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Constraining new physics with high-multiplicity: UHECR as a probe of new physics

Seong Chan Park*
Department of Physics and IPAP, Yonsei University,
Seoul 03722, Republic of Korea
E-mail: sc.park@yonsei.ac.kr

Yongsoo Jho
Department of Physics and IPAP, Yonsei University,
Seoul 03722, Republic of Korea
E-mail: jys34@yonsei.ac.kr

We study Ultra high energy cosmic ray (UHECR) as an effective tool to probe new physics interactions thanks to its high energy beyond the currently available accelerator energies. In particular, we consider electroweak sphaleron and microscopic black hole as some of the new physics examples generating genuinely large multiplicities resulting in various observable effects. We examine the characteristic features of UHECR-nucleon collision events in the atmosphere and discuss the search strategies of such events at Telescope Array Experiment (TA) and Pierre-Auger Observatory (Auger).

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*Speaker.

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1. Introduction

The observation of Ultra-High-Energy (UHE) particles have provided good opportunities to probe new physics above TeV scale. Many $\mathcal{O}(10)$ EeV cosmic ray events (by Auger and TA [1, 2]) and a few $\mathcal{O}(1)$ PeV neutrino events (by the IceCube detector [3]) have been observed so far. The scattering process of UHE cosmic rays with target nuclei in the atmosphere gives some hints for physics at TeV scale since the energy of UHE particles around $\mathcal{O}(1)$ PeV $-\mathcal{O}(10)$ EeV corresponds to the center-of-mass (CM) frame collision energy $\sqrt{s} = \mathcal{O}(1-100)$ TeV. The UHE cosmic neutrinos also can be produced by photopion production from the cosmic ray protons and the cosmic microwave background (CMB) photons, which is called the Greisen-Zatsepin-Kuzmin (GZK) mechanism. We focus on electroweak sphaleron and microscopic black hole production processes are discussed based on [4].

2. Event rates and features of air showers from new physics with high multiplicity

The electroweak sphaleron is a classical field configuration of non-abelian part of the gauge field in the electroweak theory [5, 6]. It is directly related to the non-conservation of baryon number (B) and lepton number (L) which are classically conserved global charges, even though the specific combination $B-L$ is fully conserved even at loop-level. Recently, it has been suggested that the cross section can be (exponentially) unsuppressed at the collision energy above the sphaleron potential height $E_{\rm sph} \simeq 10$ TeV [7, 8]. The minimal $(B+L)$-violating process ($\Delta B = \Delta L = \pm 3$) is our main interests. The microscopic black hole can be formed at a relatively low energy $\sqrt{s} \geq \mathcal{O}(1)$ TeV, in low-energy gravity scenarios [9, 10]. The black hole would decay into multiple number of particles through Hawking radiation [11, 12, 13, 14].

Taking the parton distribution functions (PDF), $f_q(x, \hat{Q}^2)$, for a quark, q, in nucleon, N, the total cross sections for electroweak sphaleron and microscopic blackhole are respectively are obtained after the PDF convolution for nucleon:

$$\sigma^{\nu N}_{\rm EWSph,BH}(E_{\rm lab}) = \int_{x_{\rm min}}^{1} dx\, f_q(x, 2xm_N E_{\rm lab})\, \hat{\sigma}^{\nu q}_{\rm EWSph,BH}(\hat{s}), \tag{2.1}$$

where $\hat{s} = 2xm_N E_{\rm lab}$ and the parton level cross sections are given by

$$\hat{\sigma}_{ij\to \rm EWSph}(E_{\rm CM}) \simeq \frac{p}{m_W^2}\theta(E_{\rm CM}/E_{\rm sph}), \tag{2.2}$$

$$\hat{\sigma}_{ij\to \rm BH}(E_{\rm CM}) \approx \pi\,(G_D E_{\rm CM})^{\frac{2}{D-3}}, \tag{2.3}$$

respectively for sphaleron and black hole. The input parameters are p (unknown prefactor for sphaleron process), $E_{\rm Sph}$ (sphaleron potential height), $G_D = 1/M_D^{D-2}$ (the gravitational constant in $D = 4+n$-dimensions with n-extra compact dimensions), m_N (the mass of Nucleon), $E_{\rm lab}$ (the collision energy in lab frame) and $\hat{s}$ (the collision energy at the parton level). The minimum energy for making black hole (sphaleron) is controlled by $x_{\rm min} = {\rm Min}[\hat{s}/(2m_N E_{\rm lab})]$.

Electroweak sphaleron and microscopic black hole production processes contain $\mathcal{O}(10)$ of primary hadronic components at the final states at the parton level. After the primary parton shower and hadronization, the resulting number of pions $\pi^{\pm}, \pi^0$ become larger than ordinary QCD processes. Due to the enhancement of the primary charged pion number, new physics air showers show some distinguished features from the standard model QCD air shower cases. First, their peak position (in the interaction depth) of the longitudinal distribution ($X_{\rm max}$) is become smaller since the individual energy of each charged pions decreases and new physics air showers develop more quickly. Second, their primary interaction points of air shower $P(X_0) \propto \exp\left(-\sigma_{\rm int} N_A A_{\rm atm}^{-1} X_0\right)$ have a broader distribution due to their small cross sections ($\sigma_{\rm Sph,BH} \ll \sigma_{\rm QCD}$). We summarize all the features in Fig. 1.

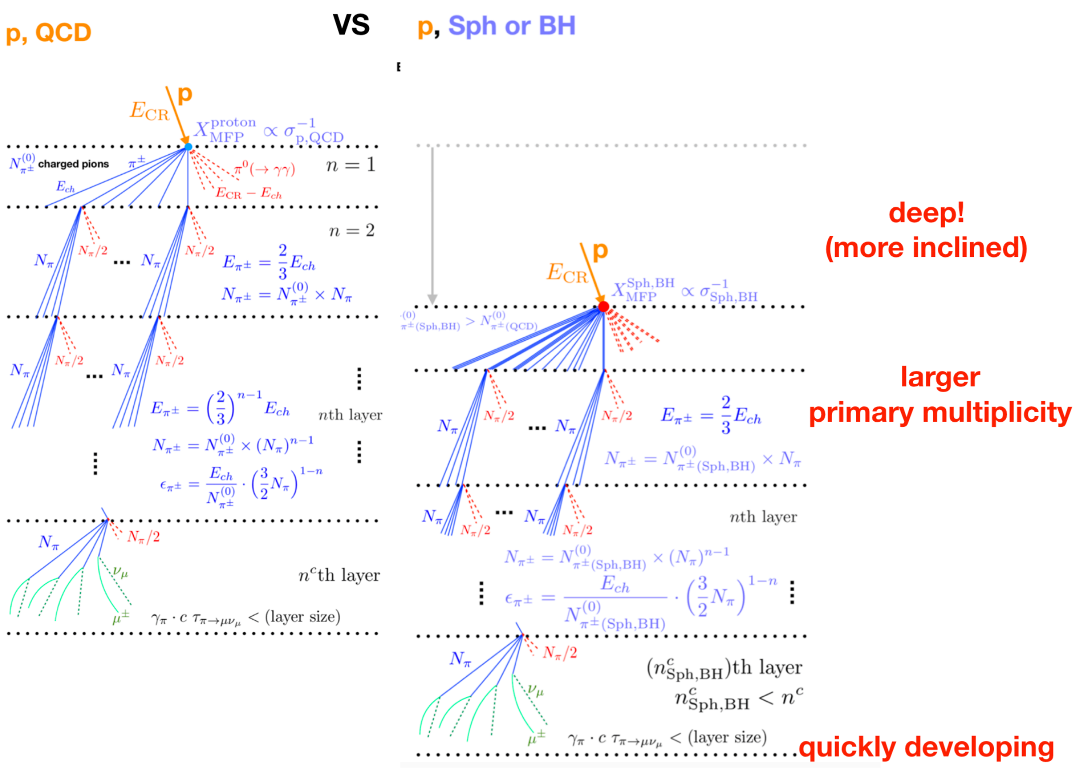

Figure 1: The schematic features of QCD and the new physics events. Details are found in Ref. [4]

3. Conclusion

With the enhanced production cross sections at high energies and the distinguished features in its air shower, new physics with high multiplicity can be probed further by using ongoing and future air-shower detector arrays and neutrino shower observatories.

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