What do the highest-energy cosmic-ray data suggest about possible new physics around 50 TeV?

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The latest observations of extensive air showers (EASs) induced by ultrahigh-energy cosmic rays appear to indicate, *prima facie*, a transition to heavy primaries at the highest energies. However, this interpretation is based on extrapolations of the Standard Model (SM) to ultra-LHC energies. We consider the alternative that after some energy threshold, the first collision of the primary in the atmosphere results in a state, the decay of which leads to a considerably increased shower particle multiplicity, so that light-primary EASs appear heavy-like. We show that a minimal implementation of such a model yields predictions for the average EAS depth and shower-to-shower fluctuations that are consistent with each other, and an excellent fit to Auger data. If such an effect indeed takes place, we predict that (a) the center-of-momentum (c.m.) energy threshold for the effect is of order 50 TeV; (b) the probability with which the effect occurs is high, and it will be detected easily by next-generation accelerators; (c) the increase in multiplicity compared to the SM prediction grows with c.m. energy roughly as $\sim E_{\rm CM}$; and (d) the cosmic-ray composition at the highest energies is light. Remarkably, if the latter is confirmed electromagnetically, this would necessitate the existence of new physics by these energies.

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I. INTRODUCTION

Ultrahigh-energy cosmic rays (UHECRs) are the highest-energy particles in the Universe. They are extremely rare (one particle per km^2 per year at energies above 10^{19} eV). Even so, thanks to the operation of cosmic-ray observatories spanning thousands of km^2, there has been, in the past fifteen years, an explosion of unprecedented-quality data [1–4]. Results from HiRes [5], the Pierre Auger Observatory [6], and the Telescope Array [7] now allow the use of UHECRs as probes of high-energy physics. The largest cumulative exposure at the highest energies ($>6.7 \times 10^4$ km^2 sr yr [8]) has been achieved by the Auger Observatory, and it is the interpretation of the latest Auger data above $10^{17.5}$ eV [9,10] that we focus on.

This plethora of high-quality data has exposed new puzzles in cosmic-ray physics. The most pressing one involves the composition of UHECRs and its evolution with energy. All composition-sensitive observables appear to indicate, *prima facie*, that, at the highest energies, heavier nuclei start to dominate over protons [3,11,12]; however, the results from these observables are not fully consistent with each other [13,14].

The distribution, in a given primary energy range, of the atmospheric slant depth $X_{\rm max}$ (expressed as column density) where the energy deposition rate of EAS particles in the atmosphere reaches its maximum value is both composition sensitive [15,16] and directly observable by fluorescence detectors. For this reason, its first two moments (average shower depth, $\langle X_{\rm max}\rangle$, and standard deviation, $\sigma_{X_{\rm max}}$) are the most widely used composition-sensitive observables. Auger data on both $\langle X_{\rm max}\rangle$ and $\sigma_{X_{\rm max}}$ show a qualitative trend towards heavy-like EASs above $\sim 2 \times 10^{18}$ eV (see Fig. 2); however, the two datasets are not straightforward to reconcile in detail, with the Auger Collaboration reporting strained fits to the observed $X_{\rm max}$ distribution in more energy bins than what is expected from random fluctuations alone: there is *no* primary composition that can fully reproduce the observed distributions [10]. Additional composition-sensitive quantities obtained from the surface water-Cherenkov detectors, when interpreted using SM EAS simulations, yield a mass composition heavier than the one derived from $X_{\rm max}$, with the discrepancy traced to an observed excess of muons compared to SM expectations [14]. This is not surprising, as the interpretation of composition-sensitive observables relies on simulations of EAS development, which in turn draw on extrapolations of SM results to ultra-LHC energies (note, however, that the muon production rate may have been underestimated even within SM predictions, e.g., Ref. [17]).

The alternative, therefore, to the UHECR composition getting heavier, is that there is some new physical effect, yet unseen in accelerators, that takes place in the first collision of UHECR primaries in the atmosphere above some energy threshold $E_{\rm th}$ and affects the shower development. That this scenario is an open possibility is widely recognized by the Auger Collaboration (e.g., Refs. [10,12,14,18]) and other authors (e.g., Refs. [19–21]). Here, we quantify phenomenological constraints encoded in Auger data for any new phenomenon that could be affecting EAS development.

Specifically, assuming that, at energies $>2\times 10^{18}$ eV—

(a) A single population of extragalactic cosmic rays dominates (i.e., the energy spectrum and composition of cosmic rays does not change due to a transition between different classes of extragalactic populations).
(b) The composition of extragalactic cosmic rays remains light.
(c) The growth of $\langle X_{\rm max}\rangle$ with energy, abnormal for protons and light nuclei, reflects the phenomenology of this new physical effect.

—we show that Auger data on $\langle X_{\rm max}\rangle$ and $\sigma_{X_{\rm max}}$ can be readily reproduced.

II. WHAT KIND OF NEW PHYSICS?

The primary requirement for a candidate new physical effect is to make light-primary EASs appear "heavy-like," which in practice translates to (a) having a smaller $\langle X_{\rm max}\rangle$ and (b) having smaller $\sigma_{X_{\rm max}}$ than the SM prediction for protons.

The phenomenology we consider is that the first collision of the primary in the atmosphere results, with high probability, in a state whose decay leads to a considerably increased particle multiplicity early in the shower. A large number of particles injected early in the shower development will lead to showers that reach their maximum at smaller values of X, as well as smaller $\sigma_{X_{\rm max}}$ (as shower-to-shower fluctuations will average out).

Several candidate particles and new physics mechanisms that might lead to such behavior are reviewed in Refs. [22,23]. They are based either on the possible existence of yet undiscovered particles (mini–black holes, strangelets) or on special phases of QCD, such as the disoriented chiral condensate (DCC). The mini–black hole paradigm has been analyzed in detail in Ref. [24], while a recent proposal based on chiral symmetry restoration in QCD can be found in Ref. [19].

The quantitative impact of such a scenario on composition-sensitive observables is model dependent; a rough phenomenological estimate is, however, straightforward to make.

III. GROWTH OF $\langle X_{\rm max}\rangle$ WITH ENERGY

For a single shower, $X_{\rm max}=X_1+X_{\rm D}$, with X_1 being the depth of the first interaction and $X_{\rm D}$ being the additional column density required for the shower to reach its maximum development. For energies below $E_{\rm th}$, SM predictions hold. $\langle X_1\rangle = m/\sigma_{\text{p-air}}$, where m is the average atomic mass of air ($\simeq$14.5 proton masses, e.g., Ref. [25]) and $\sigma_{\text{p-air}}$ is the proton-air cross section.[1] We parametrize $\sigma_{\text{p-air}}\simeq\sigma_0+\beta\log\epsilon$ for $\epsilon\le 1$, where $\epsilon=E/E_{\rm th}$. Any new phenomenon will likely affect $\sigma_{\text{p-air}}$, so that $\sigma_{\text{p-air}}\simeq\sigma_0+\beta'\log\epsilon$ for $\epsilon\ge 1$, assuming that $\sigma_{\text{p-air}}$ is continuous as the slope changes[2] from its SM value β to β'. Thus, for $\epsilon\ge 1$, $\langle X_1\rangle\simeq(m/\sigma_0)-(m\beta'/\sigma_0^2)\log\epsilon$.

The change in $X_{\rm D}$ is entirely due to an increase in particle multiplicity at the first collision, since the products will have, on average, energies below $E_{\rm th}$. We parametrize the change in multiplicity by $n(\epsilon)\equiv N(\epsilon)/N_{\rm SM}(\epsilon)>1$ (for $\epsilon\ge 1$), where $N(\epsilon)$ and $N_{\rm SM}(\epsilon)$ are the actual and SM-predicted (by shower simulations) numbers of first collision products. We can then empirically model the shower as $n(\epsilon)$ "component showers" (CS) of energy, on average, $\epsilon/n(\epsilon)$, developing independently. Since for $\epsilon\le 1$ the SM prediction [10] is $\langle X_{\rm D}\rangle\simeq\langle X_{\rm D}\rangle(1)+(65\ {\rm g/cm^2})\log\epsilon$, for $\epsilon\ge 1$ we obtain $\langle X_{\rm D}\rangle\simeq\langle X_{\rm D}\rangle(1)+(65\,{\rm g/cm^2})\log[\epsilon/n(\epsilon)]$ [where we have assumed $n(1)=1$].

The Auger Collaboration [10] fits, for $E\gtrsim 2\times10^{18}$ eV, $\langle X_{\rm max}\rangle_{\rm EG}/{\rm g\,cm^{-2}}\simeq 728+26\log(\epsilon/\epsilon_{17.5})$, where $\epsilon_{17.5}=10^{17.5}\ {\rm eV}/E_{\rm th}$. In the simplest case, the new state is produced almost in every EAS for $\epsilon\ge1$, the composition at these energies remains constant, and the difference with the SM prediction is purely due to new physics. Then, we can obtain $n(\epsilon)$ by demanding that the energy-dependent terms in the $\langle X_{\rm max}\rangle=\langle X_1\rangle+\langle X_{\rm D}\rangle$ model match the energy-dependent part of the Auger fit:

$$65\log[\epsilon/n(\epsilon)]-\frac{m\beta}{\sigma_0^2}(\delta+1)\log\epsilon=26\log\epsilon, \qquad (1)$$

where m, σ_0, and β are known (see footnote 1), and $\delta=\beta'/\beta-1$ is the fractional change of new physics β' in terms of Standard Model β. This yields

$$n(\epsilon)\simeq\epsilon^{0.52-0.08\delta}. \qquad (2)$$

IV. CHANGE OF $\sigma_{X_{\rm max}}$ WITH ENERGY

The $X_{\rm max}$ spread between showers is the joint effect of fluctuations in X_1 and in shower development, $\sigma^2_{X_{\rm max}}=\sigma^2_{X_1}+\sigma^2_{X_{\rm D}}$, with $\sigma_{X_1}=\langle X_1\rangle$ (Poisson statistics). To estimate $\sigma_{X_{\rm D}}$, we take the average $(1/n)\sum_i X_{{\rm D},i}$ of individual CS maxima to be a reasonable estimator of the overall $X_{\rm D}$. Then, $X_{\rm D}$ is the "sample mean" of n "draws" from the underlying distribution of $X_{{\rm D},i}$, and the distribution of these "sample means" has a spread that is given by the "error in the mean" formula, $\sigma_{X_{\rm D}}=\sigma_{X_{{\rm D},i}}/\sqrt{n}$. Here $\sigma_{X_{{\rm D},i}}$ is

[1] We use the Sibyll 2.1 extrapolation $\sigma_{\text{p-air}}\simeq 520\ {\rm mb}+60\ {\rm mb}\log(E/10^{17.5}\ {\rm eV})$ [25]; our results are not sensitive to this choice.

[2] More generally, $\sigma_{\text{p-air}}$ might also exhibit a discontinuity at $\epsilon=1$. For simplicity, we do not make use of this extra freedom.

the spread of $X_{D,i}$, and it can be assumed to follow the SM predictions, since the individual energies of the decay products initiating the CS are $< E_{th}$. The SM predicts that $\sigma_{X_{D,i}}$ is approximately constant (the mild decline with energy predicted by SM shower simulations for $\sigma_{X_{max}}$ in the case of protons can be reproduced by the logarithmic rise of $\sigma_{p\text{-air}}$ with energy). Therefore,

$$\sigma^2_{X_{max}}(\epsilon) = \sigma^2_{X_1}(1) - 10.7\frac{g}{cm^2}\sigma_{X_1}(1)(1+\delta)\log\epsilon + \frac{\sigma^2_{X_D}(1)}{n(\epsilon)}. \tag{3}$$

V. A PROOF-OF-PRINCIPLE MINIMAL MODEL

As a proof of principle for this concept, we show how a simple two-component astrophysical scenario (heavy Galactic cosmic rays cutting off, light extragalactic cosmic rays dominating at high energies) with EASs obeying Eqs. (2) and (3) above E_{th} reproduces well Auger data on $\langle X_{max}\rangle$, $\sigma_{X_{max}}$, and yields reasonable flux spectra for the two populations.

For a mixture of Galactic and extragalactic cosmic rays with a fraction of Galactic over total particles $f(\epsilon)$, the probability density function of X_{max} will be $p(X_{max}) = f p_G(X_{max}) + (1-f)p_{EG}(X_{max})$, so that $\langle X_{max}\rangle$ will be given by

$$\langle X_{max}\rangle = f\langle X_{max}\rangle_G + (1-f)\langle X_{max}\rangle_{EG}, \tag{4}$$

and $\sigma^2_{X_{max}}$ by

$$\sigma^2_{X_{max}} = f\sigma^2_{X_{max},G} + (1-f)\sigma^2_{X_{max},EG} + f(1-f)(\langle X_{max}\rangle_G - \langle X_{max}\rangle_{EG})^2, \tag{5}$$

with the subscripts G and EG referring to the Galactic and extragalactic populations, respectively.

There is little freedom in this model. Assuming that extragalactic cosmic rays have completely dominated for $E > 2\times 10^{18}$ eV, the evolution of $\langle X_{max}\rangle_{EG}$ can be directly read off of the Auger data in this energy range. The continuity assumption for $n(\epsilon)$, and consequently for $\langle X_{max}\rangle_{EG}(\epsilon)$, then fully determines the behavior of $\langle X_{max}\rangle_{EG}$ at Auger energies, if the value of E_{th} is known.

A similarly strong statement can be made for f. The shape of the extragalactic population flux spectrum is affected by intergalactic losses (which in turn depend on the composition of extragalactic cosmic rays, the distribution and cosmic evolution of extragalactic cosmic-ray sources, and the cosmic density of diffuse photon backgrounds) and the pileup of particles down-cascading from higher energies [26–30]. These are nontrivial to calculate theoretically, because of the uncertainties involved in the inputs, but also because any systematic uncertainties in the energy reconstruction of cosmic-ray events shift the energy location where specific absorption features appear. In contrast, the Galactic cosmic-ray flux is reasonably expected to be a declining power law (from Fermi acceleration) with an exponential cutoff (induced by Galactic accelerators reaching the maximum energy they can achieve), $F_G(\epsilon) = F_{G,0}(\epsilon/\epsilon_{17.5})^{-\gamma_G}\exp[-\epsilon/\epsilon_G]$. The values of $F_{G,0}$ and γ_G are well constrained by KASCADE-Grande data at lower energies,[3] with $F_{G,0} \simeq 2\times 10^{-15}\ \mathrm{km^{-2}\,yr^{-1}\,sr^{-1}\,eV^{-1}}$ and $\gamma_G \simeq 3$ (see Fig. 1). The value of $\epsilon_G = E_G/E_{th}$ can then be constrained by the requirement that the flux residuals $F_{total,Auger}(\epsilon) - F_G(\epsilon)$ in the lower-energy part of the Auger range, before any intergalactic propagation losses set in, be consistent with a power law (again assuming Fermi acceleration for extragalactic sources). For values outside the range $6.5\times 10^{17}\ \mathrm{eV} < E_G < 8.5\times 10^{17}$ eV, the low-energy Auger residuals (see Fig. 1, upper panel, green open circles) start to exhibit curvature in a log-log plot. We adopt $E_G = 7.5\times 10^{17}$ eV, in the middle of this range

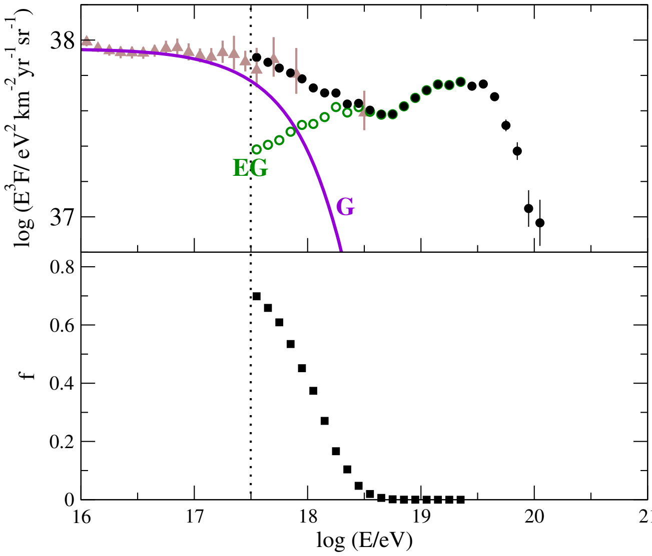

FIG. 1. *Upper panel:* Cosmic-ray spectrum between 10^{16} and 10^{20} eV. Filled circles: Auger 2017 ICRC spectrum [9] (error bars are statistical). Brown triangles: KASCADE-Grande 2015 all-particle spectrum [31], QGSJET II-04 reconstruction (error bars are systematic). Purple line: Galactic population model spectrum (this work). Open green circles: Auger total flux minus Galactic model. The vertical black dotted line indicates the lowest energy for which there are spectrum measurements from Auger. *Lower panel:* Fraction of cosmic rays of Galactic origin as a function of energy, derived from the Galactic flux model over the total observed flux.

[3]We adopt, purely empirically, the 2015 ICRC QGSJetII-04–based energy reconstruction of KASCADE-Grande events [31], which results in a near-perfect continuity with Auger measurements at overlapping energies; see Fig. 1.

(purple line, Fig. 1, upper panel). This then fixes $f(\epsilon)$ to $F_{\rm G}(\epsilon)/F_{\rm total,Auger}(\epsilon)$ (Fig. 1, lower panel).

The Galactic component is heavy. The exact composition is subject to various systematic uncertainties [31,32], so for simplicity, we take the SM predictions for carbon nuclei ($\langle X_{\max}\rangle_{\rm G,0} \simeq 670\ {\rm g/cm^2}$ and $\sigma_{X_{\max}{\rm G},0} \simeq 38\ {\rm g/cm^2}$ at $10^{17.5}$ eV, from a naive extrapolation of data presented in Refs. [10,33]) to be representative, on average, of the behavior of EAS initiated by Galactic cosmic rays.[4] We have, however, verified that more complex mixes also give good fits with other model inputs within their respective allowed ranges. Since $\sigma_{X_{\max}}$ evolves very little for heavier nuclei in the energy range relevant for the Galactic population, we take it to be constant for simplicity. Because $f(\epsilon)$ is highly suppressed by the energy at which new physics sets in, these choices affect neither our fit to Auger data at the high end of their energy range, nor our conclusions on possible new physics phenomenology.

For both a pure proton population and any reasonable light mix, $\sigma_{X_{\max}{\rm EG},0}$ will be 68$\pm$ a few g/cm^2 at $10^{17.5}$ eV [10]. We take $\sigma_{X_{\max}{\rm EG},0} = 68\ {\rm g/cm^2}$.

A nominally free parameter in our model is the threshold energy, $E_{\rm th}$, where new physics sets in. The requirement that $\langle X_{\max}\rangle_{\rm EG}$ not, at any energy, exceed (within systematic uncertainties) the SM predictions for protons is largely satisfied by the nondetection by the LHC of any effects deviating from SM predictions (which requires $E_{\rm th} \gtrsim 10^{17}$ eV and $E_{\rm CM,th} \gtrsim 14$ TeV). By the assumption that new physics has already set in by the break observed by Auger in $\langle X_{\max}\rangle$, $E_{\rm th} \lesssim 10^{18.3}$ eV. Although in what follows we use $E_{\rm th} \simeq 10^{18}$ eV ($E_{\rm CM,th} \simeq 45$ TeV), good fits to the Auger dataset can be obtained throughout this range, given the uncertainties in the Auger data and the allowed range in other model inputs. In that respect, there is no fine-tuning of the energy threshold necessary. For heavier primary nuclei, the per-nucleon threshold for mass number A is reached at a higher primary energy, $AE_{\rm th}$. For this reason, the new physics never becomes relevant for Galactic cosmic rays, as extragalactic cosmic rays have completely dominated before $AE_{\rm th}$ is reached, for any reasonable A (hence the "agnostic" dotted lines for the Galactic population at high energies in Fig. 2).

This leaves a single free parameter in our model, δ, which affects X_1. $\langle X_{\max}\rangle$ shows no sensitivity to δ, because it is dominated by $\langle X_{\rm D}\rangle$. In contrast, $\sigma_{X_{\max}}$ is more sensitive to δ; however, at the high energies where its effect becomes important, Auger $\sigma_{X_{\max}}$ data have large statistical uncertainties. In Fig. 2, we show two cases: $\delta = 0$ ($\sigma_{\text{p-air}}$ is not affected by new physics, orange line), and $\delta = 2.9$ (cyan line). Note that even the latter case is consistent with SM predictions within uncertainties [25].

[4]The composition of Galactic cosmic rays evolves strongly between the knee ($\simeq 10^{15.5}$ eV) and their final cutoff at $E_{\rm G}$. Our simple assumption cannot capture this behavior, and thus we do not expect to fit the data below $10^{17.5}$ eV.

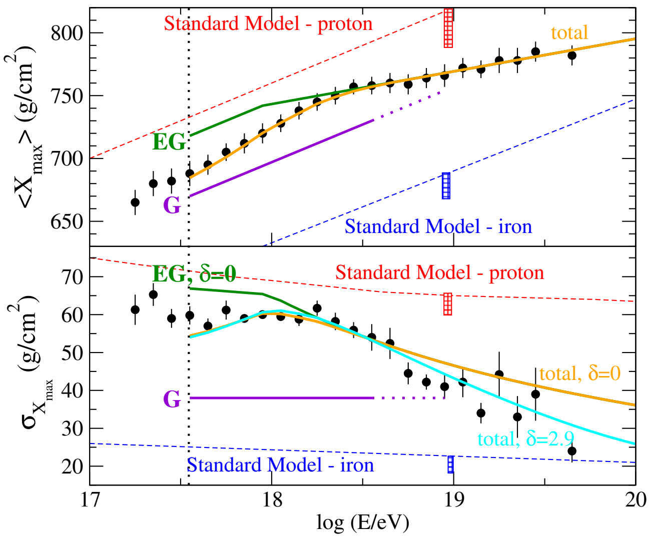

FIG. 2. *Upper panel:* $\langle X_{\max}\rangle$ as a function of energy. Filled circles: Auger 2017 ICRC data [10] (error bars are systematic). Red/blue dashed lines: SM (Sibyll) predictions for protons/iron, from Ref. [8]. The hatched boxes indicate the systematic uncertainty of SM predictions (result of using EPOS/QGSJet instead of Sibyll). Thick lines: Our model (purple: Galactic, green: extragalactic, orange: total). *Lower panel:* $\sigma_{X_{\max}}$ as a function of energy. Filled circles: Auger ICRC 2017 data [10] (error bars are statistical). Orange line: $\delta = 0$. Cyan line: $\delta = 2.9$. Other lines as above. For clarity, the extragalactic model is only shown for $\delta = 0$.

VI. RESULTS AND DISCUSSION

The resulting $\langle X_{\max}\rangle(E)$ and $\sigma_{X_{\max}}(E)$ curves are shown in Fig. 2. In the same energy range, the two datasets resemble broken logarithmic growth with two different slopes; the Auger Collaboration fits them as such [10]. Each such relation involves four free parameters, so fitting the two datasets in this way would require eight free parameters. We have incorporated in our model the slope and normalization of the high-energy branch of $\langle X_{\max}\rangle$, so a purely empirical model would need another six free parameters to fit both datasets well. Without using *any* of this freedom, we have produced model curves for two very different values of δ that perform better than astrophysical scenarios (extragalactic accelerator composition getting heavier) [12,30,34–36], and all other inputs in our model are driven by astrophysics and/or the requirement of consistency with the SM predictions at low energies.

When comparing the scenario presented here with astrophysical scenarios with a transition to heavier composition at the highest energies, one should note that the latter generally do not attempt to reproduce the entire Auger energy range (e.g., Refs. [12,30,34,35]), but focus instead above $\sim 5 \times 10^{18}$ eV, leaving room for a possible third component between Galactic cosmic rays and the highest-energy cosmic rays, an issue explicitly addressed by Ref. [12] (see, however, Refs. [36,37] for models that treat the entire Auger energy range).

In astrophysical/no-new-physics explanations of the shallow growth of $\langle X_{\max}\rangle$ at the highest energies, the energy where the Galactic accelerators cut off for heavy cosmic-ray species is $\sim 2\times 10^{18}$ eV. At energies lower than that, the elongation rate (rate of growth of $\langle X_{\max}\rangle$ with energy) is steeper than what the Standard Model predicts for constant composition; the composition therefore is still getting lighter, indicating an increasing dominance with energy of some cosmic-ray accelerator class that is producing lighter cosmic rays than the population that is cutting off. The trend is reversed at energies higher than $\sim 2\times 10^{18}$ eV, and the elongation rate becomes shallower than what is predicted by the Standard Model for constant composition, indicating that around that energy, the composition produced by cosmic-ray accelerators dominating at the highest energies starts getting heavier. The energy scale of $\sim 2\times 10^{18}$ eV is therefore meaningful both for Galactic and extragalactic accelerators in astrophysical scenarios: it is comparable to the cutoff energy for heavy elements in the former, and for protons in the latter. In our scenario, the energy scale of 2×10^{18} eV where the slopes of $\langle X_{\max}\rangle$ and $\sigma_{X_{\max}}$ are seen to change in the data is also astrophysical in origin, and it signifies extragalactic cosmic rays dominating over the Galactic population. It is *not*, however, the energy where new physics sets in. The new effect has already appeared at a lower energy. Our fit to the Auger data is not very sensitive to the energy where new physics sets in.

In astrophysical/no-new-physics scenarios, the maximum energy achievable by extragalactic accelerators is close to the energy threshold for photopion/photodissociation energy losses [the Greisen-Zatsepin-Kuzmin (GZK) cutoff [38,39]] [10]. In our scenario, extragalactic accelerators remain efficient, and their output remains light throughout the Auger energy range.

The scenario we discuss does not assume any specific model for the hypothesized high-mass state. Rather, assuming such a high-mass state is indeed produced in above-threshold collisions, we derive constraints for its interaction and decay properties (cross section and multiplicity, respectively). We have thus not treated the muon excess, since the extent to which it occurs in any specific implementation is model dependent. However, where such specific models have been studied in detail [19,23,24], they do also alleviate the muon excess problem. Ultimately, the impact of specific models on EAS phenomenology, including their ability to alleviate the muon excess, can be best studied using EAS simulations as, e.g., in Refs. [19,24].

The phenomenology we have considered here leads to **three specific predictions** with important implications for future astroparticle and particle physics experiments.

(1) The increase in multiplicity relative to the SM, $n(E)$, grows with lab-frame primary energy as $\sim E^{0.52-0.08\delta}$ (and with c.m. energy as $E_{\mathrm{CM}}^{1.04-0.16\delta}$). Curiously, the multiplicity of the decay of mini–black holes depends on the black hole mass $M_{\mathrm{BH}}\propto E_{\mathrm{CM}}$ as $M_{\mathrm{BH}}^{(n+2)/(n+1)}$ (where n is the number of extra dimensions), in general agreement with the empirical relation; however, the estimated cross section for mini–black hole production is generally too small to affect the majority of EASs.

(2) The energy threshold E_{th} for the new effect lies between $10^{17.5}$ and $10^{18.3}$ eV (c.m. energy 25–60 TeV), within reach of any next-generation accelerators.

(3) The composition of the extragalactic cosmic ray population is light and stable with energy. This could, in principle, be independently tested electromagnetically [40]. More accurate reconstructions and local measurements of the Galactic magnetic field at known distances (made possible by the $\sim 10^9$ stellar parallaxes measured by ESA's Gaia mission [41]) are aggressively pursued [42–45], so it is reasonable to expect that our understanding of the Galactic magnetic field will dramatically improve in the coming decades. This would then allow the Galactic magnetic field to be used as a "charge spectrometer" for UHECRs: the propagation of ultrarelativistic particles through a known magnetic field is sensitive to their charge, without reference to particle physics and air shower reconstructions. If such studies confirm that the composition of UHECRs remains light to the highest energies, this would *necessitate* the existence of new physics around 50 TeV. Another central factor in such efforts is good statistics at the highest energies. Next-generation cosmic-ray experiments will thus play a key role in our ability to use UHECRs as probes of new physics.

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