Photoproduction total cross section and shower development

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Abstract. A recent model for the total photoproduction cross section based on the ansatz that infrared gluons limit the rise of all total cross sections based on QCD mini-jets and soft-gluon resummation is used to simulate air showers with the AIRES program. The impact on common shower observables, especially those related with muon production, is analysed and compared with the corresponding results obtained with previous photoproduction models.

Keywords: photonuclear air shower

I. INTRODUCTION

Recently, the eikonal mini-jet model added by soft gluon resummation extended to the ultrasonic region was introduced for a description of the pp/\bar{p}\bar{p} data [1] and has been successfully applied to the description of photon induced total cross sections [2]. This description is certainly consistent with the requirements of analyticity and unitarity.

The model for proton total cross-section includes basic QCD inputs such as the parton densities obtained from experiments and well known QCD subprocess cross-sections. A few non-perturbative parameters were also included. These ingredients allowed the searching 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 is based upon the use of:
- QCD mini-jets to drive the rise of the total cross-section in the asymptotic regime;
- The eikonal representation for the total cross-section using a purely imaginary overlap function, obtained from mini-jet QCD cross-sections;
- The impact parameter distribution, input for the eikonal, obtained from the Fourier transform of the re-summed soft gluon transverse momentum distribution;
- The resummation of soft gluon emission down to zero momentum.

One should notice that the main difference of this proposal with respect to previous ones comes from the energy dependence of the impact parameter distribution and from soft gluon k_t-resummation extended to zero momentum modes. The model probes into this region and was first discussed at length in QED by Bloch and Nordsieck (BN) [3].

That hard quark-parton processes drive the rise of the total hadronic cross-section was suggested long time ago [4] when proton-proton scattering at the CERN ISR [5] confirmed the rise which cosmic ray experiments had already seen [6]. The large errors affecting the cosmic ray data at that time had cast uncertainty on a definite conclusion, but the ISR measurements definitively confirmed the rise, which was soon interpreted as a clear indication of the composite parton picture we are familiar with today.

Early mini-jet models calculated perturbatively the total cross-section based on the QCD jet cross-section, namely

\[ \sigma_{jet}^{AB}(s, p_{tmin}) = \int_{p_{tmin}}^{\sqrt{s}/2} \int_{4p_{t}^2/s}^{1} dx_1 \int_{4p_{t}^2/(x_1s)}^{1} dx_2 \]

\[ \times \sum_{i,j,k,l} f_{ijA}(x_1, p_{t1}^2)f_{kjB}(x_2, p_{t2}^2) \frac{d\tilde{a}_{ij}^{h1}(s)}{dp_{t}} \]

with \( A, B = p, \bar{p}, \gamma \), and \( p_{tmin} \approx 1 - 2 \text{ GeV} \). This parameter distinguishes hard processes for which one can use a QCD description, from the soft ones which dominate at low c.m. energy of the scattering hadrons (for \( \sqrt{s} \leq 10 \div 20 \text{ GeV} \)). The mini-jet cross-section gets its name because is dominated by low-p_t processes, which cannot be identified by jet finding algorithms but still it can be perturbatively calculated using parton-parton sub-processes and DGLAP evolved Partonic Densities Functions \( f_{ijA} \), like GRV, MRST, CTEQ [7] for the proton or GRV[8], GRS [9] and CJKL [10] for the photon. The expression of Eq. (1) rises very fast, and to ensure unitarity it is embedded in an eikonal representation, whose implementation requires modeling the impact parameter space of the colliding hadrons. Neglecting the real part of the eikonal, which at high energy is a good approximation, one writes

\[ \sigma_{tot} = 2 \int d^2b \left[ 1 - e^{-n(b, s)/2} \right] \]

The average number of collisions is splitted as \( n(b, s) = n_{soft}(b, s) + n_{hard}(b, s) \), namely into a soft contribution which will be parametrized with a suitable non-perturbative expression, and a perturbative (pQCD) term where both hard and soft gluon gluon emission con-
The above expression was inspired by an argument due to Polyakov [15], and the parameter $p < 1$ for the integral in Eq. (5) to converge.

The physical content of the above expressions is transparent: the average $b$-distribution of the scattering process, $A(b, s)$, is obtained as the Fourier transform in impact parameter space of the resummation of all soft gluons emitted in the parton-parton collisions. The original kinematics for the process $[11]:$ parton$_1 +$ parton$_2 \rightarrow$ jet$_1 +$ jet$_2 +$ initial state emitted gluon is embedded in the energy parameter $q_{\text{max}}$, which represents the maximum transverse momentum for single gluon emission and depends on the $p_t$ of the final state partons which, at leading order, are described as hadronizing in two jets. This is of course a very schematic description, which should hold at LO and upon averaging over all densities and sub-processes. A description of how to calculate $q_{\text{max}}$ for purely proton processes can be found in [1], and for photons in [2]. Here also, the physical meaning is rather clear since the acollinearity introduced by soft gluon emission reduces the parton-parton cross-section: such acollinearity is energy dependent and increasing through the energy parameter $q_{\text{max}}$.

While the mini-jet cross-section is well defined, and can be calculated both at LO or NLO, the soft gluon integrated distribution given by Eq. (5) includes an integration down to zero momentum gluons. The model puts a great emphasis on this integration in the infrared region, considering it very crucial in the calculation of very large impact parameter processes, which are those dominating all total cross-sections. This reflects in the zero momentum gluon contributions. It was long ago proposed [12] that this region, usually described through an intrinsic transverse momentum [13], [14], can be explored using an ansatz for the behaviour of the strong constant on the infrared region given by

$$\alpha_s(k_t) = \text{constant} \times \left(\frac{A}{k_t}\right)^{2p} \quad k_t \rightarrow 0$$

The extension to photon processes requires the probability $P_{\text{had}}$ that the photon behaves like a hadron [17], [18]. This quantity is non perturbative and could have some mild energy dependence. However, to minimize the parameters, it was taken as a constant, estimating it through Vector Meson Dominance.

II. SIMULATION RESULTS

We have performed simulations of extended air showers using the AIRES system [19] together with the
hadronic interactions package QGSJET-II [20]. We have run two sets of simulations, namely, (1) using the cross sections for photonuclear 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. We are going to refer to sets (1) and (2) as “old model” and “present model”, respectively.

In figure 1 the different gamma-air nucleus cross sections are displayed as a function of photon lab energy. The triangles correspond to experimental data taken from reference [21], while the open circles correspond to numerical calculations using equation (7). The solid line is a fit to the present model calculations that is valid for energies greater than 200 GeV. The dashed line corresponds to the up to now standard cross sections implemented in AIRES, that we refer as “Old model” [22]. Notice that for energies less than 200 GeV we use always 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 production of hadrons, which in turn are 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 the features used to discriminate photon from hadronic showers.

For reasons of 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 is not frequent, thus allowing photons to enter the atmosphere unconverted, and initiate normally the shower development. We have taken in our simulations a ground altitude of 1400 meters above sea level, corresponding to the altitude of current Cosmic Ray Observatories.

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 always be electrons and photons; and the number of such secondaries is not expected to change substantially when replacing the photonuclear cross sections. This can clearly be seen in figure 2 where the longitudinal developments plotted show almost no differences 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 figure 3, where it shows up clearly that the simulations with 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 ($X \simeq 1100$ g/cm$^2$).

It is also important to consider the characteristics of the muons produced in the simulations. Let us consider the representative case of $10^{19}$ eV gamma vertical showers with ground altitude 1400 m.a.s.l. This corresponds roughly to an atmospheric slant depth of 900 g/cm$^2$. Accordingly with the results displayed in figure 3 this depth is located short before the maximum of the muon longitudinal profile.

In figure 4 the lateral distribution of muons is plotted as a function of the core distance. We observe that the distributions for the old and new photonuclear models are very similar in shape, differing only in the total

Fig. 2: Longitudinal development of electrons and positrons for $10^{19}$ eV photon showers inclined 60 degrees. The solid (dashed) line corresponds to simulations with the present (old) model for photonuclear cross sections.

Fig. 3: Same as figure 2 but for the longitudinal development of muons.
The model produces a photon-air nucleus total cross section significantly larger than the previous models included in the standard extended air shower studies. The present analysis based on simulations 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. In this respect, a more detailed analysis of this kind of effects is in progress.

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Fig. 4: Lateral distribution of muons at ground level for vertical $10^{19}$ eV photon showers. The solid (dashed) line corresponds to simulations with the present (old) model for photonuclear cross sections.

Fig. 5: Same as figure 4 but for the energy distribution of ground muons.

The main objective of this contribution is to study the impact of a recently proposed QCD-based model for photoproduction [2] on air shower development. This model produces a photon-air nucleus total cross section number of particles. On the other hand, the muon energy distributions displayed in figure 5 present noticeable differences for muon energies greater than roughly 1 GeV, with the present model giving the largests number of particles at each bin. For muon energies less than 1 GeV, both distributions are virtually coincident.

III. FINAL REMARKS

The main objective of this contribution is to study the impact of a recently proposed QCD-based model for photoproduction [2] on air shower development. This model produces a photon-air nucleus total cross section.