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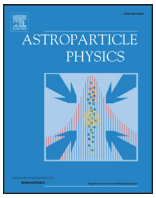

Soft particle production in very high energy hadron interactions

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A B S T R A C T

Indications of a discrepancy between simulations and data on the number of muons in cosmic ray (CR) showers exist over a large span of energies. We focus in particular on the excess of multi-muon bundles observed by the DELPHI detector at LEP and on the excess in the muon number in general reported by the Pierre Auger Observatory. Even though the primary CR energies relevant for these experiments differ by orders of magnitude, we can find a single mechanism which can simultaneously increase predicted muon counts for both, while not violating constraints from accelerators or from the longitudinal shower development as observed by the Pierre Auger Observatory. We present a brief motivation and describe a practical implementation of such a model, based on the addition of soft particles to interactions above a chosen energy threshold. Results of an extensive set of simulations show the behavior of this model in various parts of a simplified parameter space.

1. Motivation

The cosmic ray (CR) showers originated by cosmic particles with energies up to the limit of the order of 10^{20} eV provide a unique opportunity to study particle interactions at energies inaccessible to terrestrial accelerators. Dedicated models of hadronic interactions (e.g [1–3].) describe features of these showers remarkably well with the exception of muon production. Discrepancies between the data and the models have already been observed in CR showers detected by three out of the four LEP experiments which in addition to e^+e^- interactions, measured also cosmic muons, each of them with different overburden. The shallowest experiment L3+C [4] with 30 m of overburden used simultaneously a shower array on the ground. Detectors designed for collider experiments provided data superior to standard cosmic ray experiments and their tracking capabilities combined with the overburden enabled measurements of the muon content of the cores of showers at energies $10^{14} - 10^{17}$ eV. ALEPH [5] and L3+C were able to measure individual muon tracks up to saturation while DELPHI [6] made use of the fine granularity of its hadron calorimeter and measured integrated muon multiplicities. All three experiments observed high multiplicity events with a frequency which could not be fully described even by pure iron composition. The DELPHI results are the most robust from the statistical point of view.

The discrepancy between these measurements of high-multiplicity muon bundles and the models have inspired other experiments to investigate the issue. ALICE [7] has conducted dedicated cosmic-ray measurements similar do DELPHI and found results consistent with current hadronic interaction models. ALICE has better resolution in muon multiplicity then DELPHI, but smaller detection area and a smaller cut-off â only 16 GeV for vertical muons, compared to 52 GeV for DELPHI; thus those results are not directly comparable. Another experiment dedicated to muon bundles is NEVOD-DECOR [8] which however does not measure individual high-energy muons directly.

The influx of new data from LHC experiments allowed the tuning of models up to these energies. However, the tuned CR models still do not describe well, in particular, the DELPHI data as discussed later. Generally the models tuned to LHC do better than their earlier versions - e.g. QGSJET-II-03 [9] vs. QGSJET-II-04 [1]. However, they also tend to underestimate the muon component of ultra-high energy CR showers as indicated chiefly by several studies done at the Pierre Auger Observatory [10], which can access very high c.m.s. energies thanks to its sensitivity to ultra-high energy CR [11–13]. The available detection techniques of CR showers allow us to study only the gross features of the most common interactions. The ubiquity of the muon excess and span of the energy range where it occurs suggest that its origin is more probably connected with standard features of hadronic interactions rather than with some new exotic phenomena.

This paper aims to show that the addition of particles (mainly pions) with small momenta in the corresponding c.m. system, (“soft particles” from now on) to high-energy interactions in the

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CR showers could improve the description of the muon production in CR showers without significantly deviating from the framework of standard modeling of hadron interactions. Interestingly enough it turns out that if such an effect is assumed, the constraints provided by LHC experiments, the DELPHI CR measurements and the data of the Pierre Auger Observatory are sufficiently strong and do not leave much space for significant changes of the models because of the large energy span where the muon excess is consistently observed.

Obviously, the addition of soft particles is not the only possible explanation for the observed excess. Barring exotic physics, the main other possible source of muons is the uncertainty in the production of the heavy flavors [14]. However, it is now experimentally established by LHC that the heavy flavor production does not suffice to increase the muon content in the showers detected by DELPHI [15] to observable amount. Even at very high energies where one could hypothesize copious heavy flavor production this would actually lead to much larger missing energy and lower muon production as the hard muons and neutrinos produced via heavy flavors would take away energy missing in soft pion production [16].

2. DELPHI data and simulations

The main cosmic ray result from DELPHI is the measurement of bundles of muons from extensive air showers. At high observed muon multiplicities, the observed flux of events is in excess with respect to simulations even for a pure iron primary beam. Actually, due to saturation of the signal in streamer tubes – the smallest sensing units in the hadron calorimeter of DELPHI (HCAL), which signaled just passing one or more muons, DELPHI measured a lower limit of muon multiplicity in each event. Only at low multiplicities this coincides with the real muon multiplicity in HCAL. The standard detector simulation program DELSIM [17] traces all particles produced in e^+e^- interactions through the whole volume of the DELPHI detector. This would lead to prohibitive CPU times given the amount of simulated showers. We have thus created a simplified DELPHI model of muon detection which we use to interpret results of CORSIKA simulations in order to be able to compare the DELPHI data first with different new hadronic interaction models and ultimately with simulations having added soft particles. As this approach ignores many details of the experiment, it would be extremely difficult to reliably predict the overall normalization of the flux of the muon bundles and to understand which effects are due to the change of hadronic model and which simply due to the inadequacy of our simulations.

To avoid these issues, we use a different approach: from Trávníček [18] we know how the data compares with QGSJET-01 [19,20] proton and iron simulation – namely that for observed multiplicities larger than 20, there are (2.24 ± 0.17) times more events than in pure proton simulations and, for multiplicities larger than 80, there are (1.45 ± 0.23) times more events than in pure iron simulations; we denote these ratios DPH_{20} and DPH_{80} from now on and use them as benchmark observables to compare interaction models with that. To this end, we perform simulations with QGSJET-01 and use them as the basis for any further comparison. Ideally, we would like to find which model reproduces the DPH_{20} and DPH_{80} the best for a realistic mixture of primary particles (as discussed later) – not just for an extreme and most likely unrealistic assumption of pure iron primary beam.

Our simplified DELPHI is a geometric model which mimics the shape and rough properties of the HCAL – it has two parameters, one corresponding to the chance to miss a muon traversing the detection volume due to the combination of dead spaces and finite efficiency of the sensitive parts. The other parameter corresponds to HCAL granularity, which is related to the saturation that occurs when more muons pass through one streamer tube. These values are fixed by hand by tuning the dependence of reconstructed muon multiplicity on the true one against the relevant information from Trávníček [18]. Interestingly, such a simplified description of the detector reproduces the results of much more involved simulations very well, as illustrated in Fig 1 where the distributions of projected angle (to the plane perpendicular to the beam line) of observed muon bundles in DELPHI are compared for our model and that used in [6]. The rock overburden is taken into account as a simple cutoff at 52 GeV for vertical muons with simple geometric zenith-angle dependence – as the amount of mass is quite substantial, the fluctuation in energy losses of muons over the track is very small. Each CORSIKA shower is used 100 times with a random core position within 150 m of the detector, a distance chosen so that for any shower, at least a third of core positions produce no muons in the detector.

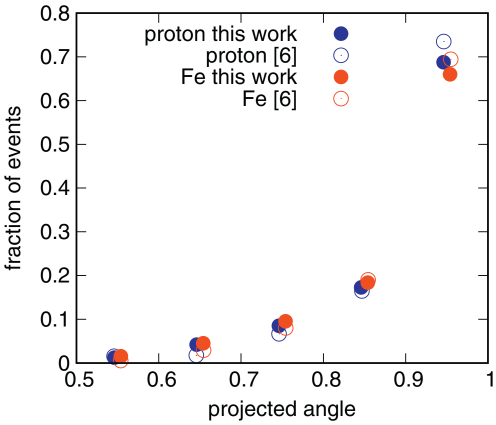

Fig. 1. Comparison of relative distribution of projected angle of muon bundles with observed multiplicity larger than 20 predicted by our simplified DELPHI model with simulated values from Abdallah et al. [6] for proton and iron primaries. The values have been slightly shifted on the *x*-axis for readability.

The CORSIKA [21] (version 7.37) simulations are carried out in the energy range of 10^{14}–10^{18} eV, which is sufficient for observed muon multiplicities above 10. The primary spectrum is simulated as E^{-1} and re-weighted in the same way as in [18] to $E^{-2.7}$ above the knee (3×10^{15} eV) and E^{-3} below the knee. We do not have to make any assumptions about the overall primary flux, because we always compare simulations to simulations with the same overall number of events. However, it is interesting to note that the flux used in [18] to derive the experimental values DPH_{20} and DPH_{80} was the maximal flux permitted by various cosmic ray experiments. Thus, any uncertainty in the flux only increases the observed effect. Varying the flux and spectrum in our simulations within the uncertainties quoted in [22] can change the DPH_{20} and DPH_{80} by up to 15 % – but only downwards. Four primaries (p, He, N and Fe) are simulated and a realistic energy-dependent primary beam is formed according to KASCADE and KASCADE-Grande data [22] (Fig. 2).[1]

The simulated zenith angle is 0–60° as inclined showers are highly suppressed due to the overburden increase with zenith angle. The low-energy model in CORSIKA is always set to be GHEISHA

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[1] Considering that in order to extract the primary composition from any EAS data, hadronic interaction models have to be used, we should be using a different composition for each model to ensure internal consistency of the procedure. While interpretations of KASCADE data for several different commonly used models are available, this is not the case for any modified models. However, there is consensus that below the knee the composition is rather light and then it gets heavier until reverting to mainly proton at 10^{18} eV according to the Auger data and this trend is reflected in our reference choice.