Results from NA61/SHINE

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Abstract. In this paper we summarize recent results from NA61/SHINE relevant for heavy ion physics, neutrino oscillations and the interpretation of air showers induced by ultra-high energy cosmic rays.

1 The NA61/SHINE Experiment

NA61/SHINE (SHINE = SPS Heavy Ion and Neutrino Experiment) \cite{1} is a multi-purpose fixed target experiment to study hadron production in hadron-nucleus and nucleus-nucleus collisions at the CERN Super Proton Synchrotron (SPS). Among its physics goals are precise hadron production measurements for improving calculations of the neutrino beam flux in the T2K neutrino oscillation experiment \cite{2} as well as for more reliable simulations of hadronic interactions in air showers. Moreover, $p+p$, $p+Pb$ and nucleus+nucleus collisions are measured to allow for a study of the properties of the onset of deconfinement and a search for the critical point of strongly interacting matter (see e.g. Ref. \cite{3}).

The layout of the NA61/SHINE detector is sketched in Fig. 1. 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. Large time-projection-chambers (TPCs) inherited from the NA49 experiment \cite{4} are used to measure the charge and momentum of particles. The momentum resolution, $\sigma(1/p) = \sigma(p)/p^2$, is about $10^{-4}$ (GeV/c)$^{-1}$ at full magnetic field and the tracking efficiency is better than 95%. Particle identification is achieved by measuring the energy loss along the tracks in the TPCs and by determining their velocity from the time of flight provided by large scintillator walls placed downstream of the TPCs. The centrality of nucleus-nucleus collisions can be estimated using the measurement of the energy of projectile spectators with a calorimeter \cite{5} located behind the time of flight detectors. For nucleon-nucleus collisions, the centrality is determined by counting low momentum particles from the target (so called ‘gray protons’) with a small TPC around the target.

NA61/SHINE started data taking in 2007. After a first run with proton on carbon at 31 GeV/c, the data acquisition system was upgraded during 2008 to increase the event recording rate by a factor of $\approx 10$. In the last four years, a wealth of data has been recorded by the experiment at beam momenta ranging from 13 to 350 GeV/c with various beam particles and targets. In this paper we present results obtained from the data relevant for heavy ion physics, neutrino oscillations and the interpretation of air showers at ultra-high energies.

2 Measurements of $p+C$ Interactions for the Improvement of Neutrino Flux Calculations

Measurements of the particle emission from targets used to create neutrino beams are important for a precise interpretation of long-baseline neutrino oscillation experiments such as Tokai-to-Kamioka (T2K) \cite{2}. Two types of measurements have been performed by NA61/SHINE to aid

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the T2K calculations of the neutrino fluxes: interactions of proton on a replica of the T2K target (a 90 cm long graphite rod) and thin (2 cm) target measurements to allow the measurement of single proton-carbon interactions. Both measurements were performed with a 31 GeV/c proton beam, similar to the one provided at J-PARC. A total of $0.2 \times 10^9$ events were recorded during the data taking in 2007 and more statistics were collected in 2009 ($4 \times 10^9$ events) and 2010 ($10 \times 10^9$ events). For the first time, the kinematic phase space of pions and kaons exiting the target and producing neutrinos in the direction of the near and far detectors of a long-baseline neutrino oscillation experiment is fully covered by a single hadron production experiment.

First results on pion and kaon yields have already been published [6, 7] and used in the T2K data analysis [8]. An example of a recent particle yield measurement for T2K is the inclusive yield of positive kaons in p+C interactions at 31 GeV/c which is shown Fig.2. The knowledge of charged kaon yields is important for T2K because kaons generate the high energy tail of the neutrino beam and contribute substantially to the intrinsic $\nu_\mu$ component. As can be seen, none of the superimposed model predictions can fully describe the small-angle data from 20 to 140 mrad. Because of these shortcomings of hadronic interaction models and similar deficits in case of a comparison of predicted pion yields to NA61/SHINE data (cf. [6]), neutrino flux predictions cannot be used directly to interpret oscillation data, but need to be modified to match the NA61/SHINE measurements. For this purpose flux simulations are re-weighted to match the measured secondary particle yields, either on an interaction-by-interaction basis using the thin-target data, or at the surface of the T2K target by using data collected with the replica-target [13]. As can be seen in Fig.3 the resulting calculated neutrino spectra at the T2K far detector are in excellent agreement using either of these two methods.

3 NA61/SHINE Results for the Interpretation of Cosmic Ray Air Showers

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 [14], KASCADE [15] or IceTop [16] 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 and the modeling of the corresponding low energy interactions contribute at least 10% to the overall uncertainty of the predicted muon number at ground (see e.g. Refs. [17–20]).

Unfortunately, there exist no comprehensive and precise particle production measurements for the most numerous projectile in air showers, the $\pi$-meson. Therefore, new data with pion beams at 158 and 350 GeV/c on a thin carbon target (as a proxy for nitrogen) were collected by the NA61/SHINE experiment at the CERN SPS and preliminary results from this data set were presented at this conference for the first time.

The production cross section in $\pi^- +$C interactions was determined in a similar manner as described in Ref. [6], by correcting the experimental interaction cross section by residual contributions from elastic and quasi-elastic scattering as well as for the inelastic contribution to which
Figure 4. Inclusive $p_T$-spectra of charged hadrons produced in $\pi^-+C$ interactions at 158 and 350 GeV/c. In each figure, the particle momentum $p$ ranges from 0.6 to 121 GeV/c in steps of $\log(p/(\text{GeV}/c)) = 0.08$ from top to bottom.

The NA61/SHINE interaction trigger is not sensitive. The uncertainties of the measurement is currently dominated by the model-dependence of this correction. Preliminary values are $\sigma_{\text{prod}} = 172 \pm 2 \, (\text{stat.}) \pm 4 \, (\text{syst.})$ and $178 \pm 2 \, (\text{stat.}) \pm 4 \, (\text{syst.})$ at 158 and 350 GeV/c respectively [22]. This measurement is compatible with previous results [27,28] and already gives the most precise value of the production cross section at around 160 GeV/c.

The momentum spectra of charged hadrons in $\pi^-+C$ interactions at 158 and 350 GeV/c are presented in Fig. 4. These spectra were obtained within a fiducial phase space in the NA61 detector, for which the detection and selec-
Figure 5. Comparison of measured charged hadron production yields in \( \pi^- + \text{C} \) interactions at 158 and 350 GeV/c to predictions from Eros1.99. Colors denote the ratio of data over MC and the different panels are for different charges and beam energies as indicated by the labels. Note that the color scale is limited, i.e. the maximum value to be understood as data/MC \( \geq 2 \).

Figure 6. Transverse momentum spectrum of negatively charged hadrons produced in \( \pi^- + \text{C} \) interactions at 158 GeV/c beam momentum at \( \langle p \rangle = 10.4 \text{ GeV/c} \).

These preliminary measurements are already useful to judge the quality of event generators used in air-shower simulations. An example of the \( p_T \) distribution of negatively charged hadrons produced in \( \pi^- + \text{C} \) interactions at a beam momentum of 158 GeV/c is shown in Fig. 6 for particle momenta with \( \langle p \rangle = 10.4 \text{ GeV/c} \) and compared to predictions by QGSJetII-03 [26], Sibyll2.1 [25] and Epos1.99 [24]. As can be seen, none of these hadronic interaction models which are used to simulate air showers can reproduce that data and especially Sibyll2.1 predicts a much too steep spectrum at high transverse momenta.

The full data set is compared to the predictions of the Epos1.99 model in Fig. 5 where the ratio of data over MC is shown. It can be seen that the underestimation of charged hadron production at large transverse momenta, which was illustrated in Fig. 6 at one particular momentum, is present at all momenta (the same holds true for Sibyll). Of all the models studied QGSJetII-03 describes our data best with only a small deficit of tracks with high
$p_T$ at large particle momentum but slightly too many particles at low traverse momenta.

It is planned to study these shortcomings of the models in more detail by measuring the spectra of identified hadrons. Moreover, NA61/SHINE will be able to validate the measurement of proton and anti-proton production in $\pi^+\mathrm{C}$ interactions from Ref. [29] on which mostly the enhanced baryon production is based on that has been proposed in Ref. [24] as a possibility to enlarge the number of muons in air showers. In addition, the NA61/SHINE data set offers the possibility to constrain the $\rho^0$ production in $\pi^+\mathrm{C}$ which may be equally important for muons observed in air showers as the baryon fraction (see e.g. Ref. [30]).

4 The NA61/SHINE Heavy Ion Program

Within its heavy ion program, NA61/SHINE aims to discover the critical point of strongly interacting matter as well as to establish the properties of the onset of deconfinement (see Ref. [3] and references therein). The full experimental program is illustrated in Fig. 8 and consists of a detailed scan of various system sizes and interaction energies.

As a first step, $p+p$ interactions were measured at six energies in 2009-2011 to serve as a reference data set for the subsequent measurement of light and medium size ion reactions in the range of $\sqrt{s_{\mathrm{NN}}} = 5–20 \ \text{GeV}$. In this conference we presented preliminary spectra of $\pi^+$ in $p+p$ collisions at 20, 31, 40, 80, and 158 GeV/$c$ that were obtained using the so-called $h^-$ analysis. The analysis is based on the fact that the majority of produced negatively charged particles are pions. Contribution of other particles (mostly $K^-$ and feed-down) is corrected for using Monte-Carlo simulations. The corresponding correction is calculated as arithmetic average of VENUS [9] and Eros [23] corrections and the difference between them contributes to the systematic error. The detector effects (acceptance, inefficiency) are corrected for using Monte Carlo as well. This approach allows obtaining $\pi^+$ spectra in full measured phase space in a uniform way. Non-target interactions, i.e. collisions with air and the detector material, are subtracted using events measured with the empty liquid-hydrogen target. The transverse-mass spectra were found to follow an exponential distribution with $m_T$. Therefore, they can be extrapolated to full phase space using an exponential fit to the high $m_T$ tail of the spectra to obtain the $m_T$-integrated rapidity spectra presented in Fig. 7 (left). The spectra are well described by a sum of two symmetrically displaced Gaussian functions. The widths of the rapidity spectra are presented in Fig. 7 (right) and compared to Pb+Pb data.

In addition to these results, preliminary inclusive spectra of identified pions, protons and kaons are also available from NA61/SHINE that were obtained by using the energy deposit in the TPCs for particle identification. With the help of the ‘identity’-method described in Ref. [33], estimates of multiplicity fluctuations in $p+p$ interactions could be given. These measurements will form the reference data set for the full ion program. As can be seen in

![Figure 8. The NA61/SHINE data taking schedule for the ion program and its proposed extension for the period 2017–2019. Big boxes denote large ($\geq 5 \times 10^7$ events) and small boxes medium size ($\sim 1–5 \times 10^6$ events) data sets. Green boxes are recorded data, red boxes denote runs to be taken within the approved physics program and gray boxes denote the proposed extension.](image-url)
calculations and increase the knowledge on interactions in the late stages of the shower development below a TeV.

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