Hadron Production Measurements with the NA61/SHINE Experiment and their Relevance for Air Shower Simulations

Ioana C. Mariş* for the NA61/SHINE Collaboration
Karlsruhe Institute of Technology (KIT), D-76021 Karlsruhe, Germany

***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 a large acceptance and good particle identification capabilities in forward direction, NA61/SHINE is well suited for measuring particle production to improve the reliability of air shower simulations. During its pilot run in 2007 proton-carbon collisions at 31 GeV/c were recorded. Dedicated runs for pion-carbon collisions at 158 and 350 GeV/c are planned for 2009. We will study the phase space regions of secondary particles that are of importance for understanding the muon production in air showers as measured by KASCADE and the Pierre Auger Observatory. The performance of the NA61/SHINE detector is discussed and preliminary results from the pilot run are presented.**

***Keywords*: NA61/SHINE, cosmic rays**

I. INTRODUCTION

Cosmic rays at very high energy ($E > 10^{14}\,\mathrm{eV}$) can be measured only indirectly by observing the secondary particles produced in cascade processes in the atmosphere. Therefore it is not surprising that many open questions in cosmic ray physics are related to the difficulty of determining the energy and mass/type of primary shower particle at these energies. For example, the mass composition of the primary particles can be obtained only from comparing air shower data with simulations of the air shower development in the atmosphere [1], [2].

The simulations involve detailed descriptions of the hadronic, muonic and electromagnetic components of the air showers. The present implementations rely on phenomenological models for the hadronic interactions and cannot describe the observed air shower properties with a good precision [3], [4]. For example, at the Pierre Auger Observatory, the observed number of muons is underestimated in simulations with commonly used hadronic interaction models [4].

Hadronic interaction models are based on extrapolations of the particles interaction properties in phase space regions which are presently not covered by particle physics experiments. The energies of the first interactions in high energy showers are not accessible by current accelerators. Furthermore, at low energies, there is a lack of precise data in the forward region and for projectiles and targets relevant for air showers [5]. The impact of the uncertainty of hadronic interaction characteristics on air shower observables does currently prevent an unambiguous analysis of air shower data in terms of e.g. the primary mass composition [1], [6].

While high energy interactions are of direct relevance to the longitudinal shower profile [7], particle production at low energy is important for the lateral distribution of shower particles at ground. The use of different hadronic interaction models for low-energy interactions ($E < 200\,\mathrm{GeV}$) leads to significant differences of the expected particles at ground [8], [9]. For example, in the case of the Auger Observatory [10], the predicted muon densities differ by more than 20% [8] with a difference of $\approx 40\%$ expected between proton and iron.

The NA61/SHINE (SHINE $\equiv$ SPS Heavy Ion and Neutrino Experiment) experiment [11] combines a rich physics program in an efficient and cost effective way offering the possibility to reach physics goals in three different fields: neutrino experiment calibration, cosmic ray simulations, and the behavior strongly interacting matter at high density.

The NA61/SHINE apparatus is an upgrade of the NA49 experiment [12]. A new time of flight detector has been tested and installed in the forward beam direction, increasing the accuracy of the particle identification. Moreover the update of the DAQ and of the readout of tracking detectors provides an increase of the maximum detection rate by a factor of 10 with respect to NA49. During its 10 years of operation the NA49 experiment delivered high precision data with beams ranging from proton to lead [13]. Among other results, the minimum bias analysis of p+p [14] and p+C [15] collisions at a beam momentum of 158 GeV/c provided information about the inclusive production of charged pions which already have been used to improve the precision of air shower simulations [16].

In the following we will investigate the phase space region important for cosmic ray experiments and compare it with the measurement capabilities of the NA61/SHINE experiment. Data taken in the 2007 pilot run are presented.

II. MUON PRODUCTION IN AIR SHOWERS

The electromagnetic component of extensive air showers originates from π^0 decays, bremsstrahlung and $e^\pm$ pair production with a small component from $\mu^\pm$ decays. The electromagnetic particles are well described by QED. The muonic component, produced mainly in decays of charged pions and kaons, depends upon the phenomenological models used to overcome the problems of perturbative QCD calculations for processes with low momentum transfer.

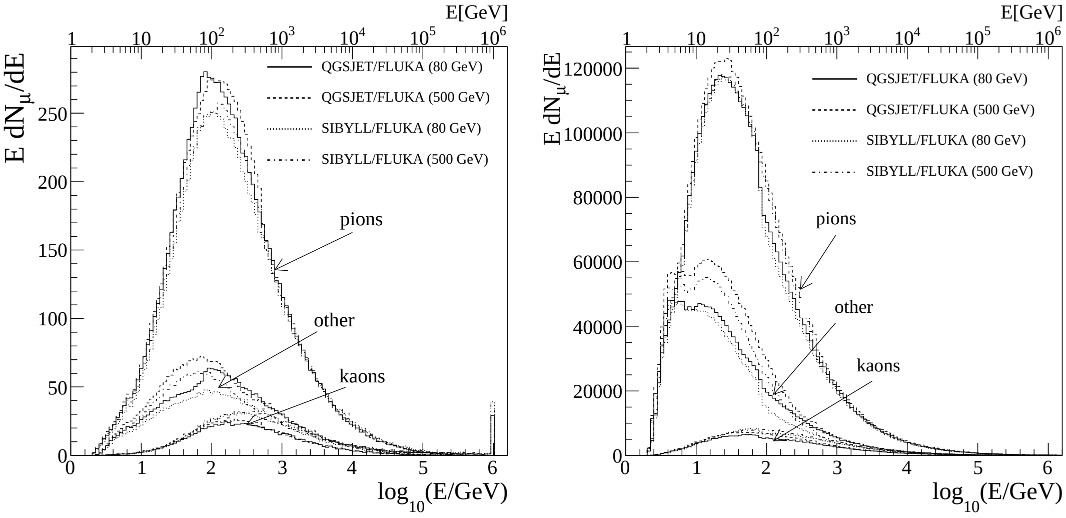

Fig. 1. Energy spectra of the grandmothers for a primary cosmic ray at 10^{15} eV (left) and 10^{19} eV (right). The transition energy between different interaction models is indicated in brackets. Only the grandmother particles of muons with a total energy larger than 250 MeV (left) and 150 MeV (right) were taken into account. The distance of the muons to the shower axis was required to be between 40 and 200 m (left) and 900 and 1100 m (right). The spectra are averaged over the total number of simulated air-showers.

In order to investigate the muon production, air shower simulations were performed assuming vertical incident protons as primary particles. To cover the knee energy range 1000 air-showers at 10^{15} eV were simulated and the particles were stored at an altitude of 100 m asl. The KASCADE experiment is sensitive to muons above 250 MeV and the distribution of particles on ground is mostly important at distances between 40 and 200 m from the air shower axis, therefore only muons in these ranges are considered. For ultra high energy cosmic rays, 5 events at 10^{19} eV were generated and the particles reaching an altitude of 1400 m were stored. At this energy the most important region is between 900 m and 1100 m from the shower axis, distance where the energy estimator and the mass composition parameters for the cosmic rays recorded by the surface detector of the Pierre Auger Observatory are evaluated. The water Cherenkov detectors are observing light from muons above 150 MeV.

The air showers were generated with a modified version of the CORSIKA [17] code for which the history of the muon production is available in the output [18]. In the following we refer by the term *grandmother* to the hadron inducing the last hadronic interaction that leads to a meson that decays into the corresponding muon. Each air shower was generated four times using different hadronic interaction models. FLUKA [19] was utilized for the description of the hadronic interaction in the low energy range and QGSJet II [20] or Sibyll 2.1 [21] to handle the high energy region. The assumption of the transition energy where the switch between the interaction models occurs influences the particle distributions at ground [22]. Therefore simulations with two transition energies were generated: at 80 GeV and 500 GeV. At the highest energies the available CPU time and storage do not allow to track all the particles in the cascade processed, therefore the electromagnetic component of these showers was neither tracked nor stored.

The energy spectra of the grandmother particles are depicted in Fig. 1. The difference in the distributions of the particles predicted by different high energy interaction models is compatible with the difference induced only by switching the transition energy. Small discontinuities at 80 and 500 GeV are observed indicating a miss-match between the predictions of low energy and high energy hadronic interaction models. The majority of muons are produced by charged pions ($\approx 95\%$) in the energy range 10-500 GeV. A $\approx 4\%$ contribution comes from kaons at 10-200 GeV.

Grandmother particles are equivalent to the beam particles for fixed target experiments. The majority of pions cover mostly the forward direction (polar angle, $\theta < 0.2\,\mathrm{rad}$). Giving the momentum range and the direction, the current and future data of the NA61/SHINE experiment are perfectly suited for improving the hadronic interaction models.

III. NA61/SHINE EXPERIMENT

The NA61/SHINE detector is located in the H2 beam line of the North experimental hall of the SPS. It employs a large hadron spectrometer for the study of the hadronic states produced in interaction of π, p, C, S or In beam particles with a variety of fixed targets at the SPS energies.

The layout of the NA61/SHINE experiment is presented in Fig. 2. The detector inherits the main components of the NA49 experiment [12]. A set of upstream scintillation or Cherenkov counters and beam position detectors (BPD) provides precise timing reference, charge and position measurement of the incoming beam particles. The components for tracking are four

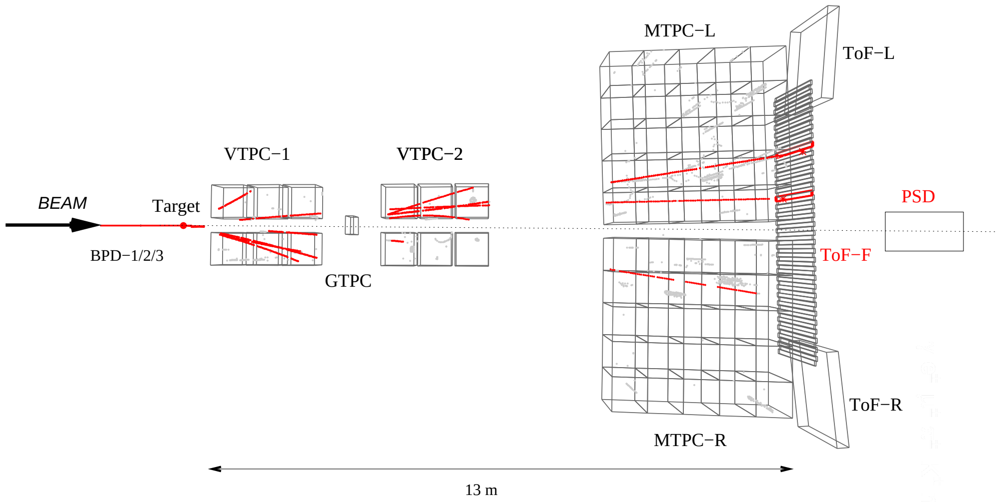

Fig. 2. A typical event recorded during the pilot run for a proton beam (31 GeV/c) on a thin carbon target. The NA61/SHINE detector layout is sketched with the exception of the vertex magnets surrounding the vertex TPCs. Two of the particles have left a signal in the forward ToF detector.

large volume Time Projection Chambers (TPCs). The vertex TPCs (VTPC-1 and VTPC-2) are located in the magnetic field of two super-conducting dipole magnets with a maximum combined bending power of 9 Tm at currents of 5000 A. The other two (MTPC-L and MTPC-R) are positioned symmetrically with respect to the beam line, downstream of the magnets. An additional gap TPC (GTPC) is located on the beam axis between the vertex TPCs.

At minimum ionization particle identification by energy loss measurement alone is not possible and even with a very good dE/dx resolution kaon selection on a track-by-track basis is not feasible. Therefore the NA49 detector was equipped with time-of-flight detectors (ToF-L and ToF-R) placed behind the MTPCs. The time resolution achieved is of 60 ps. In 2007 the experiment has been updated with a new forward time of flight detector (ToF-F), installed downstream of the MTPCs and closing the gap between ToF-L and ToF-R. The ToF-F provides a very good particle identification in the low momentum domain ($p < 6\,\mathrm{GeV/c}$). In the pilot run data for cosmic rays and T2K neutrino experiment [23] on p+C interactions at 31 GeV/c were recorded [24]. One super-module of the Particle Spectator Detector (PSD) was installed downstream of the TOF-F and tested [25]. A major enhancement for the detector performance, i.e. the TPC readout and DAQ upgrade, was achieved in the 2008 run. It results in an increase of the data rate by a factor of about 10 compared to the old setup.

An example of the combined ToF and dE/dx particle identification capabilities is illustrated in Fig. 3 for positive particles using the pilot run data. Four clusters, corresponding to positrons, pions, kaons and protons can

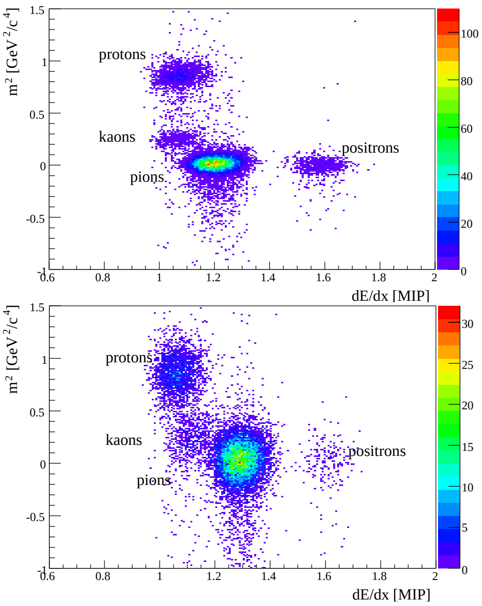

Fig. 3. Particle identification for positively charged particles using the combined ToF and dE/dx measurements in the momentum range 2-3 GeV/c (upper panel) and 4-5 GeV/c (lower panel).

be seen. At momenta above 4 GeV/c the separation of the lighter particles (e, π) from the group of heavier ones is performed essentially by dE/dx, whereas the ToF measurement is needed to distinguish between kaons and protons. Below 4 GeV/c particle identification can be performed almost exclusively by the ToF.

The detector acceptance, determined by its geometry and magnetic field, is shown in Fig. 4 for beam momenta

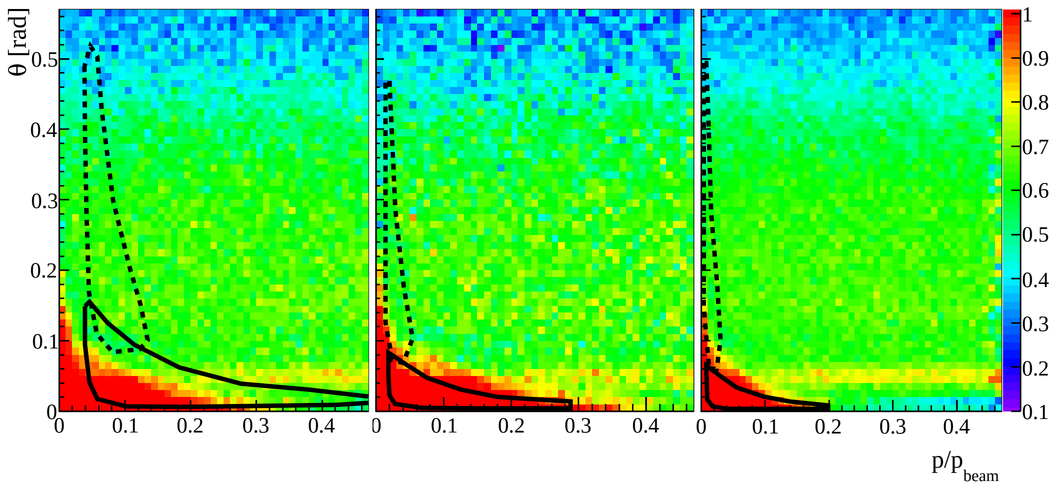

Fig. 4. The detector acceptance at beam momenta of 50 GeV/c (left), 158 GeV/c (middle) and 350 GeV/c (right). Lines correspond to the 68% contour of the cosmic ray phase space relevant for KASCADE (continuous) and Pierre Auger Observatory (dashed).

of 50 GeV/c, 158 GeV/c and 350 GeV/c. It is plotted in the plane of the polar angle, θ, versus the fraction of beam momentum carried by the secondary particles. Only tracks that were well reconstructed were selected, requiring at least 10 hits in the TPCs. The phase space of relevance for the KASCADE experiment, shown in the same figures with continuous contours is covered at full acceptance, close to 100%. At higher energies, relevant for the Pierre Auger Observatory (dashed contour), the acceptance of the detector is between 60 and 80%. The particles are at larger angles with respect to the beam due to the larger distance to the air shower axis that was required.

IV. Outlook

In 2009 the data taking program will start with p and π beams on C targets for cosmic ray and for the T2K experiments at energies of 30, 158 and 350 GeV with an expected statistics of about 18M minimum bias events. The data will cover a large region of the forward phase space of low energy hadronic interactions as needed for improving air shower modeling.

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