($1/e$) occurs at higher energies for some large-nadir trajectories, as they traverse the shallower part of the atmosphere. At the other extreme, some large-nadir trajectories exhibit a more rapid efficiency drop with increasing energy. This occurs because these trajectories inject particles in a direction opposite to the rotation due to the Lorentz force, requiring them to travel a longer distance before escaping. (These two extreme cases correspond to particles injected with large $+x$ and $-x$ components in Fig. 5.) For the $|B(<0)| = 0$ case, since particles only experience magnetic fields after entering the photosphere, even low-energy particles can accumulate sufficient column density in the high-density atmosphere.

Gamma-ray flux production—Given the orbit information, we estimate the gamma-ray production semianalytically.

The dominant production mechanism at this energy comes from the decay of neutral pions [11,67] produced in inelastic hadronic interactions. The differential pion production rate is

$$d\dot{N}_\pi = \frac{\rho}{m_p} \sigma \Phi_p \frac{dN}{dE_\pi} dE_\pi dE_p \cos \theta d\Omega dA d\ell, \quad (2)$$

where $\Phi_p(E_p)$ is the cosmic-ray intensity (in units of $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$) taken from Ref. [68], $dN/dE_\pi = \delta[E_\pi - K_\pi(E_p - m_p c^2)]$ is the pion energy distribution per interaction, following the delta function approximation from Ref. [40], with $K_\pi = 0.17$ being the fraction of pion energy (E_π) to the proton kinetic energy, $d\Omega$ represents the part of sky that the cosmic rays comes from, dA is the surface area that receives the cosmic rays with the $\cos \theta$ taking into account the projection between dA and the incident flux, and $d\ell$ is the length the cosmic rays travel in the medium. Doing the length integral yields τ , which we augment to become the efficiency factor, $\tau \rightarrow T(E_p, \Omega)$. Doing the E_p integral using the delta function, and approximating the solid angle integral with discrete sums, we obtain an expression for $d\dot{N}_\pi/(dA dE_\pi)$. It is then convolved with the gamma-ray spectrum from isotropic pion decays [67] to obtain

$$\frac{d\dot{N}_\gamma}{dA dE_\gamma} = \int_{E_{\min}}^{\infty} \frac{2 \sum \cos \theta T(\tilde{E}, \Omega) \Delta \Omega}{K_\pi \sqrt{\tilde{E}_\pi^2 - m_\pi^2 c^4}} \Phi_p(\tilde{E}) dE_\pi, \quad (3)$$

where $E_{\min} = E_\gamma + m_\pi^2 c^4 / (4E_\gamma)$, $\tilde{E} = m_p c^2 + E_\pi / K_\pi$, and the factor of 2 accounts for the two photons per pion decay. The photon flux at Earth is obtained by multiplying Eq. (3) with the surface area, $4\pi R^2$, and divided by $4\pi D^2$, where R is the radius of the Sun and $D = 1 \text{ AU}$. Hence,

$$\frac{dF}{dE_\gamma} = F_{\text{sur}} N_{\text{nuc}} \frac{R^2}{D^2} \frac{d\dot{N}_\gamma}{dA dE_\gamma}, \quad (4)$$

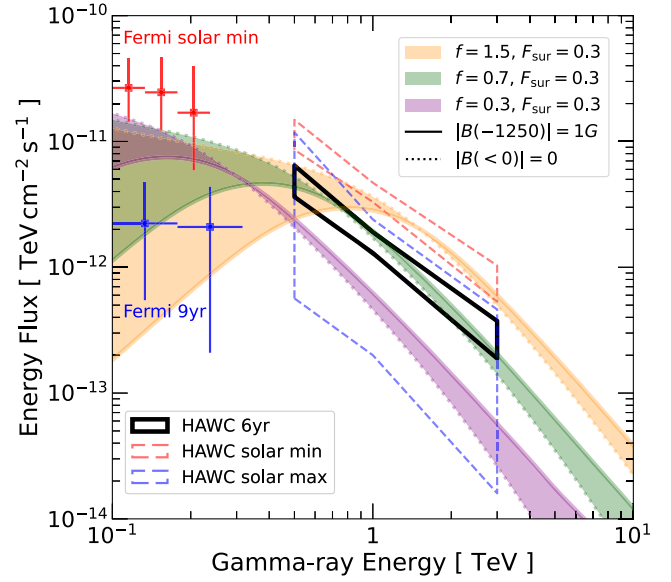


FIG. 2. Gamma ray flux produced by cosmic rays reflecting on the horizontal internetwork fields, for $f = 0.3, 0.7$, and 1.5 . The flux is directly proportional to the surface fraction F_{sur} [Eq. (4)]. Dotted lines and solid lines correspond to the $|B(<0)| = 0$ and $|B(-1250)| = 1 \text{ G}$ cases, respectively. The Fermi-LAT data at the solar minimum (2008–2010) and nine-year (2008–2017) averaged flux data [5] are shown for comparison. The recent HAWC results [9] are shown in thick boxes, with black solid line being the six-year (2014–2021) combined result, blue dashed line corresponds to solar max. (2014–2017), and red dashed line corresponds to the solar min. (2018–2021) It can be seen that our model could reasonably explain the HAWC data, e.g., with $f \simeq 0.7$ and $F_{\text{sur}} \simeq 0.3$.

where we also include N_{nuc} , the nuclear enhancement factor that takes into account the presence of nuclei (mostly Helium) in the cosmic rays and the target [69,70], taken to be 1.8 following Ref. [32], and F_{sur} , which is a free parameter that represents the surface fraction of the horizontal internetwork fields over the Sun.

Figure 2 shows the computed solar gamma-ray spectra for $f = 0.3, 0.7$, and 1.5 , and $F_{\text{sur}} = 0.3$. Considering the $|B(-1250)| = 1 \text{ G}$ case, at lower energies, the gamma-ray production is suppressed compared to the $|B(<0)| = 0$ case. At higher energies, the additional magnetic fields provide extra deflections that shift the efficiency factor towards higher energies, thus making the $|B(-1250)| = 1 \text{ G}$ case more efficient.

Conclusion and discussion—In this work, we provide a physical model that could fully explain the HAWC TeV solar observation. We show that horizontal subphotospheric internetwork fields, an extension of those seen at the photosphere, could be strong and ubiquitous enough to reflect $\sim \text{TeV}$ cosmic rays and generate the observed solar gamma rays. Our model is simple and has few parameters, as the magnetic field strength can be reasonably connected to the kinetic energy of the fluid through the scaling parameter f . Another parameter is the fraction of the

Sun that is covered by the horizontal fields, F_{sur} . As shown in Fig. 2, a reasonable choice of $f \simeq 0.7$ (consistent with simulation results [56]) combined with $F_{\text{sur}} \simeq 0.3$ could explain the HAWC 6-yr observations. While there is some degeneracy between f and F_{sur} , Hinode observations have shown that there are no large-scale time dependences for the horizontal fields in the internetwork regions from 2008 to 2013 [57,58], suggesting that f could be relatively time independent. On the other hand, F_{sur} should be higher in solar minima compared to solar maxima. This would be consistent with HAWC observation in two epochs. We leave the detailed physical interpretation for future work.

Our model has some shortcomings that can only be addressed with detailed numerical investigations with more realistic setups, before a serious physical interpretation on solar magnetism should be attempted. For instance, the details of particle shower development in the Sun under magnetic fields can only be tackled in a numerical setup. In addition, we assume that the particles traverse the same convection cell with the coherent field direction, which is probably a good assumption for small-nadir trajectories, but less so for large-nadir ones. Particles traveling across cells may encounter vertical fields in cell boundaries and different horizontal field orientations in other cells, which would likely prolong the time the particle stays in the photosphere, and could soften the spectrum at high energies. A more realistic convection cell model with different sizes and magnetic field orientations would be needed to address this.

We focus on the TeV energy range, which allows us to ignore effects from weaker magnetic fields. To fully explain the solar gamma-ray observation from TeV down to the GeV energy range, a time-dependent comprehensive model that includes solar modulations, corona magnetic fields, and network magnetic fields is likely necessary. Notably, Sun shadow observations might be used to isolate the effect of corona magnetic fields [71–75]. With such a comprehensive model, it may be possible to address other observables, such as time dependence [4,5,7,9] and surface morphology [6,8].

The understanding of TeV solar gamma rays is also important for predicting solar atmospheric neutrino flux [76–79], which could be detectable in neutrino telescopes [80,81] and has strong implications for new physics searches (e.g., see Refs. [82–84]).

In summary, we show that TeV gamma rays could be a novel probe for the magnetic fields and the fluid dynamics just under the photosphere, which are difficult to probe with traditional observational methods. This will be enabled by continued monitoring of the Sun by HAWC, LHAASO, and SWGO [85], as well as closer theory-data connection with future numerical work on the solar gamma-ray production.

Some of the results in this Letter have been derived using the HEALPY [66] and HEALPix [65] package [86].

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- [1] D. Seckel, Todor Stanev, and T. K. Gaisser, Signatures of cosmic-ray interactions on the solar surface, *Astrophys. J.* **382**, 652 (1991).
 - [2] Elena Orlando and Andrew W. Strong, Gamma-ray emission from the solar halo and disk: A study with EGRET data, *Astron. Astrophys.* **480**, 847 (2008).
 - [3] A. A. Abdo *et al.* (Fermi-LAT Collaboration), Fermi-LAT observations of two gamma-ray emission components from the quiescent sun, *Astrophys. J.* **734**, 116 (2011).
 - [4] Kenny C. Y. Ng, John F. Beacom, Annika H. G. Peter, and Carsten Rott, First observation of time variation in the solar-disk gamma-ray flux with Fermi, *Phys. Rev. D* **94**, 023004 (2016).
 - [5] Qing-Wen Tang, Kenny C. Y. Ng, Tim Linden, Bei Zhou, John F. Beacom, and Annika H. G. Peter, Unexpected dip in the solar gamma-ray spectrum, *Phys. Rev. D* **98**, 063019 (2018).
 - [6] Tim Linden, Bei Zhou, John F. Beacom, Annika H. G. Peter, Kenny C. Y. Ng, and Qing-Wen Tang, Evidence for a new component of high-energy solar gamma-ray production, *Phys. Rev. Lett.* **121**, 131103 (2018).
 - [7] Tim Linden, John F. Beacom, Annika H. G. Peter, Benjamin J. Buckman, Bei Zhou, and Guanying Zhu, First observations of solar disk gamma rays over a full solar cycle, *Phys. Rev. D* **105**, 063013 (2022).
 - [8] Bruno Arsioli and Elena Orlando, Yet another sunshine mystery: Unexpected asymmetry in GeV emission from the solar disk, *Astrophys. J.* **962**, 52 (2024).
 - [9] A. Albert *et al.* (HAWC Collaboration), Discovery of gamma rays from the quiescent sun with HAWC, *Phys. Rev. Lett.* **131**, 051201 (2023).
 - [10] M. N. Mazziotta, P. De La Torre Luque, L. Di Venere, A. Fassò, A. Ferrari, F. Loparco, P. R. Sala, and D. Serini, Cosmic-ray interactions with the Sun using the FLUKA code, *Phys. Rev. D* **101**, 083011 (2020).
 - [11] Zhe Li, Kenny C. Y. Ng, Songzhan Chen, Yuncheng Nan, and Huihai He, Simulating gamma-ray production from cosmic rays interacting with the solar atmosphere in the presence of coronal magnetic fields*, *Chin. Phys. C* **48**, 045101 (2024).

- [12] Kenneth H. Schatten, John M. Wilcox, and Norman F. Ness, A model of interplanetary and coronal magnetic fields, *Sol. Phys.* **6**, 442 (1969).
- [13] Martin D. Altschuler and Gordon Newkirk, Magnetic fields and the structure of the solar corona. I: Methods of calculating coronal fields, *Sol. Phys.* **9**, 131 (1969).
- [14] J. T. Hoeksema, Structure and evolution of the large scale solar and heliospheric magnetic fields, Ph.D. thesis, Stanford University, CA, 1984.
- [15] Y. M. Wang and N. R. Sheeley Jr., On potential field models of the solar corona, *Astrophys. J.* **392**, 310 (1992).
- [16] Miguel Gutiérrez and Manuel Masip, The Sun at TeV energies: Gammas, neutrons, neutrinos and a cosmic ray shadow, *Astropart. Phys.* **119**, 102440 (2020).
- [17] Miguel Gutiérrez, Manuel Masip, and Sergio Muñoz, The solar disk at high energies, *Astrophys. J.* **941**, 86 (2022).
- [18] Prabir Banik, Arunava Bhadra, and Sanjay K. Ghosh, Sun as a cosmic ray TeVatron, [arXiv:2305.17086](https://arxiv.org/abs/2305.17086).
- [19] Hugh S. Hudson, Alec MacKinnon, Mikolaj Szydlarski, and Mats Carlsson, Cosmic ray interactions in the solar atmosphere, *Mon. Not. R. Astron. Soc.* **491**, 4852 (2020).
- [20] Jung-Tsung Li, John F. Beacom, Spencer Griffith, and Annika H. G. Peter, Small-scale magnetic fields are critical to shaping solar gamma-ray emission, *Astrophys. J.* **961**, 167 (2024).
- [21] Jung-Tsung Li, Mahboubeh Asgari-Targhi, John F. Beacom, and Annika H. G. Peter, Convection-driven multi-scale magnetic fields determine the observed solar-disk gamma rays, [arXiv:2508.14154](https://arxiv.org/abs/2508.14154).
- [22] Eleonora Puzzoni, Federico Fraschetti, József Kóta, and Joe Giacalone, Role of magnetic arcades in explaining the puzzle of the gamma-ray emission from the solar disk, *Astrophys. J.* **973**, 118 (2024).
- [23] Eleonora Puzzoni, Federico Fraschetti, Jozsef Kota, and Joe Giacalone, Solar disk gamma-ray emission via synthetic magnetic field from photosphere to low corona, *Astrophys. J. Lett.* **989**, L3 (2025).
- [24] R. Ramaty, B. Kozlovsky, and R. E. Lingenfelter, Solar gamma rays, *Space Sci. Rev.* **18**, 341 (1975).
- [25] R. J. Murphy, C. D. Dermer, and R. Ramaty, High-energy processes in solar flares, *Astrophys. J. Suppl. Ser.* **63**, 721 (1987).
- [26] Benzion Kozlovsky, Ronald J. Murphy, and Reuven Ramaty, Nuclear deexcitation gamma-ray lines from accelerated particle interactions, *Astrophys. J. Suppl. Ser.* **141**, 523 (2002).
- [27] Nicola Omodei, Melissa Pesce-Rollins, Francesco Longo, Alice Allafort, and Säm Krucker, Fermi-LAT observations of the 2017 September 10 solar flare, *Astrophys. J. Lett.* **865**, L7 (2018).
- [28] G. H. Share, R. J. Murphy, S. M. White, A. K. Tolbert, B. R. Dennis, R. A. Schwartz, D. F. Smart, and M. A. Shea, Characteristics of late-phase > 100 MeV gamma-ray emission in solar eruptive events, *Astrophys. J.* **869**, 182 (2018).
- [29] M. Ackermann *et al.* (Fermi-LAT Collaboration), High-energy gamma-ray emission from solar flares: Summary of Fermi large area telescope detections and analysis of two M-class flares, *Astrophys. J.* **787**, 15 (2014).
- [30] Elena Orlando and Andrew Strong, Gamma-rays from halos around stars and the Sun, *Astrophys. Space Sci.* **309**, 359 (2007).
- [31] Igor V. Moskalenko, Troy A. Porter, and Seth W. Digel, Inverse Compton scattering on solar photons, heliospheric modulation, and neutrino astrophysics, *Astrophys. J.* **652**, L65 (2006); **664**, L143(E) (2007).
- [32] Bei Zhou, Kenny C. Y. Ng, John F. Beacom, and Annika H. G. Peter, TeV solar gamma rays from cosmic-ray interactions, *Phys. Rev. D* **96**, 023015 (2017).
- [33] Elena Orlando and Andrew Strong, StellarICS: Inverse Compton emission from the quiet Sun and stars from keV to TeV, *J. Cosmol. Astropart. Phys.* **04** (2021) 004.
- [34] Anderson C. M. Lai and Kenny C. Y. Ng, Anisotropic photon and electron scattering without ultrarelativistic approximation, *Phys. Rev. D* **107**, 063026 (2023).
- [35] Hong-Gang Yang, Yu Gao, Yin-Zhe Ma, and Roland M. Crocker, Solar gamma ray probe of local cosmic ray electrons, *Phys. Rev. D* **108**, L061304 (2023).
- [36] Vahe' Petrosian, Elena Orlando, and Andrew Strong, Transport of cosmic-ray electrons from 1 au to the Sun, *Astrophys. J.* **943**, 21 (2023).
- [37] Elena Orlando, Vahe' Petrosian, and Andrew Strong, A new component from the quiet Sun from radio to gamma rays: Synchrotron radiation by galactic cosmic-ray electrons, *Astrophys. J.* **943**, 173 (2023).
- [38] Norman H. Bakera and Stefan Temesváry, Tables of Convective Stellar Envelope Models (Institute for Space Studies, 1966), https://books.google.com/books/about/Tables_of_Convective_Stellar_Envelope_Mo.html?id=tsyHNAAACAAJ&redir_esc=y.
- [39] Jorge E. Vernazza, Eugene H. Avrett, and Rudolf Loeser, Structure of the solar chromosphere. Basic computations and summary of the results, *Astrophys. J.* **184**, 605 (1973).
- [40] S. R. Kelner, Felex A. Aharonian, and V. V. Bugayov, Energy spectra of gamma-rays, electrons and neutrinos produced at proton-proton interactions in the very high energy regime, *Phys. Rev. D* **74**, 034018 (2006); **79**, 039901(E) (2009).
- [41] S. Wedemeyer-Bohm, A. Lagg, and A. Nordlund, Coupling from the photosphere to the chromosphere and the corona, *Space Sci. Rev.* **144**, 317 (2009).
- [42] Thomas Wiegmann, Julia K. Thalmann, and Sami K. Solanki, The magnetic field in the solar atmosphere, *Astron. Astrophys. Rev.* **22**, 78 (2014).
- [43] Sami K. Solanki, Bernd Inhester, and Manfred Schüssler, The solar magnetic field, *Rep. Prog. Phys.* **69**, 563 (2006).
- [44] J. Sánchez Almeida and M. Martínez González, The magnetic fields of the quiet Sun, in *Solar Polarization 6*, Astronomical Society of the Pacific Conference Series Vol. 437, edited by J. R. Kuhn, D. M. Harrington, H. Lin, S. V. Berdyugina, J. Trujillo-Bueno, S. L. Keil, and T. Rimmele (Astronomical Society of the Pacific, San Francisco, 2011), p. 451, <https://ui.adsabs.harvard.edu/abs/2011ASPC..437..451S/abstract>.
- [45] Javier Trujillo Bueno, N. Shchukina, and A. Asensio Ramos, A substantial amount of hidden magnetic energy in the quiet Sun, *Nature (London)* **430**, 326 (2004).
- [46] Luis Bellot Rubio and David Orozco Suárez, Quiet Sun magnetic fields: An observational view, *Living Rev. Solar Phys.* **16**, 1 (2019).
- [47] Matthias Rempel, Tanayveer Bhatia, Luis Bellot Rubio, and Maarit J. Korpi-Lagg, Small-scale dynamos: From idealized

- models to solar and stellar applications, *Space Sci. Rev.* **219**, 36 (2023).
- [48] B. W. Lites, K. D. Leka, A. Skumanich, V. Martinez Pillet, and T. Shimizu, Small-scale horizontal magnetic fields in the solar photosphere, *Astrophys. J.* **460**, 1019 (1996).
- [49] D. Orozco Suarez *et al.*, Quiet Sun internetwork magnetic fields from the inversion of Hinode measurements, *Astrophys. J. Lett.* **670**, L61 (2007).
- [50] B. W. Lites, M. Kubo, H. Socas-Navarro, T. Berger, Z. Frank, R. Shine, T. Tarbell, A. Title, K. Ichimoto, Y. Katsukawa, S. Tsuneta, Y. Suematsu, T. Shimizu, and S. Nagata, The horizontal magnetic flux of the quiet-Sun internetwork as observed with the hinode spectro-polarimeter, *Astrophys. J.* **672**, 1237 (2008).
- [51] M. Schuessler and A. Voegler, Strong horizontal photospheric magnetic field in a surface dynamo simulation, *Astron. Astrophys.* **481**, L5 (2008).
- [52] O. Steiner, R. Rezaei, W. Schaffenberger, and S. Wedemeyer-Böhm, The horizontal internetwork magnetic field: Numerical simulations in comparison to observations with hinode, *Astrophys. J. Lett.* **680**, L85 (2008).
- [53] O. Steiner, Magnetic coupling in the quiet solar atmosphere, in *Magnetic Coupling between the Interior and Atmosphere of the Sun*, Astrophysics and Space Science Proceedings Vol. 19 (2010), pp. 166–185, [arXiv:0904.2026](https://arxiv.org/abs/0904.2026).
- [54] Marius Potgieter, Solar modulation of cosmic rays, *Living Rev. Solar Phys.* **10**, 3 (2013).
- [55] Jung-Tsung Li, John F. Beacom, and Annika H. G. Peter, Galactic cosmic-ray propagation in the inner heliosphere: Improved force-field model, *Astrophys. J.* **937**, 27 (2022).
- [56] M. Rempel, Numerical simulations of quiet Sun magnetism: On the contribution from a small-scale dynamo, *Astrophys. J.* **789**, 132 (2014).
- [57] Bruce W. Lites, Rebecca Centeno, and Scott W. McIntosh, The solar cycle dependence of the weak internetwork flux, *Publ. Astron. Soc. Jpn.* **66**, S4 (2014).
- [58] Khalid Al-Janabi *et al.* (Hinode Review Team), Achievements of Hinode in the first eleven years, *Publ. Astron. Soc. Jpn.* **71**, R1 (2019).
- [59] W. Unno, M. A. Kondo, and D. R. Xiong, Solar convection zone given by nonlocal mixing-length theory, *Publ. Astron. Soc. Jpn.* **37**, 235 (1985).
- [60] L. Deng, D. R. Xiong, and K. L. Chan, An anisotropic nonlocal convection theory, *Astrophys. J.* **643**, 426 (2006).
- [61] Da-run Xiong, Convection theory and relevant problems in stellar structure, evolution and pulsation stability part I. Convection theory and structure of convection zone and stellar evolution, *Front. Astron. Space Sci.* **7**, 95 (2021).
- [62] R. F. Stein and Å. Nordlund, Simulations of solar granulation. I. General properties, *Astrophys. J.* **499**, 914 (1998).
- [63] Hideyuki Hotta, Yuto Bekki, Laurent Gizon, Quentin Noraz, and Mark Rast, Dynamics of large-scale solar flows, *Space Sci. Rev.* **219**, 77 (2023).
- [64] Mark S. Miesch, Nicholas A. Featherstone, Matthias Rempel, and Regner Trampedach, On the amplitude of convective velocities in the deep solar interior, *Astrophys. J.* **757**, 128 (2012).
- [65] K. M. Górski, E. Hivon, A. J. Banday, B. D. Wandelt, F. K. Hansen, M. Reinecke, and M. Bartelmann, HEALPix: A framework for high-resolution discretization and fast analysis of data distributed on the sphere, *Astrophys. J.* **622**, 759 (2005).
- [66] Andrea Zonca, Leo Singer, Daniel Lenz, Martin Reinecke, Cyrille Rosset, Eric Hivon, and Krzysztof Gorski, HEALPY: Equal area pixelization and spherical harmonics transforms for data on the sphere in Python, *J. Open Source Software* **4**, 1298 (2019).
- [67] T. K. Gaisser, Cosmic rays and particle physics (Cambridge University Press, Cambridge, UK, 1990). <https://ui.adsabs.harvard.edu/abs/2016crpp.book.....G/abstract>
- [68] Paolo Lipari and Silvia Vernetto, The shape of the cosmic ray proton spectrum, *Astropart. Phys.* **120**, 102441 (2020).
- [69] Masaki Mori, Nuclear enhancement factor in calculation of Galactic diffuse gamma-rays: A new estimate with DPMJET-3, *Astropart. Phys.* **31**, 341 (2009).
- [70] Michael Kachelriess, Igor V. Moskalenko, and Sergey S. Ostapchenko, Nuclear enhancement of the photon yield in cosmic ray interactions, *Astrophys. J.* **789**, 136 (2014).
- [71] M. Amenomori *et al.* (Tibet ASgamma Collaboration), Probe of the solar magnetic field using the “cosmic-ray shadow” of the Sun, *Phys. Rev. Lett.* **111**, 011101 (2013).
- [72] M. Amenomori *et al.* (Tibet AS γ Collaboration), Evaluation of the interplanetary magnetic field strength using the cosmic-ray shadow of the Sun, *Phys. Rev. Lett.* **120**, 031101 (2018).
- [73] M. G. Aartsen *et al.* (IceCube Collaboration), Detection of the temporal variation of the Sun’s cosmic ray shadow with the IceCube detector, *Astrophys. J.* **872**, 133 (2019).
- [74] Julia Becker Tjus, Paolo Desiati, Niklas Döpper, Horst Fichtner, Jens Kleimann, Mike Kroll, and Frederik Tenholt, Cosmic-ray propagation around the Sun—investigating the influence of the solar magnetic field on the cosmic-ray Sun shadow, *Astron. Astrophys.* **633**, A83 (2020).
- [75] M. G. Aartsen *et al.* (IceCube Collaboration), Measurements of the time-dependent cosmic-ray Sun shadow with seven years of IceCube data: Comparison with the Solar cycle and magnetic field models, *Phys. Rev. D* **103**, 042005 (2021).
- [76] G. Ingelman and M. Thunman, High-energy neutrino production by cosmic ray interactions in the sun, *Phys. Rev. D* **54**, 4385 (1996).
- [77] Kenny C. Y. Ng, John F. Beacom, Annika H. G. Peter, and Carsten Rott, Solar atmospheric neutrinos: A new neutrino floor for dark matter searches, *Phys. Rev. D* **96**, 103006 (2017).
- [78] C. A. Argüelles, G. de Wasseige, A. Fedynitch, and B. J. P. Jones, Solar atmospheric neutrinos and the sensitivity floor for solar dark matter annihilation searches, *J. Cosmol. Astropart. Phys.* **07** (2017) 024.
- [79] Joakim Edsjo, Jessica Elevant, Rikard Enberg, and Carl Niblaeus, Neutrinos from cosmic ray interactions in the Sun, *J. Cosmol. Astropart. Phys.* **06** (2017) 033.
- [80] M. G. Aartsen *et al.* (IceCube Collaboration), Searches for neutrinos from cosmic-ray interactions in the Sun using seven years of IceCube data, *J. Cosmol. Astropart. Phys.* **02** (2021) 025.
- [81] Joshua Villarreal *et al.* (IceCube Collaboration), Recent progress in solar atmospheric neutrino searches with IceCube, *Proc. Sci. ICRC2021* (2021) 1174 [[arXiv:2107.13696](https://arxiv.org/abs/2107.13696)].

- [82] M.G. Aartsen *et al.* (IceCube Collaboration), Search for annihilating dark matter in the Sun with 3 years of IceCube data, *Eur. Phys. J. C* **77**, 146 (2017); **79**, 214(E) (2019).
- [83] Rebecca K. Leane, Kenny C. Y. Ng, and John F. Beacom, Powerful solar signatures of long-lived dark mediators, *Phys. Rev. D* **95**, 123016 (2017).
- [84] Carl Niblaeus, Ankit Beniwal, and Joakim Edsjo, Neutrinos and gamma rays from long-lived mediator

decays in the Sun, *J. Cosmol. Astropart. Phys.* **11** (2019) 011.

- [85] P. Abreu *et al.*, The southern wide-field gamma-ray observatory (SWG0): A next-generation ground-based survey instrument for VHE gamma-ray astronomy, [arXiv:1907.07737](https://arxiv.org/abs/1907.07737).
- [86] <http://healpix.sourceforge.net>

End Matter

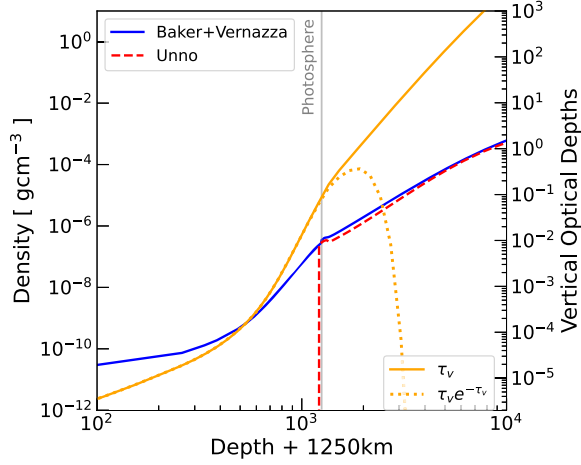


FIG. 3. Solar density model from Refs. [38,39] (in agreement with Ref. [59] below the photosphere). In orange lines, we show the vertical optical depths, showing that a few hundred km below the photosphere is the most optimal depth for producing solar gamma rays.

Appendix A: Density—Figure 3 shows the density [38,39] as a function of depth (d). Both τ_v and $\tau_v e^{-\tau_v}$ are shown with the right axis of Fig. 3. We can see that the efficiency factor peaks at 10^2 – 10^3 km depth.

Appendix B: Magnetic field models—Figure 4 shows the magnitude of the magnetic fields used in our horizontal field model, as well as the flow speed model.

Appendix C: Orbit simulations and the efficiency factor—Orbit simulation samples: Figure 5 shows a sample of simulated particle trajectories obtained. The $|B(-1250)| = 1$ G model is used with $f = 1$ and the particles have an energy of 10 TeV.

The efficiency factor: As discussed in the main text, we take the approximation that the trajectories are determined by the magnetic fields alone and neglect the effects of interactions. We can then approximate the interaction efficiency by the combination of three factors. The first one is the proton interaction probability, which is $\tau = \int_L n \sigma_{pp} d\ell$, where σ_{pp} is the hadron cross section

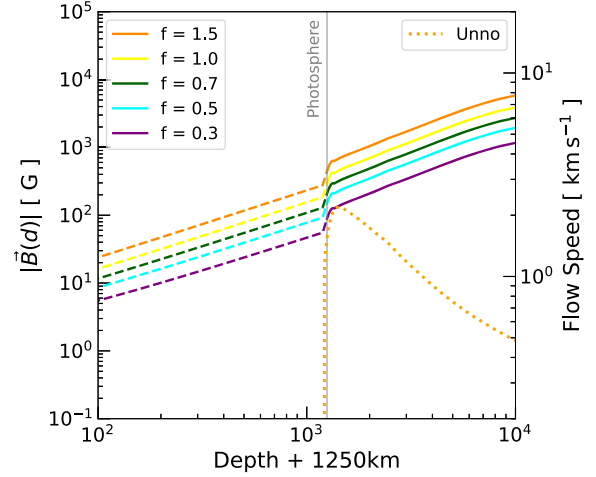


FIG. 4. (Left axis) Magnetic field models used in this calculation. The photosphere is located at depth = 0. Above the photosphere, the $|B(-1250)| = 1$ G case (dashed lines) extrapolates the field to 1 G, while the $|B(< 0)| = 0$ case sets the field to be zero. (Right axis) The flow speed model used in this work from Ref. [59].

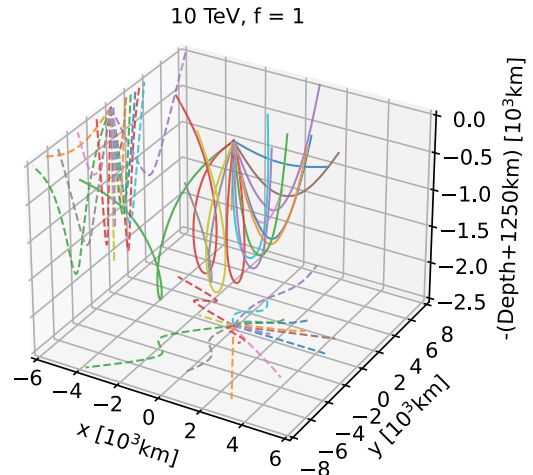


FIG. 5. An example of the orbit simulation, showing 15 of the 368 tracks used for the calculation for the $|B(-1250)| = 1$ G case with $f = 1$ and 10 TeV proton energy. The field lines are pointed at the $+y$ direction. The dashed lines are the tracks projected to the xy and yz planes, respectively.

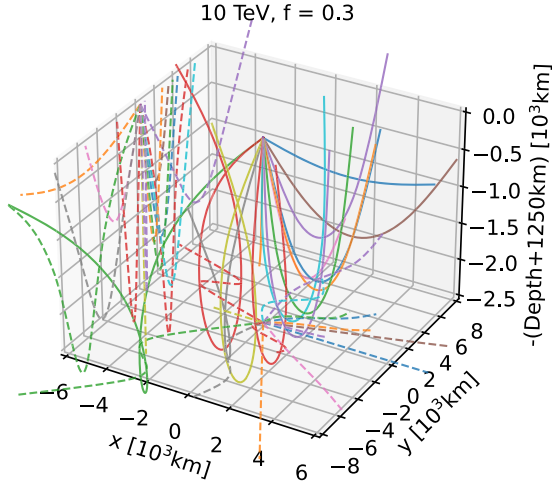


FIG. 6. Same as Fig. 5, but for the $f = 0.3$ case. Note that the scale of the plot remained the same for easy comparison.

and L here is the total path length the proton travels. The second factor is the proton attenuation, which is $\exp(-\int_{L_1} n\sigma_{pp}d\ell)$, where L_1 is the proton track before it interacts and produces a photon. The third factor is the photon attenuation, which is $\exp(-\int_{L_2} n\sigma_{p\gamma}d\ell)$, where $\sigma_{p\gamma}$ is the photon attenuation cross section, and L_2 is the photon track from the production point to escape, which we approximate as the remaining track of the proton.

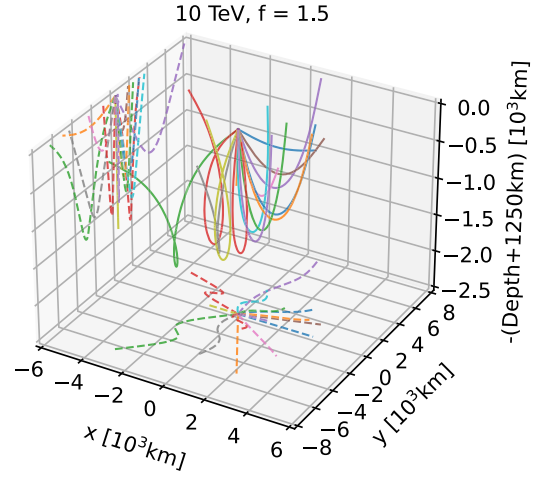


FIG. 7. Same as Fig. 5, but for the $f = 1.5$ case. Note that the scale of the plot remained the same for easy comparison.

The total efficiency factor is then

$$\mathcal{T} = \tau \times \exp\left(-\int_{L_1} n\sigma_{pp}d\ell\right) \exp\left(-\int_{L_2} n\sigma_{p\gamma}d\ell\right) \simeq \tau e^{-\tau}. \quad (\text{C1})$$

The “ $\simeq$ ” follows from the photon track assumption, as $L = L_1 + L_2$, and that hadron cross section is comparable to the photon attenuation cross section.