

Photoproduction total cross section and shower developmentF. Cornet,¹ C. A. García Canal,² A. Grau,¹ G. Pancheri,³ and S. J. Sciutto²¹*Departamento de Física Teórica y del Cosmos and Centro Andaluz de Física de Partículas, Universidad de Granada, E-18071 Granada, Spain*²*Departamento de Física, Universidad Nacional de La Plata, IFLP, CONICET, Casilla de Correo 67, 1900 La Plata, Argentina*³*INFN Frascati National Laboratories, Via Enrico Fermi 40, I-00044 Frascati, Italy*
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The total photoproduction cross section at ultrahigh energies is obtained using a model based on QCD minijets and soft-gluon resummation and the ansatz that infrared gluons limit the rise of total cross sections. This cross section is introduced into the Monte Carlo system AIRES to simulate extended air showers initiated by cosmic ray photons. The impact of the new photoproduction cross section on common shower observables, especially those related to muon production, is compared with previous results.

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I. INTRODUCTION

The determination of the composition of ultrahigh energy (UHE), i.e., with energies larger than 10^{18} eV, cosmic rays is an important open problem in cosmic ray physics. A good knowledge of the percentage of protons, heavy nuclei and photons hitting the atmosphere can provide important clues to understand the origin of those cosmic rays and their acceleration mechanism. The Pierre Auger Observatory [1] has devoted much effort to this end and has recently determined that the composition of UHE cosmic rays varies from mainly protons at $E = 10^{17.5}$ eV to the presence of heavy nuclei at $E = 10^{19.5}$ eV [2]. However, as no photons have been found up to now, the following bounds on the fraction of photons arriving at Earth have been set: 3.8%, 2.4%, 3.5% and 11.7% for photon energies above 2×10^{18} eV, 3×10^{18} eV, 5×10^{18} eV and 10×10^{18} eV, respectively [3]. An important parameter to obtain these bounds is the photon-proton total cross section from which one can estimate the photon-nucleus total cross section.

There are no experimental values for $\sigma_{\text{total}}^{\gamma p}$ at very high cosmic ray energies, so one has to rely on extrapolations of accelerator data, which in the case of photoproduction, are limited to $\sqrt{s} \lesssim 200$ GeV. Consequently, the extrapolation to higher energies leaves considerable uncertainties. One possibility is to use recent LHC data, up to $\sqrt{s} = 8$ TeV, and to use models describing both photoproduction and proton-proton scattering to infer, from pp data, the higher energy behavior of $\sigma_{\text{total}}^{\gamma p}$. Notice that the release of LHC data on the total proton-proton cross section has led to slight adjustments of the model parameters in most current hadronic models. The reason follows from the fact that lower energy data on hadron-hadron scattering, notably at $\sqrt{s} = 540$ GeV and 1800 GeV, have an uncertainty of 10% or more. Thus, often, a band, rather than a single curve, was provided. After TOTEM data appeared [4,5], the models

could be sharpened by taking into account the much smaller error reported. In turn, this sharpened tuning could be used for the high energy extrapolation of $\sigma_{\text{total}}^{\gamma p}$.

Here we follow the mentioned procedure. The updates of previous predictions [6] for $\sigma_{\text{total}}^{\gamma p}$ on the basis of LHC data are then used as input to the AIRES [7] system to simulate extended air showers initiated by photons.

The model for the total cross section, which we apply here, includes basic QCD inputs such as the parton densities obtained from experiments and well-known QCD subprocess cross sections [8]. A few nonperturbative parameters are also included. These ingredients allow the search for the effects of the hadronic structure of the photon through the analysis of the total cross sections in which they are involved.

In summary, the model developed in [8] is based upon the use of the following:

- (i) QCD minijets to drive the rise of the total cross section in the asymptotic regime.
- (ii) The eikonal representation for the total cross section using a purely imaginary overlap function, obtained from minijet QCD cross sections.
- (iii) The impact parameter distribution, input for the eikonal, obtained from the Fourier transform of the resummed soft-gluon transverse momentum distribution.
- (iv) The resummation of soft-gluon emission down to zero momentum.

The last element is the specific feature of this model, hereafter called the BN model from the well-known Bloch and Nordsieck [9] study of the infrared catastrophe, which occurs in electrodynamics when the soft photon momentum goes to zero. In the model, the resummation of QCD soft gluons is applied and covers the region where $k_i^{\text{gluon}} \rightarrow 0$ with an ansatz, discussed below. One should notice that the main difference of this proposal with respect to other

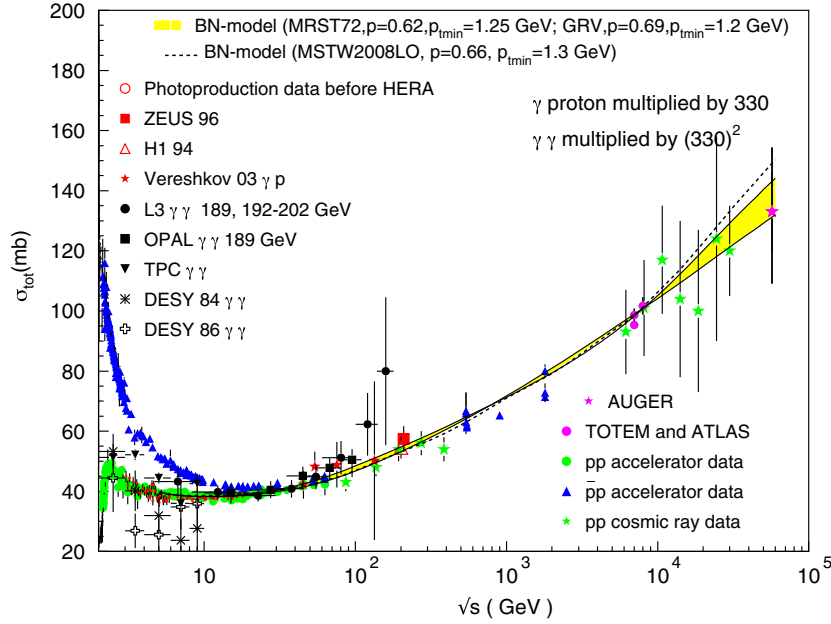


FIG. 1 (color online). Total proton-proton, $p\bar{p}$, γp , $\gamma\gamma$ cross sections, normalized at low energy so as to show common features. This figure is updated from [6] to include recent data. The yellow band and the dashed line are obtained from a description of pp scattering with an eikonal model inclusive of minijets and soft-gluon resummation, described in the text and called the BN model.

minijet models comes from the energy dependence of the impact parameter distribution and from soft-gluon k_t resummation extended to zero momentum modes. The model presented in the next section probes into this region.

II. BLOCH-NORDSIECK MODEL FOR TOTAL CROSS SECTIONS

In this section we update previous results from the BN model for the $\gamma - p$ total cross section [6], which will be put into the AIRES simulation program.

The BN model [8] is based on two features of all hadronic cross sections:

- (i) As the c.m. energy increases from fixed target experiments to those at colliders, both purely hadronic and with photons, such as HERA (γp), all total cross sections first decrease and then, around $\sqrt{s} = 10 - 20$ GeV for the pp case, start increasing. Minijet models attribute this transition to the onset of hard and semihard parton-parton collisions, which can be described by perturbative QCD. Such a suggestion was made a long time ago [10] when proton-proton scattering at the CERN intersecting storage rings (ISR) [11] confirmed the increase that cosmic ray experiments had already seen [12]. The large errors affecting the cosmic ray experimental data had cast uncertainty on a definite conclusion, but the ISR measurements definitively confirmed the increase, which was soon interpreted as a clear indication of the composite parton picture we are familiar with today. The role of minijets both in

minimum bias physics [13] and in the increase of the total cross section [14] was then further developed and has been put into many simulation programs.

- (ii) The observed increase, which may initially be considered to follow a power law, must obey the limitations of the Froissart bound, namely,

$$\sigma_{\text{total}}(s) \approx [\ln s]^2 \text{ as } s \uparrow \text{ at most} \quad (1)$$

where the bound is connected to the existence of a cutoff in impact parameter space [15].

Both features are embedded into Fig. 1, where the proton and photon cross sections are shown together, normalized at low energy, to highlight their common features. The yellow band, superimposed to the data, comes from the BN model we describe below.

The first feature of the total cross section, i.e., the increase at high energy, is obtained in minijet models, through a perturbative calculation based on the QCD jet cross section, namely,

$$\begin{aligned} \sigma_{\text{jet}}^{AB}(s, p_{t \text{ min}}) &= \int_{p_{t \text{ min}}}^{\sqrt{s}/2} dp_t \int_{4p_t^2/s}^1 dx_1 \int_{4p_t^2/(x_1 s)}^1 dx_2 \\ &\times \sum_{i,j,k,l} f_{i|A}(x_1, p_t^2) f_{j|B}(x_2, p_t^2) \frac{d\hat{\sigma}_{ij}^{kl}(\hat{s})}{dp_t}, \end{aligned} \quad (2)$$

with $A, B = p, \bar{p}, \gamma$, and $d\hat{\sigma}_{ij}^{kl}(\hat{s})/dp_t$ is the parton-parton differential cross section, calculable from QCD, using the

asymptotic freedom expression for the running coupling constant. The parameter $p_{t\min} \approx 1 - 2$ GeV separates hard processes, for which one can use a perturbative QCD description, from the soft ones which dominate at low c.m. energy of the scattering hadrons. The minijet cross section is dominated by low- p_t processes, which cannot be identified by jet-finding algorithms but can still be perturbatively calculated using parton-parton subprocesses and Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) [16–18] evolved LO partonic density functions (PDFs) $f_{i|A}$, such as Glück-Reya-Vogt (GRV) [19], Martin-Roberts-Sirling-Thorne (MRST) [20], and CTEQ [21] for the proton or GRV [22], Glück-Reya-Shienbein (GRS) [23], and Cornet-Jankowski-Krawczyk-Lorca (CJKL) [24] for the photon.

Equation (2) gives a minijet cross section which increases very fast with energy. In order to ensure unitarity [14], the minijet cross section is embedded in an eikonal representation, whose implementation requires modeling the impact parameter space of the colliding hadrons. We notice that, in order to obey the limitations imposed by the Froissart bound [15], such modeling should include a large distance cutoff. In the BN model this is obtained by means of soft-gluon resummation down to zero momentum gluons.

In eikonal minijet models one starts with

$$\sigma_{\text{total}} = 2 \int d^2\mathbf{b} [1 - e^{-n(b,s)/2}], \quad (3)$$

where b is the impact parameter and the real part of the eikonal has been neglected. This is a good approximation at high energy. The average number of collisions $n(b,s)$ can be split into a soft contribution, which will be parametrized with a suitable nonperturbative expression, and a perturbative (pQCD) term, where both hard and soft-gluon emission contribute, namely, $n(b,s) = n_{\text{soft}}(b,s) + n_{\text{hard}}(b,s)$. In the minijet model of [8] the authors propose

$$n_{\text{hard}}(b,s) = A_{\text{BN}}(b,s) \sigma_{\text{jet}}(s) \quad (4)$$

with

$$\begin{aligned} A_{\text{BN}}(b,s) &= N \int d^2\mathbf{K}_\perp e^{-i\mathbf{K}_\perp \cdot \mathbf{b}} \frac{d^2P(\mathbf{K}_\perp)}{d^2\mathbf{K}_\perp} \\ &= \frac{e^{-h(b,q_{\max})}}{\int d^2\mathbf{b} e^{-h(b,q_{\max})}} \end{aligned} \quad (5)$$

and

$$h(b,q_{\max}) = \frac{16}{3} \int_0^{q_{\max}} \frac{\alpha_s(k_t^2)}{\pi} \frac{dk_t}{k_t} \log \frac{2q_{\max}}{k_t} [1 - J_0(k_t b)]. \quad (6)$$

The physical content of Eq. (5) is as follows: $A_{\text{BN}}(b,s)$ is obtained as the Fourier transform of the probability $d^2P(\mathbf{K}_\perp)/d^2\mathbf{K}_\perp$ that in a collision between two collinear partons, soft-gluon emission gives rise to an overall transverse momentum unbalance \mathbf{K}_\perp . This probability can be calculated through resummation of all soft gluons emitted in an otherwise collinear parton-parton collision. This leads to the exponentiation of the integrated single soft-gluon spectrum, given by the function $h(b,q_{\max})$ of Eq. (6).

The energy parameter q_{\max} represents the maximum transverse momentum for *single* gluon emission and embeds the kinematics of the process,

$$\begin{aligned} \text{parton}_1 + \text{parton}_2 &\rightarrow \text{jet}_1 + \text{jet}_2 \\ &+ \text{initial state emitted gluon.} \end{aligned} \quad (7)$$

Its calculation is detailed in [25] and follows the original formulation of [26]. As shown in [25], the energy parameter q_{\max} depends linearly on the p_t of the final state partons which, at leading order, are described as hadronizing in two jets. This description should hold at LO and upon averaging over all densities and subprocesses. Thus, q_{\max} depends on the PDFs chosen for the calculation of the minijet cross section. A description of q_{\max} and its dependence on energy, PDFs and $p_{t\min}$ was recently presented in [27] for purely proton processes; for the photon case, it can be found in [6].

Because the acollinearity introduced by soft-gluon emission reduces the cross section, the distribution of

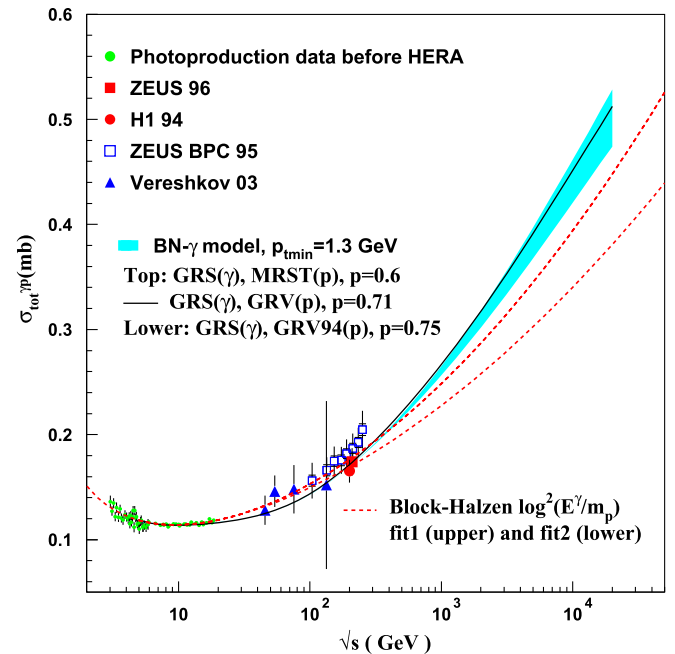


FIG. 2 (color online). Total photoproduction cross section and its description with the BN model and with the analytic model of Refs. [34,35].

Eq. (5) can give a cutoff in \mathbf{b} space, dynamically generated by soft-gluon emission; thus, it can reduce the very fast rise due to the minijet cross section. This effect is energy dependent and increases through the energy parameter q_{\max} , with the strength of the cutoff depending on the infrared region. This region is crucial to the calculation of the very large impact parameter processes, dominating all total cross sections.

In the BN model, the zero momentum gluon contribution is implemented by means of a singular but integrable behavior of the quark-gluon coupling constant in the infrared region, characterized by a singularity parameter $1/2 < p < 1$. For details we refer the reader to Refs. [8,28]. To fit this parameter, in this model one uses the expression

$$\alpha_s(k_t^2) = \frac{12\pi}{33 - 2N_f} \frac{p}{\ln[1 + p(\frac{k_t}{\Lambda_{\text{QCD}}})^{2p}]} \quad (8)$$

$$\xrightarrow{k_t \rightarrow 0} \frac{12\pi}{33 - 2N_f} \left(\frac{\Lambda_{\text{QCD}}}{k_t}\right)^{2p}.$$

This expression reduces to the usual asymptotic freedom expression for $k_t \gg \Lambda_{\text{QCD}}$, while the singular behavior for $k_t \rightarrow 0$ leads to a cutoff in impact parameter space, which is exponential for $p = 1/2$ and almost Gaussian for $p \lesssim 1$, and provides a mechanism for the implementation of the Froissart bound. As was shown in [28], the singular behavior of the coupling constant in the infrared limit leads to a large impact parameter behavior such as $A_{\text{BN}}(b, s) \approx \exp[-(b\bar{\Lambda})^{2p}]$. When coupled with the strong rise of the minijet cross section $\sigma_{\text{jet}} \approx s^\epsilon$, with $\epsilon \approx 0.3 - 0.4$, one obtains

$$\sigma_{\text{total}}^{pp} \rightarrow [\ln s]^{1/p} \quad \sqrt{s} \rightarrow \infty. \quad (9)$$

The singularity parameter p , together with $p_{t\min}$ and the choice of PDFs, completely determines $n_{\text{hard}}(b, s)$ and constitutes the high energy parameter set of the BN model. The choice of LO rather than next-to-leading order densities is discussed in [8] and follows from the ansatz that resummation takes into account most of the major next-to-leading order contributions. The remaining uncertainty, from nonresummed finite radiative corrections, is included in the parameters p and $p_{t\min}$, which are determined phenomenologically.

Prior to the start of LHC, with the above inputs and a phenomenological parametrization of the low energy region, the BN model gave a good description of pp and $p\bar{p}$ total cross sections, predicting $\sigma(\sqrt{s} = 14 \text{ TeV}) = 100 \pm 12 \text{ mb}$ [29]. The error corresponds to different choices of the PDFs and of the parameter set $\{p, p_{t\min}\}$, and it reflects the difficulty of determining the optimal sets

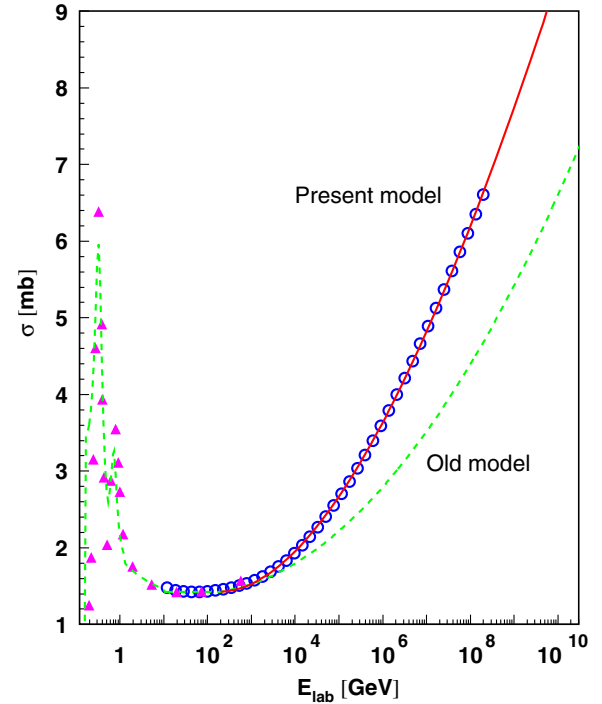


FIG. 3 (color online). Photon-air nucleus cross sections used in our simulations, plotted versus the photon lab energy. The triangles correspond to experimental data taken from Ref. [38]. The open circles correspond to the present model, and the solid line corresponds to a fit to these data, valid for energies greater than 200 GeV. The dashed line corresponds to the cross sections used in AIRES.

of parameters because of the large error from $p\bar{p}$ measurements at $Sp\bar{p}S$ and Tevatron energies.

The measurement of the total pp cross section at the LHC at energies $\sqrt{s} = 7$ and 8 TeV has allowed to reduce the parametric uncertainties present in most models. In Fig. 1 we present our updated analysis, with a band corresponding to the predictions for pp obtained with two different sets of LO PDFs, MRST and GRV. The yellow band shows how the BN model accommodates recent results for $\sigma_{\text{total}}^{pp}$, including the extraction of the pp cross sections from cosmic ray measurement by the AUGER Collaboration, at $\sqrt{s} = 57 \text{ TeV}$ [30]. With the choice of parameters as indicated in the figure and the set of MRST densities from [20], the value expected at $\sqrt{s} = 14 \text{ TeV}$ is $\sigma_{\text{total}}^{pp} = 112.24 \text{ mb}$. In addition, we also plot pp results obtained in [27] using more recent PDFs, such as MSTW08, indicated by the dashed line. Using older LO densities, such as GRV [19], one can also obtain a good description i.e., $\sigma_{\text{total}}^{pp} = 109.3 \text{ mb}$; namely, once the TOTEM, ATLAS and AUGER points (with their errors) are included in the description, the results, for different densities, are rather stable up to LHC energies. However, it must be pointed out that beyond the present LHC range ($\sqrt{s} = 7, 8 \text{ TeV}$), there is a band of uncertainty in the model

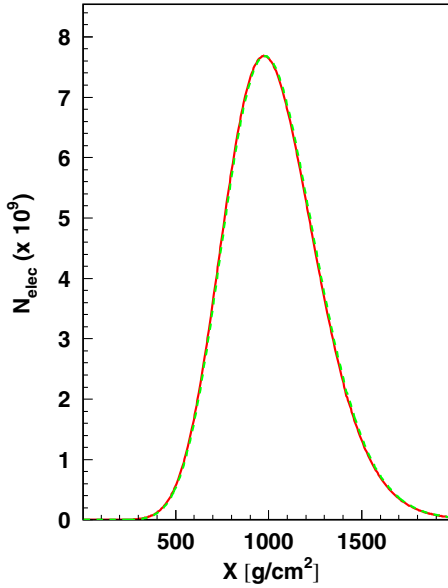


FIG. 4 (color online). Longitudinal development at sea level of electrons and positrons for 10^{19} eV photon showers inclined 60° . The solid (dashed) line corresponds to simulations with the present (old) model for the photonuclear cross section.

predictions, which corresponds to different extrapolations of the low x behavior of the densities as the energy increases. When the next LHC data are available, this band will hopefully be narrowed further. Meanwhile, in the update of our γp results described next, we use for the proton the same two sets of LO PDFs, MRST and GRV, used by our code in [6]. This choice may be modified in future applications.

We can now update the model for γp , which had been proposed before the LHC. In [6], following the model proposed by Fletcher, Gaisser, and Halzen in [31], the BN

model was applied to photoproduction with the following minimal modifications:

$$\sigma_{\text{tot}}^{\gamma p} = 2P_{\text{had}} \int d^2b [1 - e^{-n^{\gamma p}(b,s)/2}] \quad (10)$$

$$P_{\text{had}} = \sum_{V=\rho,\omega,\phi} \frac{4\pi\alpha}{f_V^2}, \quad (11)$$

$$\begin{aligned} n^{\gamma p}(b,s) &= n_{\text{soft}}^{\gamma p}(b,s) + n_{\text{hard}}^{\gamma p}(b,s) \\ &= n_{\text{soft}}^{\gamma p}(b,s) + A(b,s)\sigma_{\text{jet}}^{\gamma p}(s)/P_{\text{had}}, \end{aligned} \quad (12)$$

$$n_{\text{soft}}^{\gamma p}(b,s) = \frac{2}{3} n_{\text{soft}}^{pp}(b,s). \quad (13)$$

The extension to the photon process requires the probability P_{had} that the photon behaves like a hadron [31,32]. This quantity is nonperturbative and could have some mild energy dependence. However, to minimize the parameters, it was taken to be a constant, estimating it through vector meson dominance. In the analysis of [6], the value $P_{\text{had}} = \frac{1}{240}$ was used.

To determine the γp cross section that will be used as input for the ARES shower simulation program [7], we use Eq. (10). We update the values of the model parameters to take into account the impact of the recent LHC [4,5,33] and AUGER Observatory [30] results on the pp cross section, which appeared after the original analysis of [6].

The result is shown in Fig. 2, with a band of values for $\sigma_{\text{total}}^{\gamma p}$, and it is compared with fits by Block and collaborators [34,35], which impose a Froissart limit saturating the high energy behavior. The band reflects results from the BN model with two different PDF sets. For this application of

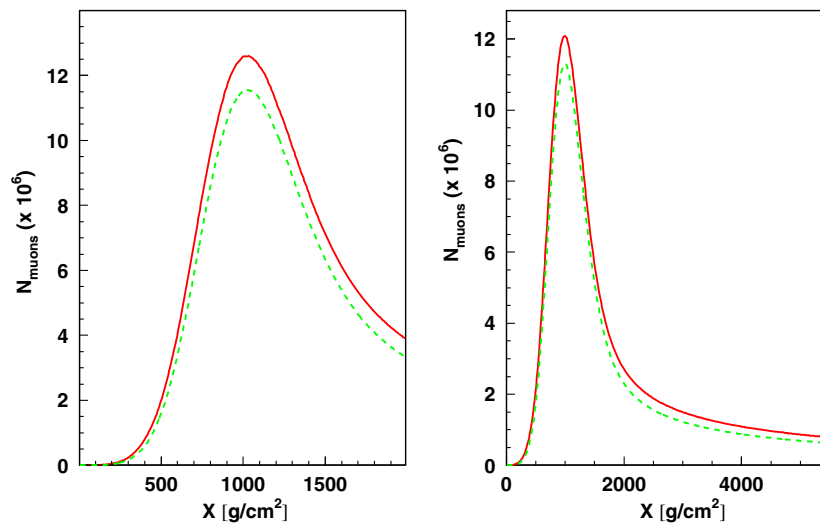


FIG. 5 (color online). Longitudinal development of muons for 10^{19} eV photon showers inclined 60° (left panel) and 80° (right panel) degrees. The solid (dashed) line corresponds to simulations with the present (old) model for the photonuclear cross section.

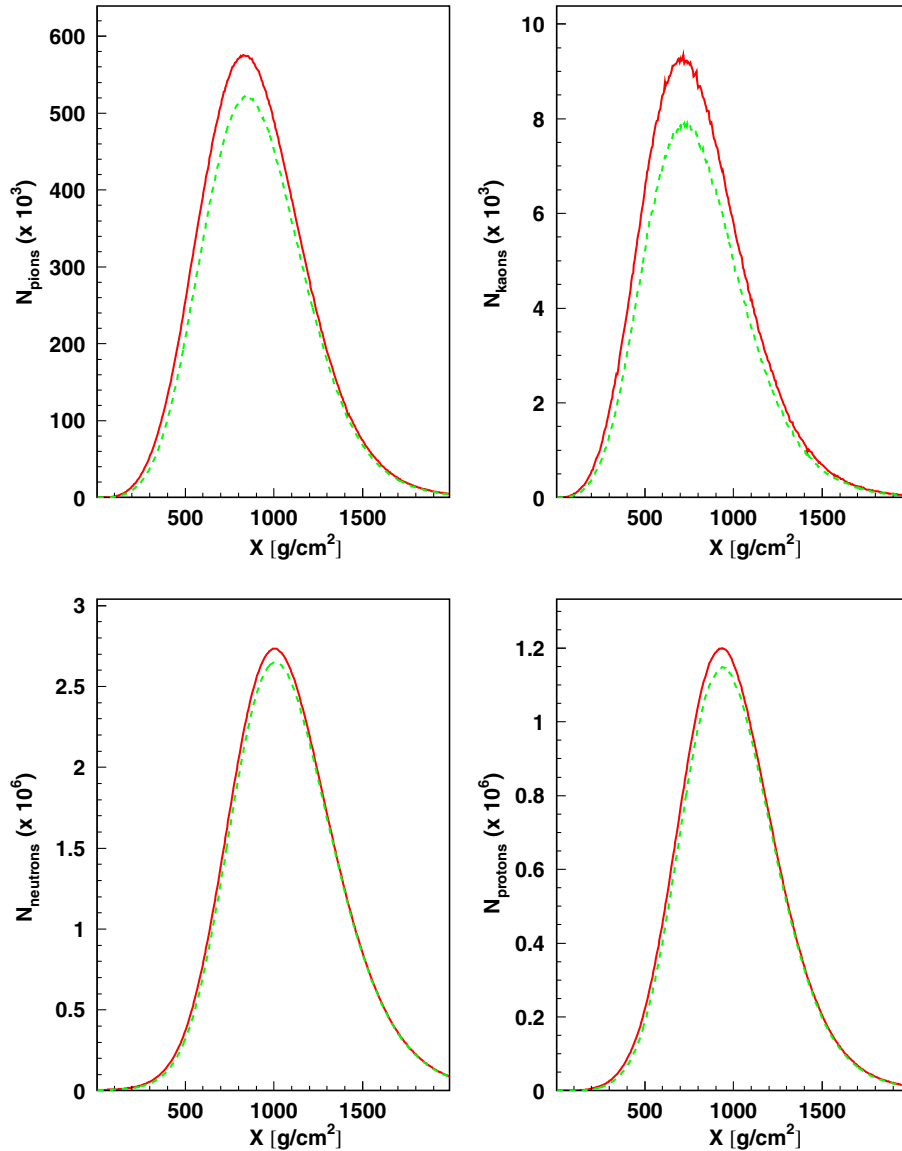


FIG. 6 (color online). Same as Fig. 4 but for the longitudinal development of hadrons. The upper left panel shows the pions, the upper right panel shows the kaons, the lower left shows the neutrons, and the lower right panel shows the protons.

the BN model, labeled as $BN - \gamma$, we have used GRS densities for the photon and the two PDF sets for the proton as in Fig. 1. The most recent type of PDFs, MSTW2008 [36], gives results similar to MRST for pp and has similar uncertainties in the extrapolation to higher, AUGER-type energies [27]. Other parameters are obtained by comparison with the proton-proton results, within a few percent from those which give the yellow band for proton-proton in Fig. 1.

III. SIMULATION RESULTS

We have performed simulations of extended air showers using the AIRES system [7] linked to the package QGSJET-II [37] for processing high energy

hadronic interactions. We have run two sets of simulations, namely, (1) using the cross sections for photoneuclear reactions at energies greater than 200 GeV that are provided with the currently public version of AIRES, and (2) replacing those cross sections by the ones corresponding to the present model. More precisely, we have chosen to use the γp cross sections corresponding to the upper curve of the blue band in Fig. 2 and fit 2 of [34,35], appropriately scaled to give the photon-air cross section required in AIRES. We are going to refer to sets (1) and (2) as “old model” and “present model,” respectively. In Fig. 3 the gamma-air nucleus cross sections corresponding to both sets are displayed as a function of the photon lab energy. The triangles correspond to experimental data taken from

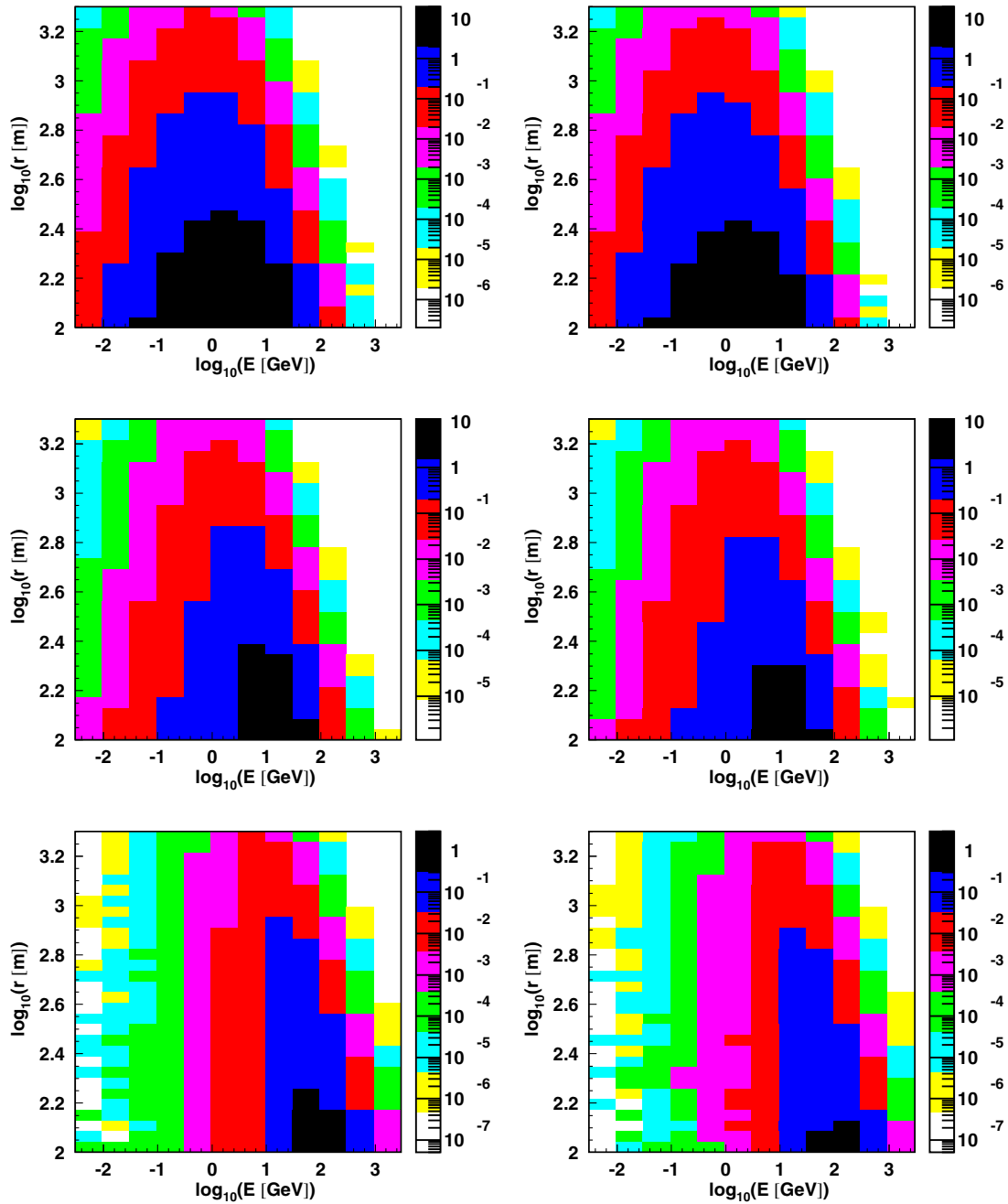


FIG. 7 (color online). Energy versus lateral (three-dimensional) distance to the shower axis distribution of ground muons for 10^{19} eV photon showers. The normalized density of muons $d\rho_{\mu}/d\log_{10}E$ (in m^{-2}) is represented in a color scale. The left (right) column plots correspond to simulations with the present (old) model for photonuclear cross sections. The upper, middle, and lower plots correspond to zenith angles of 45° , 60° , and 80° , respectively.

Ref. [38], while the open circles correspond to numerical calculations using the present model, valid for energies greater than 200 GeV. The dashed line corresponds to the up-to-now standard cross sections implemented in AIRES, the “old model” [34]. Notice that for energies below 200 GeV, we always use the same cross sections, which are calculated from fits to experimental data.

An important case to study the impact of changing the photonuclear cross sections at high energy is the case of showers initiated by photons. In such showers, the photonuclear reactions constitute the main channel for hadron production, which in turn is responsible for the production of muons, mainly via pion decay. It is a well-known fact that showers initiated by photons have noticeably less muons than showers initiated by hadrons, and this is one of

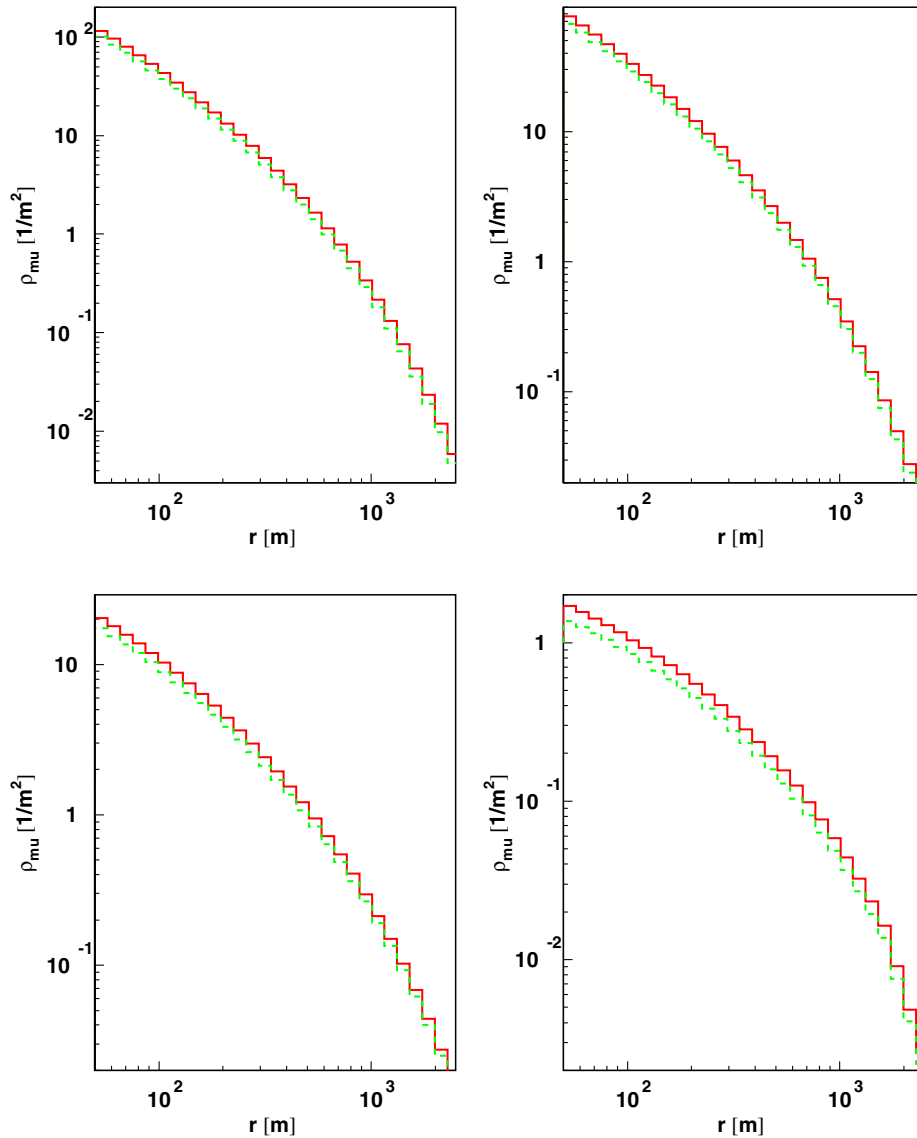


FIG. 8 (color online). Lateral distributions of ground muons for 10^{19} eV photon showers inclined 0 (upper-left panel), 45 (upper-right panel), 60 (lower-left panel), and 80 (lower-right panel) degrees. The solid (dashed) line corresponds to simulations with the present (old) model for photonuclear cross sections.

the features used to discriminate photonic from hadronic showers.

For brevity, in this paper we present results only for the very representative case of 10^{19} eV gamma showers. At this primary energy, geomagnetic conversion [39] is not frequent, thus allowing photons to enter the atmosphere unconverted and normally initiate the shower development. In most of our simulations, we have taken a ground altitude of 1400 meters above sea level (m.a.s.l.), corresponding to the altitude of current cosmic ray observatories. In some cases, that will be clearly identified in the text, we have used, for convenience, a sea-level ground altitude.

The most probable photon interactions at the mentioned energy are electromagnetic (i.e., pair production), and for that reason most of the shower secondaries will be electrons

and photons; the number of such secondaries is not expected to change substantially when replacing the photonuclear cross sections. This can clearly be seen in Fig. 4, where the average shower longitudinal development of electrons and positrons plotted shows almost no difference between the old and present models.

On the other hand, muon production is noticeably increased when using the new photon cross sections. We present our results for the longitudinal development of muons in Fig. 5, where it is clearly seen that the simulations with the present model produce more muons in virtually the entire shower life. The relative difference with respect to the old model is about 12% at the maximum ($X \approx 1100$ g/cm²). The difference persists even in the very late stage of shower development, as it can clearly be seen

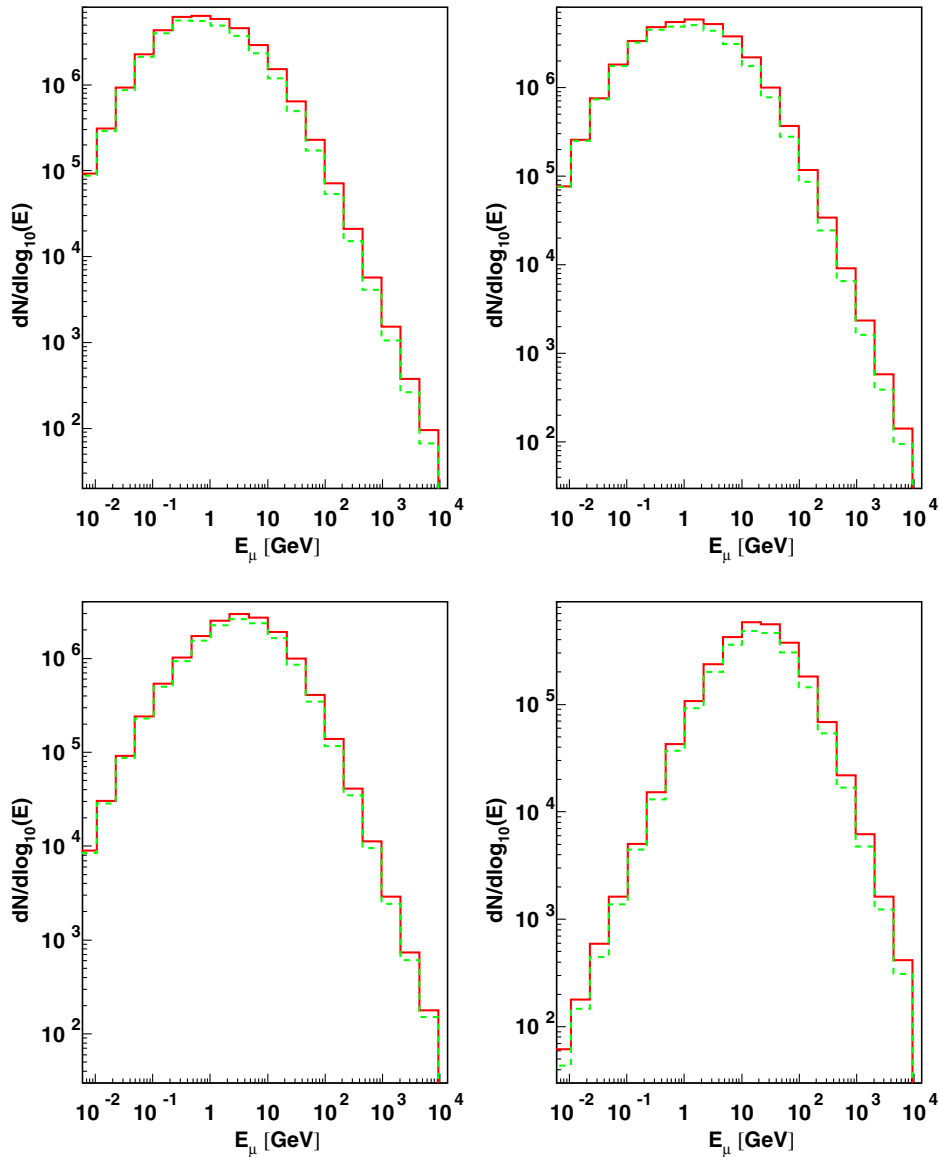


FIG. 9 (color online). Energy distributions of ground muons for 10^{19} eV photon showers inclined 0 (upper-left panel), 45 (upper-right panel), 60 (lower-left panel), and 80 (lower-right panel) degrees. The solid (dashed) line corresponds to simulations with the present (old) model for photonuclear cross sections.

in the case of 80° inclined showers displayed on the right side of Fig. 5.

It is important to recall that shower muons are generated after the decay of unstable hadrons, mainly charged pions and kaons. Hence, the enlarged number of muons that show up in Fig. 5 would necessarily be connected with enlarged hadron production, especially pions and kaons. The results of our simulations agree with this expectation. The results for the longitudinal development of charged pions, charged kaons, neutrons, and protons, plotted in Fig. 6 for the representative case of 10^{19} eV gamma showers inclined 60° , illustrate this point. These plots reveal a significant increase in the average number of produced pions and kaons, when comparing the simulations performed with the present model to the ones run with the old model. The plots

for neutrons and protons also indicate noticeable but smaller increments. The current figures are obtained using QGSJET-II to simulate hadronic interactions. Simulations performed with other hadronic collision packages could give numerically different results, but with the characteristic that larger hadron production will always be expected in the case of the present model because of its increased gamma-nucleus cross section, which enlarges the probability of hadronic collisions, especially for very energetic photons, present mostly at the early stages of shower development. The secondary particles generated after that initial shower multiplication process are the ones recorded in the plots of figure 6, and their number will be increased every time there is an increased hadronic collision probability.

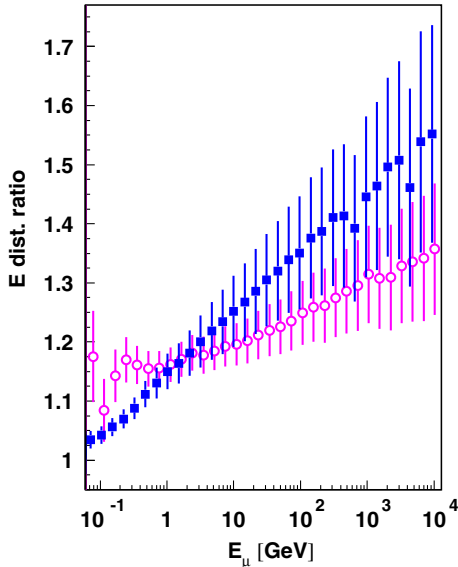


FIG. 10 (color online). Ratio between ground muon energy distributions obtained with the present and old models, for 10^{19} eV photon showers. The solid squares (open circles) correspond to a shower inclination of 45 (80)°. Error bars are calculated by propagation of the individual rms statistical errors of each of the distributions. The abscissas of the 80 ° data set have been shifted by 10% to improve error bar visibility.

It is also important to consider the characteristics of the muons produced in the simulations, especially those that reach the ground level. We focus on the representative case of 10^{19} eV gamma showers with ground altitude 1400 m.a.s.l. This roughly corresponds to an atmospheric slant depth of 900 g/cm^2 . Accordingly, with the results displayed in Fig. 5, this depth is located just before the maximum of the muon longitudinal profile.

In Fig. 7 the two-dimensional (energy versus three-dimensional distance to the shower axis) normalized density distribution of ground muons is represented in a variety of cases. The left (right) column show the distributions obtained from simulations performed using the present (old) model for photonuclear cross sections. The upper, middle, and lower rows correspond to zenith angles of 45 , 60 , and 80 °, respectively. The color scales used to represent the muon densities are unique in each row. Comparing the distributions corresponding to the different inclinations, we see clearly that the number of ground muons diminishes and their energy spectrum hardens as long as the zenith angle is increased (notice the different color scales used at each angle). Needless to say, this is the expected behavior for showers of varying inclination, which, at the same time, will show a very significant change in the ratio between the electromagnetic and muon ground particle distribution (see, for example, Ref. [40]). When comparing the results corresponding to simulations performed using the present and old models of photonuclear cross sections (left and right plots of Fig. 7, respectively), it is possible to notice that the

densities of muons corresponding to the present model are larger than the respective ones for the old model. The differences are approximately independent of muon energy and distance to the shower axis, as will be discussed in more detail in the following paragraphs.

The lateral and energy distributions of ground muons for various shower inclination angles are displayed in Figs. 8 and 9, respectively. As in the case of the distributions in Fig. 7, the simulations correspond to 10^{19} eV gamma showers, with ground altitude of 1400 m.a.s.l.

In the case of the lateral distribution of muons (Fig. 8), we observe that the distributions for the old and new photonuclear models are very similar in shape, differing only in the total number of particles. It can also be observed that the difference between photonuclear models becomes more significant for large zenith angles.

On the other hand, the muon energy distributions displayed in Fig. 9 present noticeable differences for muon energies greater than roughly 1 GeV, with the present model giving the largest number of particles in each bin. For muon energies lower than 1 GeV and zenith angles up to 60 °, both distributions are virtually coincident; in the case of showers inclined 80 °, the present model gives a larger number of particles in the entire muon spectrum. To better illustrate this characteristic of the impact of the photonuclear cross section on the average number of muons at ground level, we also include plots of the ratio between both muon energy distributions. In Fig. 10, such ratios are plotted as functions of the muon energy for the representative cases of 45 (solid squares) and 80 (open circles) degrees of inclination. The increased number of high energy muons resulting after the simulations using the present model for photonuclear cross sections shows up clearly in the case of showers inclined 45 °, reaching average values of more than 50% for muon energies of 10^4 GeV. In the case of showers inclined 80 °, the relative difference is always below 35% and remains virtually constant at approximately 15% for muon energies below 1 GeV.

IV. FINAL REMARKS

The main objective of this paper is to present a QCD-based model for photoproduction, updated from the previous analysis [6] in light of recent LHC results for total pp cross sections, and to study the impact of this new model on the photon-initiated air shower development. This model produces a photon-air nucleus total cross section significantly larger than the previous model included in the standard extended air shower studies. The present analysis based on simulations using the AIRES system clearly shows that for photon-initiated showers, the total muon production is increased in a measurable way. This result could be of direct importance in future determinations of bounds for the highest energy cosmic photon flux, particularly in the case of very inclined showers whose analysis is strongly based on

ground muon distributions [41]. In this respect, a more detailed analysis of these kinds of effects is in progress.

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