Implications of the LHC results for the cosmic data interpretations

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Abstract

Absence of the signals of the physics beyond the Standard Model at the available LHC energies means that the several of cosmic data peculiarities could be associated with an emergency of the new scattering mode. This reflective scattering mode can be used for explanations of the measurements performed under the study of extensive air showers (EAS).
Introduction

The cosmic rays studies are an important data source in astrophysics. They simultaneously provide a window on the future results of accelerator studies at the energies already covered by and far beyond of the LHC [1]. The primary flux of cosmic particles is composed mainly from the protons. The measurements are performed with the extensive air showers developed in the atmosphere, since beyond the energy $10^{14}$ eV this flux has low intensity. Thus, the cosmic rays studies suffer from low intensity of the primary flux at the energies higher than $10^{14}$ eV and related necessity to exploit the particular model extrapolations for the interpretations of the EAS results.

The number of model interpretations can be reduced due to the results obtained at the accelerators. To be more specific, we consider a knee in the energy spectrum of cosmic particles. The energy spectrum follows a simple power-like law $F(E) = cE^{-\gamma}$ but it changes the slope in the energy region of $\sqrt{s} = 3 – 6$ TeV[2,3] and becomes steeper: index $\gamma$ increases from 2.7 to 3.1. Just this change is called a knee.

The dominant interpretation associates this change with astrophysics. However, it can also be related to the dynamics of the primary particle interactions with the atmosphere. In particular, the knee was interpreted as a result of appearance of the new particles with a small inelastic cross-section and/or small inelasticity. These new particles were associated with effects of the supersymmetry, technicolor and other new physics beyond the Standard Model (SM) (cf. e.g. [4]). But, nowadays the latter option seems to be disfavored by the LHC results [5]. Physics beyond the SM has not been found so far in the energy range $\sqrt{s} = 3 – 6$ TeV. This fact can have the two alternative interpretations. To adopt an astrophysical origin of the knee and other peculiarities, it should be accepted that cosmic rays content changes with energy from light to a more heavy particles [6]. This option seems to be presently a favorable one as it was stressed in the above paper.

There is a second possibility which is not excluded by the data and, moreover, the LHC data have pointed out its existence [7]. This option does not presume change in the primary cosmic rays composition. It continues to correlate the observed effects with dynamics of the primary cosmic ray interactions with atmosphere and gradually turning on new scattering mode with the energy. Namely, there is a possibility to consider the observed effects in EAS as the manifestations of emerging the reflective scattering mode with the energy increase [8].

We discuss this possibility in the next section.
1 The reflective scattering mode and interpretation of the EAS data

The elastic scattering $S$-matrix element can be expressed through the elastic scattering amplitude $f(s, b)$ by the relation $S(s, b) = 1 + 2if(s, b)$\(^1\). It can also be represented in the form

$$S(s, b) = \kappa(s, b) \exp[2i\delta(s, b)],$$

which includes two real functions $\kappa(s, b)$ and $\delta(s, b)$. The function $\kappa(0 \leq \kappa \leq 1)$ is a transmission coefficient \([9]\), and the value $\kappa = 0$ corresponds to a complete absorption of the initial state.

We consider scattering at high energies and use therefore an approximation of the pure imaginary scattering amplitude when the function $S(s, b)$ is real. The selection of elastic scattering mode, namely, absorptive or reflective one, is governed by the phase $\delta(s, b)$. The standard assumption is that $\kappa(s, b) \rightarrow 0$ at the fixed impact parameter $b$ and $s \rightarrow \infty$. This is called a black disk limit since in this case the elastic scattering amplitude $f(s, b)$ has a completely absorptive origin and is limited by the inequality $f(s, b) \leq 1/2$.

There is another option, namely, the function $S(s, b) \rightarrow -1$ at fixed $b$ and $s \rightarrow \infty$, i.e. transmission coefficient $\kappa \rightarrow 1$ and $\delta = \pi/2$. The mechanism corresponding to such a dependence can be described as a pure reflective scattering \([8]\). The distinct feature of the reflective scattering mode is that the amplitude varies in the range $1/2 < f(s, b) \leq 1$, as it is allowed by unitarity \([10]\). Model estimates show that new scattering mode starts to develop right beyond the Tevatron energy range, i.e. at $\sqrt{s_0} > 2$ TeV \([8]\), which corresponds to the energy in the laboratory system $E_0 \simeq 2$ PeV. The energy value $s_0$ is determined by the relation $\kappa(s, b = 0) = 0$. This reflective scattering mode starts to develop at the LHC and it has been revealed in the data \([7]\) at $\sqrt{s} = 7$ TeV. The description of this mode can be found in \([8, 10, 11]\). The most important feature is a self-damping of the inelastic channels at small values of the impact parameter. The reflective scattering leads to the asymptotic limit $P(s, b = 0) \rightarrow 1$ at $s \rightarrow \infty$, where $P$ is a probability of the absence of the inelastic interactions, namely, $P(s, b) \equiv \kappa^2(s, b) = 1 - 4h_{inel}(s, b)$, where the function $h_{inel}(s, b)$ is a contribution of the inelastic channels to the unitarity relation. The latter function is also called the inelastic overlap function. The self-damping of the inelastic channels is responsible for the transformation of central to a peripheral form of the inelastic channel contribution $h_{inel}(s, b)$ with the collision energy growth (Fig. 1). It leads to a dominant role of elastic scattering at

\(^1\)At high energies the real part of the scattering amplitude is small and can be neglected, allowing the substitution $f \rightarrow if$. 

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Figure 1: Transition of the inelastic channel contribution from central to a peripheral profile with an increasing center-of-mass energy.

$s \to \infty$: the cross-section of the inelastic processes rises at $s \to \infty$ with energy as $\ln s$, while elastic and total cross-sections behave asymptotically as $\ln^2 s$.

Beyond the new mode threshold energy $s_0$ the two regions in the impact parameter space coexist: the central region where self-damping of inelastic channels takes place and the peripheral region $b > r(s)$ of the shadow or absorptive scattering. The function $r(s)$ is determined by the equation $\kappa(s, b = r(s)) = 0$. The collisions at the small impact parameter scattering are almost elastic ones at the energies $s \gg s_0$. But at the LHC energies, the value of $r(s)$ is small and the elastic amplitude only slightly exceeds the black disk limit in head-on collisions at $b < r(s)$ at the LHC energies [7].

The head-on colliding particles, at the energies far beyond the LHC ones, would provide appearance of a long-penetrating component in the EAS and such particles would spend relatively small part of their energy for the production of secondaries. The head-on collisions would lead therefore to a smaller number of secondary particle providing a steeper decrease of the energy spectrum, i.e. it will result in the appearance of the knee. The self-damping leads to suppression of particle production processes at small impact parameters and it would be responsible for the slow down of the energy dependence of the average multiplicity [12].

The schematic energy dependence of the function $P(s, b = 0)$ is shown in Fig. 2. Various particular models can be utilized for calculation of the function $P(s, b)$ and they would lead to the variations in the particular functional energy dependence, but the distinct feature related to the all models with the reflective scattering mode is the non-monotonous energy dependence of the function $P(s, b = 0)$ with its minimum at the energy $s_0$.

As it was noted, the reflective scattering mode emerges at the LHC energies as it was predicted in [10] and independently in [13], it was confirmed on the base of the experimental data analysis in [7], and studies of the EAS originated from the primary cosmic particles interactions with atmosphere provide further evidence.
Figure 2: A schematic energy dependence of the function $P(s, b = 0)$ in the typical models with reflective scattering.

for it. The main contribution to the mean multiplicity comes from the region of $b \sim r(s)$ leading to the events with the alignment which also has been observed in EAS [1].

The detected EAS composition is correlated with the behavior of the function $P(s, b = 0)$. It is clear that its larger value means higher fraction of the elastic (proton) component. Therefore, increase of this component would result in the enhancement of the relative fraction of the protons in the observed cosmic rays spectrum since just the protons mainly constitute the primary cosmic rays. Otherwise, decrease of $P(s, b = 0)$ means the increase of the pion component in EAS and consequently an increasing number of muons observed in form of the multi-muon events. The experimental data revealed that relative fraction of protons in cosmic rays shows non-monotonous energy dependence which is similar to $P(s, b = 0)$ dependence (cf. Fig. 3).

2 Conclusion

We considered an approach where the corresponding particle generation mechanism in EAS is affected by the unitarity effects, and the energy region between the knee and the ankle coincides with the region where the reflective scattering mode becomes more and more prominent.

Other interesting cosmic rays phenomena such as Centauro and anti-Centauro events have also been observed, but those cannot be explained solely by the emergent reflective scattering. The reflective scattering itself needs to be interpreted at the dynamical level and such interpretation could provide, in particular, a hint to
Figure 3: Relative fraction of the protons in EAS, figure is taken from [14]; the further related details can be found there.

explanation of the other cosmic peculiarities.

The distinctive feature of the reflective scattering mode is the peripheral impact parameter distribution of the probability of the inelastic production. This can be associated with the production of the hollow fireball in the intermediate state of hadron–hadron interaction. The projection of this fireball onto the transverse plane looks like a black ring. The interpretation of this hollow fireball can be borrowed from the papers written about two decades ago [15, 16]. It was supposed that the interior of this fireball filled by the disoriented chiral condensate which finally irradiates away. This irradiation is supposed to be coherent, classical with a given isospin in each event, i.e. in one event the isospin can be directed along with $\pi^0$ while in other event its direction can be orthogonal leading to production of charged pions. It would explain appearance of the Centauro and anti-Centauro events.

Thus, the emergent reflective scattering mode could provide a clue for the understanding of the peculiarities observed in the EAS studies of the cosmic radiation. The further studies of the proton scattering in the forward region at the LHC will be very helpful for the improved interpretation of the results of the cosmic rays experiments.
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