



Hadroproduction Measurements with NA61/SHINE for the Understanding of Extensive Air Showers

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Abstract: NA61/SHINE is a fixed-target experiment to study hadron production in hadron-nucleus and nucleus-nucleus collisions at the CERN SPS. Due to the very good acceptance and particle identification in forward direction, NA61/SHINE is well suited for measuring particle production to improve the reliability of air shower simulations. Data with proton and pion beams have been taken in 2007, 2009 and 2010. Here we present our measurement of the double-differential pion production cross section in $\pi + C$ collisions at a beam energy of 31 GeV and compare the data with predictions of low-energy hadronic interaction models.

Keywords:

1 Introduction

Ultra-high energy cosmic rays initiate extensive air showers (EAS) when they collide with the nuclei of the atmosphere. The interpretation of EAS data as for instance recorded by the Pierre Auger Observatory [4] or the KASCADE air shower array [5] relies to a large extent on the understanding of these air showers and specifically on the correct modeling of hadron-air interactions that occur during the shower development. The relevant particle energies span a wide range from primary energies of $\gtrsim 10^{20}$ eV down to energies of 10^9 eV. The mesons that decay to muons at ground level typically originate from low energy interactions in the late stages of an air shower. Depending on the primary energy and detection distance, the corresponding interaction energies are between 10 and 1000 GeV (cf. Fig 1). As it has been noted in e.g. [6–9], the modeling of low energy interactions contribute at least 10% to the overall uncertainty of the predicted muon number at ground. Since these energies are within the reach of fixed target experiments, precise measurements of hadronic particle production at, for instance, the Super Proton Synchrotron at CERN can help to diminish the uncertainties of air shower simulations.

An example of current difficulties to describe air shower measurements at ultra-high energies is the excess of the number of ground level muons wrt. to air shower simulations [11–13] as reported by the Pierre Auger Observatory [15]. A solution to this inconsistency was proposed in [14], where it was pointed out that an increased production of baryons and anti-baryons in hadron-air collisions, would lead to an increase in the number of muons

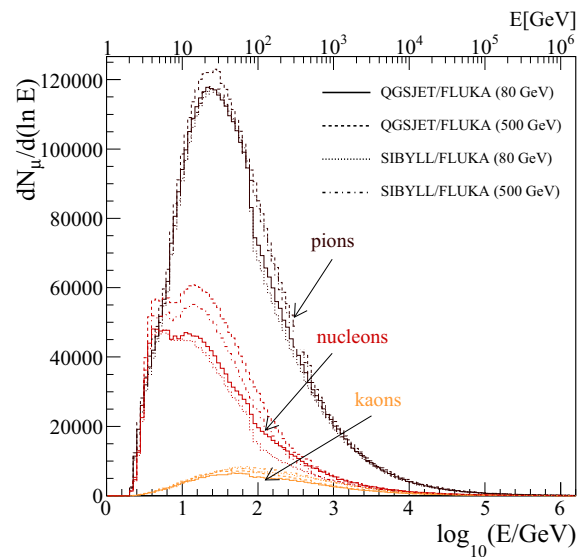


Figure 1: Particle types and energies involved in the last interaction leading to muon detected at ground level ($E_0 = 10^{19}$ eV, detection distance ≈ 1 km) [10].

at ground level. As can be seen in Fig. 2, an enhanced (anti-)baryon production, as e.g. currently implemented in the EPOS-model, should be easily distinguishable from previous model assumptions at fixed target energies.

Unfortunately, there exist no comprehensive and precise particle production measurements for the most numerous projectile in air showers, the π -meson. Therefore, new da-

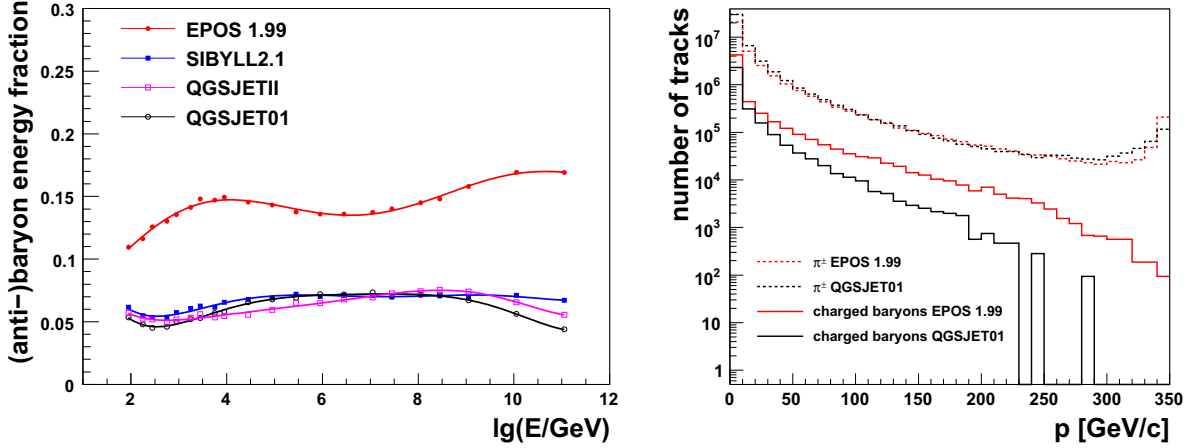


Figure 2: Left panel: Energy fraction of produced baryons and anti-baryons in π -air collision as a function of pion momentum. Right panel: Expected number of charged tracks as a function of secondary momentum for the NA61 π^- -C data set at 350 GeV/c.

ta with pion beams at 158 and 350 GeV/c on a thin carbon target (as a proxy for nitrogen) has been recently collected by the NA61 experiment at the SPS.

2 The NA61/SHINE Experiment

NA61/SHINE (SHINE = SPS Heavy Ion and Neutrino Experiment) [1] is an experiment at the CERN SPS using the upgraded NA49 hadron spectrometer. Among its physics goals are precise hadron production measurements for improving calculations of the neutrino beam flux in the T2K neutrino oscillation experiment [2] as well as for more reliable simulations of cosmic-ray air showers. Moreover, p+p, p+Pb and nucleus+nucleus collisions will be studied extensively to allow for a study of properties of the onset of

de-confinement and search for the critical point of strongly interacting matter (see e.g. [3]).

The NA61 detector uses large time-projection-chambers to measure the particle charges and momenta as well as their energy loss for particle type identification. Large scintillator walls provide an estimate of the particle's squared mass from the time-of-flight through the detector. The momentum resolution, $\sigma(1/p) = \sigma(p)/p^2$, is about $10^{-4} \text{ (GeV/c)}^{-1}$ at full magnetic field and the tracking efficiency is better than 95%. A set of scintillation and Cherenkov counters as well as beam position detectors upstream of the spectrometer provide timing reference, identification and position measurements of the incoming beam particles.

NA61 started data taking in 2007. After a pilot run with proton on carbon at 31 GeV/c, the data acquisition system has been upgraded during 2008 to increase the event processing rate by a factor of ≈ 10 . In the last two years, NA61 took data at beam energies from 13 to 350 GeV with proton and pion projectiles and proton and carbon targets (cf. Tab. 1).

3 Data Analysis

In this paper we present results on the inclusive production of positive and negative pions from p+C interactions at 31 GeV/c recorded during the 2007 pilot run [16]. The pion spectra have been obtained using three independent analysis techniques: Firstly, with the so-called h^- method all negative hadrons produced in a collision are assumed to be pions and the small contribution of other species is corrected for using simulations. Due to the large contribution from protons, this method can only be applied to determine the π^- spectra. Secondly, with the dE/dx method π -mesons are identified explicitly using the energy deposit

	p [GeV/c]	year	N_{trig} [10^6]
$\pi^- + \text{C}$	158	2009	5.5
$\pi^- + \text{C}$	350	2009	4.6
p+C	31	2007	0.7
p+C	31	2009	5.4
p+p	13	2010	0.7
p+p	20	2009	2.2
p+p	31	2009	3.1
p+p	40	2009	5.2
p+p	80	2009	4.5
p+p	158	2009	3.5
p+p	158	2010	43.9

Table 1: Number of thin target triggers collected by NA61 (typically 85% interaction triggers and 15% minimum bias beam triggers).

measured in the TPCs. This method works only in momentum regions where Bethe-Bloch bands do not overlap. Finally, using the dE/dx -plus-ToF method, $\pi^\pm$ can be identified over a wide momentum range using the combination of energy loss and m^2 from the time-of-flight measurement. This method provides the most precise particle identification, but it is limited to the angular acceptance of the time-of-flight detectors. Using a combination of all three methods, NA61 is able to measure $\pi^\pm$ -spectra with a large acceptance in angle and momentum and to cross-check the systematic uncertainties of the methods in the overlapping phase space regions.

4 Results

The production spectra of positive and negative pions in p+C interactions at 31 GeV/c from the 2007 pilot run are presented in Fig. 4 [16].

Systematic errors on the pion spectra were estimated by varying track selection and identification criteria as well as parameters used to calculate the corrections. The accuracy of corrections for acceptance and reconstruction efficiency was checked by comparison of results obtained using two independent subsamples of tracks: emitted to the left and to the right with respect to the incoming beam direction (track topology). The dominant contributions to the systematic error come from the uncertainty in the correction for weak decays and secondary interactions for all three analysis methods mentioned in the last section. The total systematic uncertainties for the individual measurement points are typically at the 5% level.

The spectra in Fig. 4 are normalized to the π +C production cross section which we obtained by subtracting the quasi-elastic contribution from the measured total inelastic cross section of

$$\sigma_{\text{inel}} = 257.2 \pm 1.9 \pm 8.9 \text{ mb.}$$

which yields

$$\sigma_{\text{prod}} = 229.3 \pm 1.9 \pm 9.0 \text{ mb.}$$

A comparison to previous measurements of σ_{prod} is shown in Fig. 3.

As a first application of these measurement, it is interesting to compare the spectra to the predictions of event generators for hadronic interaction. Here we concentrate on the hadronic interaction models FLUKA2008 [20], URQMD1.3.1 [22] and VENUS4.12 [21]. All three models are part of the CORSIKA [23] framework for the simulation of air showers and are typically used to generate hadron-air interactions at energies below 80 GeV. To assure that all relevant settings of the generators are identical to the ones used in air shower simulations, we simulated single p+C interactions directly with CORSIKA in the so-called *interaction test mode*. As can be seen in Fig. 4, VENUS and URQMD simulations can not describe our measurements at all production angles. The best agreement is found for the

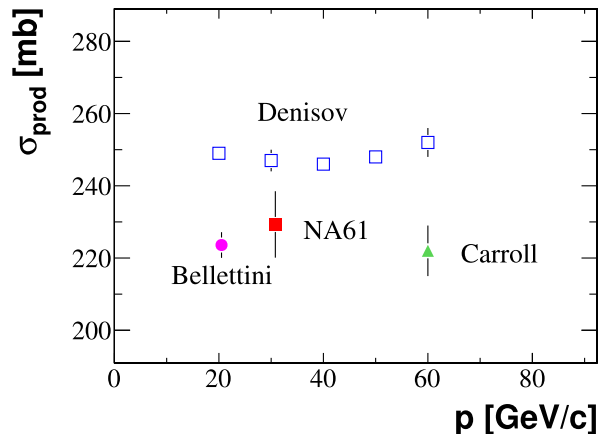


Figure 3: Beam momentum dependence of the production cross section for p+C interactions. The NA61/SHINE result (filled square) is compared with previous measurements [17–19]. For the NA61/SHINE point, the error bar indicates statistical and systematic uncertainties added in quadrature. The result from [17] was recalculated by subtracting from the measured inelastic cross section a quasi-elastic contribution at 20 GeV/c of $(30.4 \pm 1.9 \text{ (sys)})$ mb.

spectra generated with FLUKA, that show a good overall agreement with our data.

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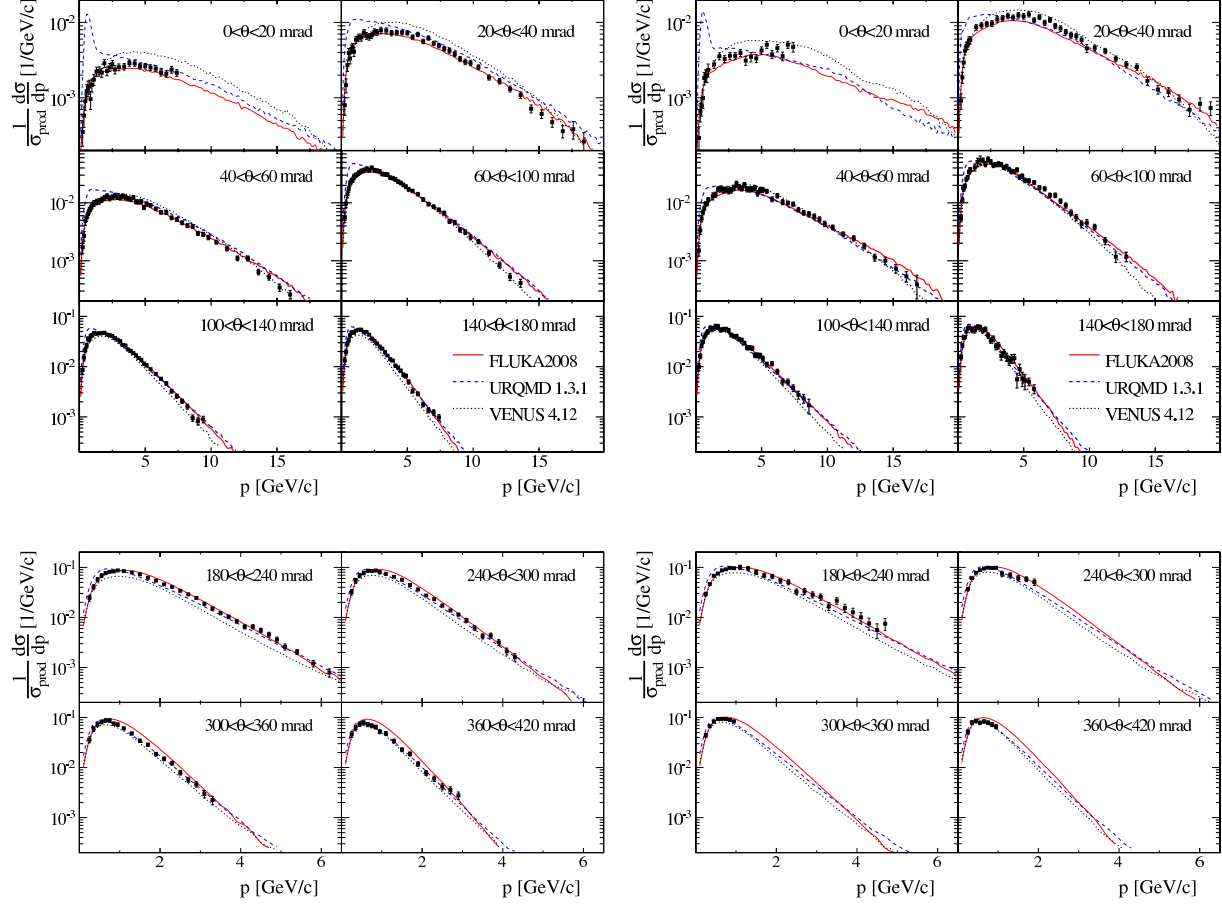


Figure 4: The π^- (left panel) and π^+ (right panel) spectra in p+C interactions at 31 GeV/c compared to FLUKA2008, URQMD1.3.1 and VENUS4.12 models.

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