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Multi-PeV Signals from a New Astrophysical Neutrino Flux beyond the Glashow Resonance

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The IceCube neutrino discovery was punctuated by three showers with $E_\nu \approx 1$–2 PeV. Interest is intense in possible fluxes at higher energies, though a deficit of $E_\nu \approx 6$ PeV Glashow resonance events implies a spectrum that is soft and/or cutoff below ~few PeV. However, IceCube recently reported a through-going track depositing 2.6 ± 0.3 PeV. A muon depositing so much energy can imply $E_{\nu_\mu} \gtrsim 10$ PeV. Alternatively, we find a tau can deposit this much energy, requiring $E_{\nu_\tau} \sim 10\times$ higher. We show that extending soft spectral fits from TeV-PeV data is unlikely to yield such an event, while an $\sim E_\nu^{-2}$ flux predicts excessive Glashow events. These instead hint at a new flux, with the hierarchy of ν_μ and ν_τ energies implying astrophysical neutrinos at $E_\nu \sim 100$ PeV if a tau. We address implications for ultrahigh-energy cosmic-ray and neutrino origins.

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Introduction.—The discovery of astrophysical neutrinos by IceCube [1–9] allows for new characterizations of the high-energy universe. Neutrinos can arise from cosmic-ray interactions within sources (e.g., [10–12]) and with extragalactic photon backgrounds (e.g., [13–20]). The fluxes vary greatly depending on assumptions, and data may yield insight into the inner workings of ultrahigh-energy cosmic-ray (UHECR) accelerators [21] or unexpected physical effects [22,23].

Along with dozens of ~10–100 TeV events, IceCube detected three contained-vertex showers with deposited energy $E_{\rm dep} \approx 1$–2 PeV (likely with $E_\nu \approx E_{\rm dep}$) [1,3]. The neutrino spectrum indicated below PeV energies is significantly softer than E_ν^{-2}, reaching a sharp upper limit at $E_\nu \gtrsim 5$ PeV (5×10^6 GeV; Fig. 1) due to a lack of ~6 PeV showers from on shell $\bar{\nu}_e e \to W^-$ Glashow resonance [24] scattering.

However, IceCube recently reported an upgoing through-going track depositing $E_{\rm dep} = 2.6 \pm 0.3$ PeV [7–9]. We will see that the required E_ν to produce this event is $\gg E_{\rm dep}$, significantly larger than even the PeV shower events. This highest-energy event raises important questions concerning astrophysical neutrinos, including, subtly, what flavor of neutrino produces such a track?

We first consider the standard assumption that the track is a muon. We show (i) soft astrophysical neutrino spectra (e.g., $E_\nu^{-2.6}$) are unlikely to produce such muons, and (ii) harder spectra (e.g., $\sim E_\nu^{-2}$) overproduce Glashow shower rates. This motivates us to better characterize the super-Glashow energy regime. We examine heuristic spectral models covering a variety of production scenarios and their expected signals.

We also consider an intriguing possibility of a track left by a tau lepton. Though detection methods for ν_τ have been discussed over many years (e.g., [35–46]), no distinct τ-like

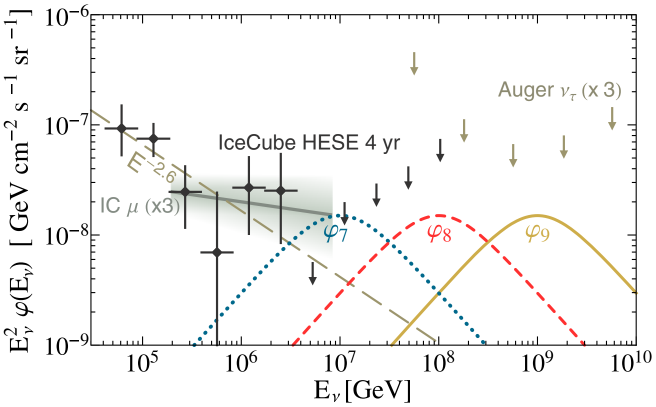

FIG. 1. IceCube 4 yr contained HESE data [5] (which do *not* include the $E_{\rm dep} = 2.6$ PeV track event), IceCube 6 yr ν_μ band (assumes the PeV track is a muon [9]), and Auger ν_τ upper limits [25]. Also, an $E_\nu^{-2.6}$ flux (long dashed) and extragalactic spectral models peaking near 10^7 GeV (φ_7; dotted), 10^8 GeV (φ_8; dashed), and 10^9 GeV (φ_9; solid). Models φ_7 and φ_8 resemble BL Lac AGN models, while rescaled combinations of φ_7 and φ_9 approximate cosmogenic neutrinos (see [26]). All data and fluxes are summed over flavors (and $\nu + \bar{\nu}$), assuming $\varphi_{\nu_e} = \varphi_{\nu_\mu} = \varphi_{\nu_\tau}$ and $\varphi_\nu = \varphi_{\bar{\nu}}$.

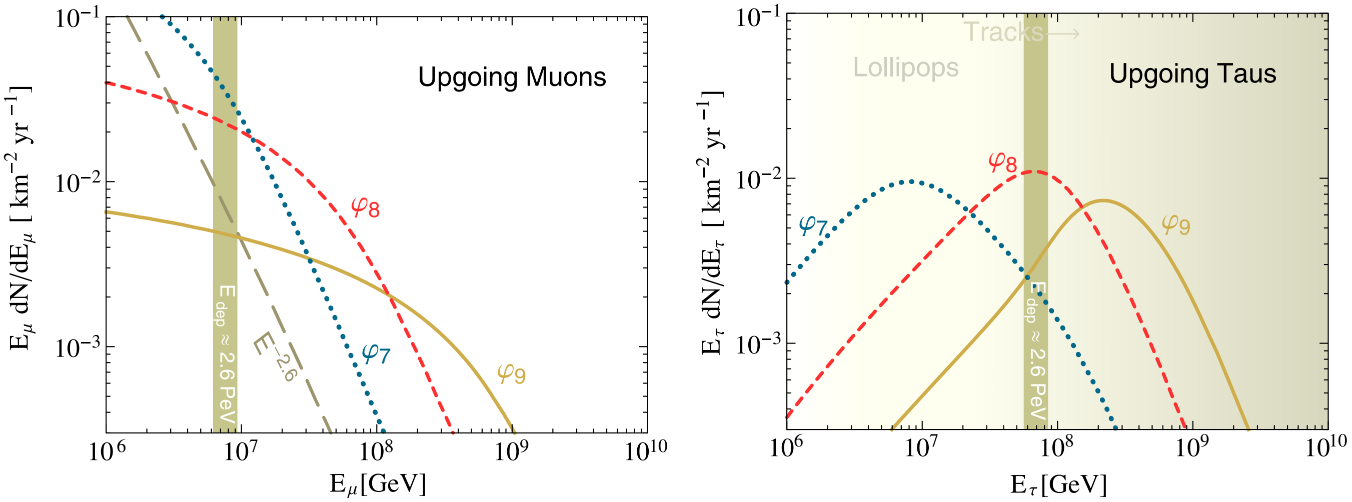

FIG. 2. (Left) Spectra of upgoing muons (with E_μ entering detector) from neutrino models in Fig. 1. To deposit ~2.6 PeV suggests $E_\mu \gtrsim 8$ PeV (vertical band), with a $\gtrsim$10 PeV energy of the ν_μ. (Right) The same for taus, denoting ranges of dominant entering-tau event topologies. Through-going tau deposition of ~2.6 PeV suggests $E_\tau \gtrsim 70$ PeV (vertical band), a much larger E_ν than a muon depositing the same energy.

event has yet been identified by IceCube [47]. Energy deposition by taus within the detector leads to many possible signals (see Fig. 2 and [46]). However, through-going tau tracks are little discussed and energy-loss stochasticity presents difficulty in individually identifying PeV tracks as muons or very-long-lived taus with decay length $\gamma_\tau c\tau_\tau \approx (E_\tau/20\ \text{PeV})$ km.

For either scenario, we deduce that a harder, higher-energy astrophysical neutrino flux than previously measured is more likely present. A tau track traversing the ~1 km detector without decaying would imply a much higher parent neutrino energy and give an unexpected window into astrophysical neutrinos at ~100 PeV. We address differences in the energy spectrum and angular distribution of tau and muon events and discuss implications for outstanding problems in UHECR and neutrino physics.

Multi-PeV tracks.—Analytic methods have been presented for charged-current (CC) and neutral-current (NC) showerlike event rates in IceCube [48,49] and muon fluxes from ν_μ interactions [50–52], though these cannot be directly applied to long-lived taus.

We determine the tau flux spectrum dN_τ/dE_τ in ice using a volumetric source term $Q(E_\tau)$ for taus produced by ν_τ

$$\frac{d}{dE_\tau}\left(b_\tau(E_\tau)\frac{dN_\tau}{dE_\tau}\right)+\frac{m_\tau}{c\tau_\tau E_\tau}\frac{dN_\tau}{dE_\tau}=Q(E_\tau), \qquad (1)$$

with tau energy loss $b_\tau(E_\tau)=dE_\tau/dX$, mass m_τ, and lifetime τ_τ. We find $b_\tau(E_\tau)=b_0\rho(E_\tau/\text{GeV})^{\kappa_\tau}$, within density ρ with $b_0=-4.6\times10^{-9}\,\text{GeV}\,\text{cm}^2\,\text{g}^{-1}$ and $\kappa_\tau=5/4$, adequately approximates parametrized Monte Carlo results of [45] in our E_τ range of interest. This form is simple to implement in solving Eq. (1) via an integrating factor solution (e.g., [53]). After simplification, we obtain

$$\frac{dN_\tau}{dE_\tau}=\frac{1}{-b_\tau(E_\tau)}\exp\left(\frac{m_\tau}{c\tau_\tau\kappa_\tau b_\tau(E_\tau)}\right) \times\int_{E_\tau}^{E^{\max}}dEQ(E)\exp\left(-\frac{m_\tau}{c\tau_\tau\kappa_\tau b_\tau(E)}\right). \qquad (2)$$

For muons, the exponential terms vanish ($\tau_\mu \gg \tau_\tau$) and $b_\mu(E_\mu)=-\alpha_\mu-\beta_\mu E_\mu$, using a stochastic loss fit [54]: $\alpha_\mu = 2.49\times10^{-3}\ \text{GeV}\,\text{cm}^2\,\text{g}^{-1}$ and $\beta_\mu = 4.22\times10^{-6}\ \text{cm}^2\,\text{g}^{-1}$.

We first consider downgoing events, where fluxes are simpler. At PeV and greater energies, the differential νN CC cross section $d\sigma_{\text{CC}}/dy$ is strongly peaked at $y=0$ [55]. We use $E_\tau=\langle 1-y\rangle E_\nu$, approximating $\langle 1-y\rangle = 0.8 = q$ (ignoring weak E_ν dependence [55]),

$$Q(E_\tau)\approx N_A\rho\varphi_\tau(E_\tau/q)\sigma_{\text{CC}}(E_\tau/q)/q, \qquad (3)$$

where $N_A\rho$ is the molar density of ice. We find this adequately approximates the birth spectrum of taus (and muons) using the differential cross section.

$E^{\max}$ relates the energy at the detector to a birth energy at the surface. The particle range from arbitrary energy losses can be inverted (see [56]), though the $b(E)$ above allow for analytic solutions. For taus, $E_\tau^{\max}=[E_\tau^{-1/4}+b_0\ell(\theta)/4]^{-4}$, where $\ell(\theta)$ is the column depth to the surface at θ in centimeters water equivalent (we assume a 2 km depth). For muons, $E_\mu^{\max}=\{\exp[\beta_\mu\ell(\theta)](\alpha_\mu+\beta_\mu E_\mu)-\alpha_\mu\}/\beta_\mu$.

For upgoing fluxes, effectively $E^{\max}\to\infty$. We use $\ell_\oplus(\theta)$ [57] for attenuation, $e^{-\tau_\oplus}$, with $\tau_\oplus = N_A\ell_\oplus(\theta)\sigma_{\text{tot}}(E_\nu)$. For ν_e and ν_μ, $\sigma_{\text{tot}}=\sigma_{\nu N}$, with $\sigma_{\text{tot}}=\sigma_{\bar\nu N}$ for $\bar\nu_\mu$. For $\bar\nu_e$, we must add $\sigma_{\bar\nu_e e}$, which practically excludes a $W^-\to\mu^-\bar\nu_\mu$ origin of the 2.6 PeV track.

Upgoing ν_τ fluxes are complicated by regeneration, decays of taus produced within Earth back into ν_τ. The

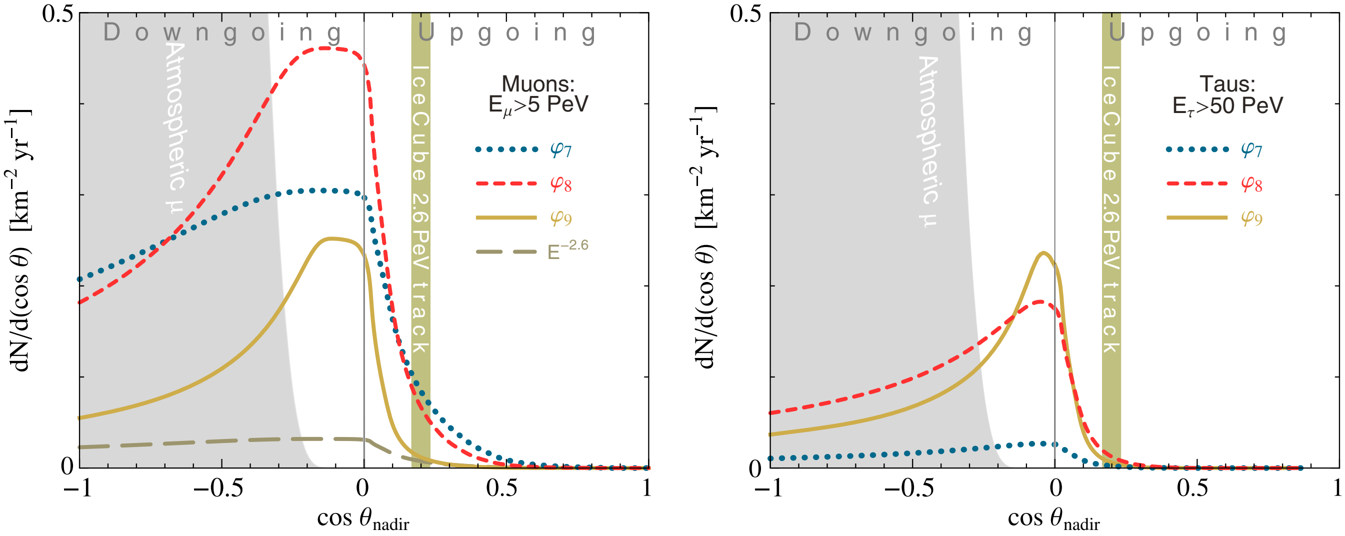

FIG. 3. (Left) Angular distribution of $E_\mu > 5$ PeV muons for neutrino models in Fig. 1. (Right) The same for $E_\tau > 50$ PeV taus. The cutoffs towards larger upgoing angles are due to Earth attenuation, while the decline to larger downgoing angles is due to the finite ice depth. Both are compared to the direction of the track event ($\theta_{\rm nadir} \approx 78.5°$) and background atmospheric muons with $E_\mu > 5$ PeV at the detector (shaded).

total ν_τ number flux is conserved, although the spectrum is distorted towards lower E_{ν_τ}. We estimate the surviving ν_τ flux by converting the interacting fraction for each E_{ν_τ} into a continuous distribution based on [44] (neglecting regenerated ν_μ/ν_e).

Super-Glashow fluxes.—E_ν probed by a fully through-going track event depends on the parent neutrino flavor. If the 2.6 PeV track event is from a muon, estimating $E_{\rm dep}$ in ~1 km by integrating $b_\mu(E_\mu)$ implies $E_\mu \gtrsim 8$ PeV upon entering IceCube (Fig. 2, left).

Compared to a muon with the same energy, the energy loss rate of a tau is much smaller. Depositing $E_{\rm dep} = 2.6$ PeV in ~1 km from $b_\tau(E_\tau)$ alone (i.e., not including any energy from the ν_τ interaction or tau decay, both assumed to occur outside the detector) implies $E_\tau \approx 67$ PeV. The light yield may even be less than a muon of this $E_{\rm dep}$ dependent upon photonuclear losses [46]. Since $E_\tau \gg E_\mu$, the difference in neutrino energy required for a through-going tau track is significant.

Figure 2 shows spectra of muons (left) and taus (right) versus energy entering the detector. We see that an $E_\nu^{-2.6}$ spectrum similar to IceCube fits [4,5] (Fig. 1) implies a very low rate of multi-PeV muons (and a negligible tau rate not shown). A prompt PeV neutrino flux should be steeper with a lower normalization than the $E_\nu^{-2.6}$ model [5,58,59], with $< 0.01\%$ probability of an atmospheric origin for the track event [7–9]. A quantitative comparison with plausible astrophysical models can provide flux levels yielding more adequate rates.

The neutrino spectrum from pp scattering roughly traces the proton spectrum within the source. Spectra from $p\gamma$ scattering, set by protons and target photons above the photopion threshold, tend to be hard prior to being broken and/or cutoff.

We consider spectra to examine super-Glashow neutrino flux levels at Earth described as

$$\varphi_i(E_\nu) = f_i[(E_\nu/E_i)^{\alpha\eta} + (E_\nu/E_i)^{\beta\eta}]^{1/\eta}, \tag{4}$$

with $\alpha = -1$, $\beta = -3$, broken at $E_i = 10^7$, 10^8, and 10^9 GeV, corresponding to models φ_7, φ_8, and φ_9, respectively, with $\eta = -1$ to smoothly mimic source variation and cosmic evolution. One could instead use exponential cutoffs, though the spectral peak, rather than high-energy tail, mostly sets rates.

The φ_i spectra (Fig. 1) use equal peak normalization, though each can be rescaled and/or summed for model-dependent descriptions (e.g., [60–64]). Model φ_7 peaks near E_{ν_μ} for a minimal muon interpretation of the 2.6 PeV track. It also approximates the $p\gamma$ spectral shape in high-energy-peaked BL Lac active galactic nuclei (AGN) models, while φ_8 resembles low-energy-peaked BL Lac [11,61]. Model φ_9 approximates the cosmogenic neutrino spectrum from Greisen-Zatsepin-Kuzmin (GZK) $p\gamma$ interactions on the cosmic microwave background (CMB) and φ_7 approximates lower-energy proton interactions with the extragalactic background light (EBL), which can be combined for various cosmogenic scenarios (see Supplemental Material [26]).

Multi-PeV rates.—Figure 2 shows upgoing muon and tau spectra from φ_i models (Fig. 1). Muon and tau energy deposition are more or less stochastic (e.g., [54,65]). For concreteness, we consider $E_\mu > 5$ PeV and $E_\tau > 50$ PeV

TABLE I. Events in 5 km^2 yr (tracks: $E_\mu > 5$ PeV or $E_\tau > 50$ PeV; upgoing or downgoing within $\cos\theta_{\mathrm{nadir}} > -0.2$) and 5 km^3 yr (showers: $E_{\mathrm{em}} > 5$ PeV).

	$E_\nu^{-2.13}$	$E_\nu^{-2.13}e$	$E_\nu^{-2.6}$	$E_\nu^{-2.6}c$	φ_7	φ_8	φ_9
Upgoing μ	0.05	0.04	0.05	0.02	0.22	0.25	0.08
Down μ	0.05	0.04	0.08	0.01	0.30	0.46	0.25
Upgoing τ	⋯	⋯	⋯	⋯	0.01	0.08	0.07
Down τ	⋯	⋯	⋯	⋯	0.03	0.17	0.19
Track sum	0.1	0.08	0.13	0.03	0.56	0.96	0.59
$\bar{\nu}_e e$ shower	3.0	1.6	1.0	1.0	2.6	0.36	0.04
$\nu_e + \bar{\nu}_e$ CC	0.48	0.28	0.26	0.16	0.87	0.50	0.12
$\nu + \bar{\nu}$ NC	0.01	0.01	0.05	0.0	0.18	0.42	0.16

rates (and in Fig. 3). This still corresponds to tau energies allowing traversal of IceCube before decaying.

Downgoing muons and taus are also relevant from the angular region where background is low enough to safely assume an astrophysical origin. A PeV muon flux is expected from atmospheric cosmic-ray interactions. We estimate this background relating the muon spectrum at the surface to that reaching the detector accounting for energy loss (e.g., [50]). Being concerned with PeV energies and above, we use a spectrum approximating prompt muons [66], $dN/dE_\mu \propto E_\mu^{-3}$, neglecting muon bundles (discussed by IceCube [66]). Figure 3 shows the angular distribution of atmospheric muons with $E_\mu > 5$ PeV at detector depth. The ice effectively eliminates these $\lesssim 10°$ above the "horizon".

Figure 3 compares the angular distributions of $E_\mu > 5$ PeV muons and $E_\tau > 50$ PeV taus. Table I shows rates in 5 km^2 yr, with showers for 5 km^3 yr calculated as in [48,49], including downgoing tracks within $-0.2 < \cos\theta_{\mathrm{nadir}} < 0$. Adding to upgoing rates yields ~0.5–1 one total muon + τ track for each of φ_7, φ_8, and φ_9, while $E_\nu^{-2.6}$ remains small. We see for $\varphi_7 \to \varphi_8 \to \varphi_9$ the tau-to-muon track ratio approaches unity.

The Fig. 2 spectra do not attempt to correct for IceCube energy resolution. While for muons this is fairly straightforward, with reconstruction yielding better resolution at high energies [65], for taus the correspondence between energy and decay length complicates event topologies. Figure 2 illustrates energies characteristic of entering-tau classes: "lollipops," in which a tau enters the detector and decays (i.e., in its last ~1 km), transitioning (via shading) to "tracks" traversing the entire detector. Overestimating E_τ, for instance, does not result in an increase in actual range and would not change the topology.

The energies required to deposit ~2.6 PeV calculated here are indicative. Uncertainty in tau photonuclear losses affects the visible signal [46] and a more thorough investigation should be carried out by IceCube. Even with a more precise calculation, our conclusion will remain valid: the energy of a tau must be much larger than that of a muon in order to deposit the same amount of track energy. The τ-track signal is often neglected (cf., [35]), and even if this track turns out to favor a muon, we encourage optimizing tools for through-going taus.

Implications and conclusions.—IceCube discovered astrophysical neutrinos via an abundance of $\lesssim$PeV events. Even a single highly energetic $E_\nu \gtrsim 10$ PeV event is a first direct hint of neutrinos beyond the Glashow resonance, though a deficit of ~6 PeV Glashow showers precludes a simple power-law description spanning these regimes. A tau track event would give insight into the astrophysical neutrino spectrum approaching $E_\nu \sim 100$ PeV.

Whither Glashow?: A "successful" model should yield sufficient track rates to account for the event depositing 2.6 PeV, without overproducing multi-PeV showers. The rates from our nominal φ_i models are in plausible ranges to source a track event; however, puzzles remain.

φ_7 is the minimal model such to yield $E_\mu \gtrsim 5$ PeV muons, though disfavored at $\gtrsim$99% by Glashow rates unless the normalization is greatly reduced. This would suppress track rates.

φ_8 yields fewer muons than φ_7, though much fewer Glasgow events and a sizable τ-track fraction. We find via a likelihood calculation that φ_8 with a slightly decreased normalization is most favored [26]. A tau track identification would point to such a model.

φ_9, though less likely for ~2.6 PeV tracks, shower rates are small. The upgoing tau spectrum peaks at $E_\tau \sim 200$ PeV. We note an Antarctic Impulsive Transient Antenna (ANITA) 600 ± 400 PeV shower event could be an upgoing tau decaying above the ice, though at ~20° upgoing is perplexing [67]. While φ_9 itself is viable, an accompanying φ_7-like GZK flux [26] disfavors many combinations.

We find that $E_\nu^{-2.6}$ is disfavored at the ~90% level due to low track rates. We also find that Glashow rates (Table I) disfavor the best fit $E_\nu^{-2.13}$ spectrum (cutoff at 10 PeV; Fig. 1) from IceCube muon studies [9] at $\gtrsim$99% [26]. Intermediate models $E_\nu^{-2.13}\exp(-E_\nu/6.9\ \mathrm{PeV})$ or $E_\nu^{-2.6}$ cutoff at 10 PeV perform no better (in Table I models "$E_\nu^{-2.13}e$" and "$E_\nu^{-2.6}c$", respectively; see [26]). Importantly, examining muons alone cannot account for the Glashow shower deficit, while pure power-law fits miss spectral transitions.

In IceCube-Gen2 [68,69], Glashow shower rates can be ~20× higher. Many through-going tau tracks in IceCube would instead be contained, resolving more distinctive topologies [36,41,46]. An extended surface array [70] allows greater veto coverage for downgoing tracks [71]. Such combinations would discriminate [48,49,72,73] between intrinsically small trans-Glashow fluxes and exotic scenarios, such as cooled-muon models yielding neutrino spectra from π^+ decays with $\varphi_\nu \gg \varphi_{\bar{\nu}}$ and negligible Glashow rates (see [48]).

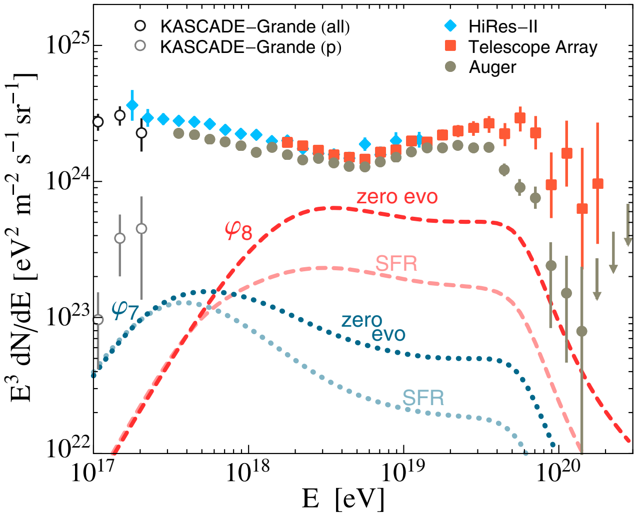

FIG. 4. Ultrahigh-energy cosmic-ray data [79–82] and proton fluxes associated with neutrino models φ_7 (dotted) and φ_8 (dashed) assuming zero (dark) or star formation rate (light) source evolution.

Standard model and beyond: While we quote event rates for all low-background directions, the 2.6 ± 0.3 PeV track comes from a relatively large angle below the horizon. This becomes suspicious if similar tracks are not soon detected from downgoing and shallower angles. We have seen that the cutoffs in Fig. 3 angular distributions are flattened if Earth opacity is decreased. This could arise from new physics or if $\sigma_{\rm CC}(E_\nu)$ saturates at $\gtrsim$PeV due to small-x QCD effects [74].

New-physics effects are also confronted; e.g., for Lorentz invariance violating scenarios [75], the multi-PeV track significantly extends previous bounds.

UHECR connections: For our neutrino emissivities [26], we assume $\pi^\pm\mu^\pm$ decays yield six neutrinos for each neutron of $E_n \sim 20E_\nu$ decaying to a proton with $E_p \approx E_n$ [48]. Taking optically thin sources, such as BL Lacs [61] motivating φ_7 and φ_8, we calculate proton spectra [48], imposing no cutoff to the high-energy $\beta = -3$ spectrum. We do not use φ_9 (motivated by GZK neutrinos and thus implicitly connected to UHECR).

Figure 4 shows the UHECR proton flux from φ_7 and φ_8 for zero evolution, as often assumed for BL Lacs, or cosmic star formation rate [76–78] evolution. These fall below the data [79–82], though φ_8 is close at $\gtrsim 10^{18}$ eV, where the composition is light [83–85]. Fewer pions per neutron would raise the flux [48], though saturation would leave no room for UHECR mechanisms besides neutron escape from IceCube sources.

Conclusions.—The $E_{\rm dep} \approx 2.6$ PeV IceCube track event implies the highest E_ν interaction to date. If this track is from a muon, it may indicate a $\gtrsim 10$ PeV neutrino energy. Alternatively, we find through-going taus leaving such tracks imply neutrino energy in the $\sim$100 PeV range, giving a glimpse of astrophysical neutrinos from unexpectedly high energies.

Our calculations show such tracks are unlikely from extending a soft neutrino flux yielding the $\gtrsim$40 TeV IceCube events. Fluxes like the $\sim E_\nu^{-2.1}$ spectrum from analyses of IceCube muons alone imply excessive Glashow shower rates. We conclude that this combination of low track rates from soft spectra and a deficit of $\sim$6 PeV shower detections favors a new hard astrophysical neutrino flux beyond the Glashow resonance.

The huge separation of parent ν_μ/ν_τ energies producing a through-going track depositing the same energy highlights the importance of developing charged lepton flavor identification for individual tracks. The models that we considered suggest the IceCube multi-PeV track is the tip of a super-Glashow iceberg and detectors such as IceCube Gen-2 [68], ARIANNA [86], and ARA [87] can improve prospects of addressing flavor ratios, the birthplaces of UHECR, and more.

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