# Multiple UHECR Events from Galactic Hadron Jets

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**Abstract**

We propose a new observational test of top-down source models for the ultra-high-energy cosmic-rays (UHECRs), based on the simultaneous observation of two or more photons from the same Galactic hadron jet. We derive a general formula allowing one to calculate the probability of detecting such 'multiple events', for any particular top-down model, once the physical parameters of the associated hadron jets are known. We then apply our results to a generic top-down model involving the decay of a supermassive particle, and show that under reasonable assumptions the next-generation UHECR detectors would be able to detect multiple events on a timescale of a few years, depending on the mass of the top-down progenitor. Either the observation or the non-observation of such events will provide constraints on the UHECR top-down models and/or the physics of hadronization at ultra-high energy.

## 1. Introduction

Among the models proposed for the origin of the puzzling ultra-high-energy cosmic-rays (UHECRs), a number of independent propositions can be described as belonging to the class of *top-down models*. All these models involve the production of a (still to be discovered) 'X particle', with a mass larger than $10^{21}$ eV and up to the Planck scale ($10^{28}$ eV), which then decays into elementary particles and simple hadrons through a hadronization process similar to the one observed at lower energy when hadron jets are produced in high-energy collision experiments in terrestrial accelerators [1]. In this way, the X-particle decay process creates a large number of mainly photons and neutrinos (plus electrons, positons, protons, etc.), with a spectrum of energies extending up to a significant fraction of the X-particle mass, so that no astrophysical acceleration process is required to produce the observed UHECRs.

An important, common feature of such processes is that the decay products are generated within two or more *hadron jets*, having a very small opening angle. Although the phenomenology of such jets is not known experimentally at energies above TeV, the theory of hadronization and the analysis of the available data at

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low energy allows one to speculate about the structure and content of hadron jets that would be produced at energies many orders of magnitude higher, through the decay of supermassive X particles. In this communication, I argue that the hadron jets involved in top-down models for UHECRs can be so much collimated, and the photons inside these jets so close to one another that two of them (or more) reach a large enough detector on Earth at the same time, producing two simultaneously observed and almost perfectly parallel extensive air showers (EAS).

Such *multiple UHECR events* can occur if: i) the X particle decays close enough to Earth, ii) the opening angle of Galactic hadron jets is small enough, iii) the number of photons in each jet is high enough, and iv) the detector covers a large enough area on Earth. In the following, we derive a general formula to calculate the expected probability of observing multiple events for top-down models for which the physical properties of the jets are specified or can be evaluated. We show that both EUSO and the Pierre Auger Observatory (PAO) are large enough to detect double or triple events during their lifetime, or to constrain some properties of the possible X-particle models involved in the generation of UHECRs.

## 2. Basic assumptions

In the following, we assume that the observed UHECRs are due to an unknown top-down process. Whatever the associated X particles and their production mechanism (either in the very early Universe or continuously through topological defects interactions or collapse), we follow common belief and consider that the observed flux of UHECRs is dominated by X-particle decays in the halo of our Galaxy, due to the large density contrast with respect to the rest of the universe. It is also believed that for such Galactic top-down models, the large majority of the observed UHECRs should be photons, which happen to propagate in straight lines across the Galaxy, so that they remain within the highly collimated jets in which they were originally created (through $\pi^0$ decay, essentially). Let $N_\gamma$ denote the number of UHE photons in a jet, $\theta_{\rm jet}$ the jet opening angle, $D$ the distance to the point where the parent X-particle decayed and $S_\perp$ the surface area of the UHECR detector orthogonal to the jet axis. The average number of UHECRs that will be detected (if that particular Galactic hadron jet intersects the detector) is simply given by:

$$\mu = \frac{N_\gamma S_\perp}{\pi \theta_{\rm jet}^2 D^2}. \tag{1}$$

In reality, the distribution of UHE photons in both energy and angular spaces is complex, and the jet structure can only be estimated stochastically. In particular, a few particles can be found far away from the jet axis, and the number of photons above a given energy, $N_\gamma(\geq E)$, depends on the opening angle consider. We have argued in ref. [3] for a simple, generic model of UHE hadron jets, based on a reasonable extrapolation of the physics known at CERN energies ([2] and Dokshitzer, private communication). In this model, we evaluate the jet opening angle for X particles with masses $M_{\rm X} \geq 10^{23}$ eV to be of the order of $\theta_{\rm jet} \simeq 2\times10^{-11}$ radians, and the approximate number of jet photons above energy $E$, $N_\gamma(\geq E) \simeq 1.7 \times 10^3 (E/10^{20}\,{\rm eV})^{-1}(M_{\rm X}c^2/10^{25}\,{\rm eV})$.

This allows us to determine the multiplicity of a particular UHECR event using Eq. (1), provided we know the distance at which the parent X particle decayed. Of course, this is unknown event by event, but we can derive the distribution function of the decay distances, $P(D)$, and use it to calculate the probability to detect a multiple event once a total number of $N_{\rm evt}$ UHECRs will have been recorded. To this aim, we follow the usual assumption that the primary X particles are distributed over the Halo in the same way as the dark matter. It can then be shown that $P(D)$ does not change significantly for any of the standard profiles (see [3]), and can be well approximated by ${\rm d}P(D) = p(D){\rm d}D = {\rm d}D/D_0$ for $0 \leq D \leq D_0$, where $D_0 \simeq 17$ kpc is an effective radius beyond which UHECR sources contribute a negligible flux at Earth.

## 3. Detection timescales of multiple UHECR events

Assuming that the X-particle decays in the Galactic halo are statistically independent (as would most certainly be the case), one finds that the probability of observing multiple UHECR events of any multiplicity, $n$, increases with the total number of UHECRs detected, $N_{\rm evt}$, as $\mathcal{P}_{\geq n}(N_{\rm evt}) = 1 - e^{-N_{\rm evt}/N_n}$, where $N_n$ is thus the characteristic number of events which have to be detected before it becomes reasonably probable ($\sim$ 63%) to detect an event of multiplicity larger than $n$. Now the UHECRs detection rate depends on the aperture the detector, $\mathcal{A}_{\rm d}$, and its duty cycle, $\delta$, and reads: $\dot{N}_{\rm evt}(\geq E) = \Phi_{\rm CR}(\geq E) \times \mathcal{A}_{\rm d} \times \delta$. This allows us to rewrite the probability of detecting multiple UHECR events as a function of time, instead of $N_{\rm evt}$: $\mathcal{P}_{\geq n}(t) = 1 - e^{-t/\tau_n}$, where $\tau_n = N_n/\dot{N}_{\rm evt}$ is the multiple event detection timescale, which is fully determined by the hadron jets, dark-matter distribution and detector characteristics. In Ref. [03], we have shown that the detection timescale for double events and higher multiplicities writes:

$$\tau_2 = \frac{\sqrt{2}\,\theta_{\rm jet}(E_{\rm th})\,D_0}{\pi\,N_{\gamma,\geq E_{\rm th}}^{1/2}\,\Phi_{\geq E_{\rm th}}^{\rm td}\,S_{\rm d}^{3/2}\delta}\;, \quad \text{and} \quad \tau_{n+2} = \frac{2n}{2n-1}\tau_{n+1}. \tag{2}$$

Using the observed flux at $10^{20}$ eV and the parameters derived for the generic top-down model above, one obtains:

$$\tau_2 \simeq (2.1\ {\rm yr}) \times \left(\frac{S_{\rm d}}{3000\,{\rm km}^2}\right)^{-3/2} \left(\frac{\delta}{100\%}\right)^{-1} \left(\frac{E_{\rm th}}{10^{19}\,{\rm eV}}\right)^{3/2} \left(\frac{M_{\rm X}}{10^{25}\,{\rm eV}}\right)^{-1/2}. \tag{3}$$

In the case of the next generation UHECR observatories, the detection surface on the ground will be $3000\,\mathrm{km}^2$ for the PAO (one site), and $1.5\times 10^5\,\mathrm{km}^2$ for EUSO. The detector's duty cycles are respectively 100% and 14%, and the energy thresholds are $10^{19}$ eV for the PAO and $5\times 10^{19}$ eV for EUSO. With these number, one finds, for an X-particle at the GUT scale ($M_\mathrm{X} = 10^{25}\,\mathrm{eV}$):

$$\tau_2(\mathrm{PAO}) = 2.1\,\mathrm{yr} \quad \text{and} \quad \tau_2(\mathrm{EUSO}) = 0.48\,\mathrm{yr}, \tag{4}$$

which are smaller than the observatories' lifetimes (15 and 3 years, respectively). The timescales for triple, quadruple and quintuple event detections are respectively 2 times, 2.67 and 3.2 times larger, as follows from Eq. (2).

## 4. Conclusion

We have shown that top-down models for UHECR origin have a common consequence: they all can lead to the detection of multiple events, i.e. simultaneous, parallel extensive air showers. The detection timescale for such events depends on the characteristics of the X-particle decay process (i.e. the hadron jet structure) and on the size of the detector (the larger, the better). However, within reasonable assumptions it was shown that both the PAO and EUSO should be able to detect a few multiple UHECR events within their lifetime (more details can be found in [3]). This would be a striking proof that UHECRs result from a top-down mechanism. The statistics of multiple events could then be used to constrain the physics of hadronization at ultra-high energy. On the other hand, the above calculations can be used to set constraints on the top-down models which are likely to explain the UHECR phenomenology. Finally, we note that the detection of multiple UHECR events would be greatly favoured by much larger detectors, but that these detectors would not need to have good angular and energy resolution at all, since the relevant feature of multiple events is just their simultaneity. Huge detectors of relatively modest price could thus be envisaged.

1. about UHECR top-down models: see e.g. the review by Bhattacharjee P., Sigl G. 2000, Phys. Reports 327, 109, and the recent book: Physics and Astrophysics of Ultra-High Energy Cosmic Rays, ed. M. Lemoine and G. Sigl, Springer-Verlag, Berlin (2001), and e.g. Berezinsky V., Kachelrieß M., Vilenkin A. 1997, Phys. Rev. Lett. 79, 4302; Birker M., Sarkar S. 1998, Astropart. Phys. 9, 297; Sarkar S., Toldra R. 2002, Nucl.Phys. B621, 495.
2. Dokshitzer Yu. L., Khoze V. A., Mueller A. H., Troyan S. I. 1991, Basics of Perturbative QCD, ed. J. Tran Thanh Van (Editions Frontières, Saclay)
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