Hadron production measurement from NA61/SHINE

Alexander Korzenev[∗] , on behalf of the NA61/SHINE collaboration
DPNC, University of Geneva, Switzerland
E-mail: Alexanter.Korzenev@cern.ch

New results of NA61/SHINE on determination of charged hadron yields in proton-carbon interactions are presented. They aim to improve predictions of the neutrino flux in the T2K experiment. The data were recorded using a secondary-proton beam of 31 GeV/c momentum from CERN SPS which impinges on a graphite target. To determine the inclusive production cross section for charged pions, kaons and protons the thin $(0.04\,\lambda_I)$ target was exploited. Results of this measurement are used in the T2K beam simulation program to reweight hadron yields in the interaction vertex. At the same time, NA61/SHINE results obtained with the T2K replica target $(1.9\,\lambda_I)$ allow to constrain hadron yields at the surface of the target. It would correspond to the constraint up to 90% of the neutrino flux, thus reducing significantly a model dependence of the neutrino beam prediction. All measured spectra are compared to predictions of hadron production models.

In addition a status of the analysis of data collected by NA61/SHINE for the NuMI target (Fermilab) is reviewed. These data will be used further in neutrino beam calculations for the MINERvA, MINOS(+) and LBNE experiments.

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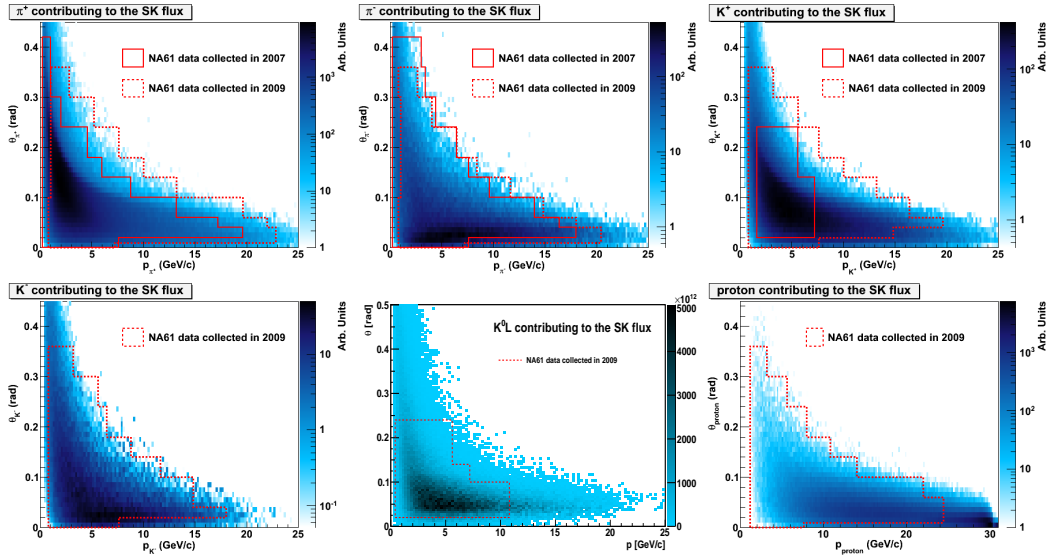*July 18-24, 2013*
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[∗]Speaker.

Figure 1: The phase space of π^+, π^-, K^+, K^-, K^0_L and protons contributing to the predicted neutrino flux at SK in the "positive" focusing configuration [1], and the regions covered by new 2009 data (*dashed line*) and by previously published NA61/SHINE measurements (*solid line*) [4, 5].

A precise prediction of the expected neutrino flux is required for the T2K experiment [1]. It is used to calculate a neutrino cross section at the near detector, while at the far detector it provides an estimate of the expected signal for the study of neutrino oscillations. Prediction of the neutrino flux is constrained by using dedicated hadron production measurements. These measurements were therefore performed in the NA61/SHINE experiment [2] at CERN. We refer the reader to [3] for the description of main detector components, software, calibration and analysis methods which were basically inherited from the NA49 experiment.

The cross section measurement using a secondary-proton beam of 31 GeV/c momentum from CERN SPS scattered off a thin graphite target (0.04 λ_I) have been performed by NA61 in years 2007 and 2009. The first NA61 physics papers were devoted to the production of $\pi^\pm$ and K^+ [4, 5]. For this analysis data collected in 2007 have been used. By now these results were integrated to the T2K beam simulation program to constrain the production of hadrons in the primary interaction of the beam protons in the target [6, 7].

Although pilot data 2007 covered a significant part of the relevant hadron production phase space of T2K [1] the statistical uncertainty is quite large. In the year 2008 important changes have been introduced to the experimental setup of NA61: new trigger logic, TPC read-out and DAQ upgrade, additional sections of ToF wall, new beam-telescope detectors. As a consequence of these upgrades the number of events recorded in 2009 and 2010 for about a same period of time have been increased by an order of magnitude as compared to the 2007 data. This larger sample allows simultaneous extraction of yields of $\pi^\pm$, $K^\pm$, K^0_s and protons. Furthermore the phase space of NA61 has been increased (see Fig. 1). Additional sections of ToF improve the coverage at high θ. In the forward direction one profits from the use of the Gap TPC detector. It plays a key role in the analysis of forward produced particles. The coverage of this kinematic domain is important for the muon monitor measurements in T2K [8]. Statistics collected in 2007 and 2009 with the thin

target is 0.7 and 5.4 millions of triggers, respectively.

An essential fraction of the neutrino flux arises from secondary re-interactions as long targets are used in T2K [1, 9]. The lack of direct data, hence the use of sparse data sets, to cover these contributions limits the achievable precision on the flux prediction. Therefore measurements with a full-size replica of the T2K target (1.9 λ_I) have been performed by NA61 in years 2007, 2009 and 2010. A total of 0.2, 4 and 10 millions of triggers have been recorded on tape, respectively. Analysis of these data will allow to reduce the systematic uncertainties of neutrino flux due to the treatment of secondary re-interactions in the target.

Normalization and production cross section

For the normalization of hadron spectra and the calculation of the production cross section we use a procedure described in [4, 3]. The idea is to measure an interaction probability for cases when the graphite target was inserted and removed. Using these values one calculates the so-called "trigger" cross section which, in turn, is an input for the analysis of "physics" cross sections. Due to upgrade of the spectrometer and higher beam intensity in 2009 the procedure was slightly modified as compared to the analysis of the 2007 data.

In the 2009 campaign the beam trigger ran simultaneously with physics triggers. The ability to apply the event-by-event selection improved the systematics significantly. To account for the high rate the beam trigger was prescaled by a factor of 100.

As a result of the analysis of the 2009 data we obtain the inelastic cross section

Figure 2: A comparison of the production cross section to the previously published results obtained at different beam momenta [15, 16, 17].

$$\sigma_{inel} = 261.3 \pm 2.8(\text{stat}) \pm 2.2(\text{model}) \pm 1.0(\text{trig}) \text{ mb}$$

which comprises all processes due to strong p + C interactions excluding the coherent nuclear elastic scattering. By subtracting from σ_{inel} the cross section of quasielastic interactions, which amounts to 27.8 ± 2.2 (stat) mb, one determines the production cross section

$$\sigma_{prod} = 233.5 \pm 2.8(\text{stat}) \pm 4.2(\text{model}) \pm 1.0(\text{trig}) \text{ mb}.$$

It is used further to normalize hadron cross sections to be able to compare to MC models. All model-dependent corrections were estimated with GEANT4.9.5 [11, 12] using FTF_BIC physics list. A comparison to the previously published results is presented in Fig. 2.

The total uncertainty of σ_{prod} is 5.1 mb, almost a factor of two smaller than the one obtained with the 2007 data. The dominant contribution to the uncertainty comes from the physics model used to recalculate the production cross section from the "trigger" cross section.

Measurement of a charged hadron cross section for T2K

Depending on the momentum interval and the particle type, different analysis techniques were tested for the analysis of data 2007 [4]. More than 90% of primary negatively charged particles
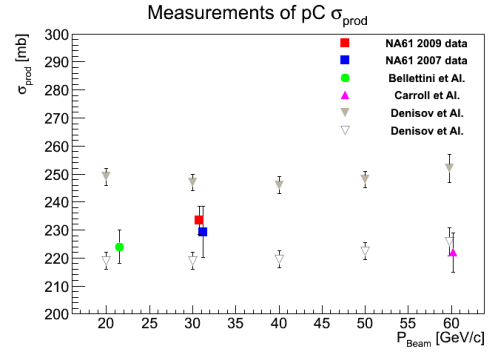
produced at this energy are π^-. Thus the analysis of π^- spectra can be done without additional particle identification (so called h^- approach). For other species of particles the identification is mandatory. In particular for the region of momenta $p > 1$ GeV/c, which is the most crucial for T2K neutrino kinematics, a combined analysis of time-of-flight (ToF) measurements and energy loss, dE/dx, measurements in TPC was used.

Raw particle yields have been corrected step-by-step using the NA61 Monte Carlo simulation program with VENUS [10] for primary interactions and a GEANT 3-based part for tracking of secondary particles through the detector. The following effects have been accounted for: geometrical acceptance of the spectrometer; efficiency of the reconstruction chain; decays before reaching the ToF wall; ToF detection efficiency; pions coming from Λ and K_s^0 decays (feed-down correction).

Spectra of π^+ and π^- obtained with data 2007 and 2009 are presented in Fig. 3. For data 2007 three analysis techniques were applied: dE/dx method for momenta smaller than 1 GeV/c; combined ToF-dE/dx method for momenta larger than 1 GeV/c; h^- method for π^- cross section. Spectra were compared in overlapping regions to check their consistency. Complementary domains were combined to reach maximum acceptance. Due to large statistics in 2009 it was decided to use only the ToF-dE/dx method since it provides high selection purity of the sample and low dependence on a MC model.

The analysis of $K^\pm$ is more complicated due to their small fraction in the overall sample [5]. For instance the K^+ signal vanishes over the predominant pion one at the low momentum range while at higher momenta protons dominate. Analysis technique is basically similar to the ToF–dE/dx one used for pions. In general statistical error of the K^+ spectra with data 2007 is by a factor of 3 larger than the systematic one [5] and only two interval in θ were considered. Data collected in 2009 improved the precision strongly. In Fig.4 the differential cross section of kaons normalized to the production cross section is shown. Larger statistics of 2009 allowed to split the phase space into 9 intervals in θ. Graphs are overlapped by several recommended GEANT4 physics lists [11, 12].

Distribution of proton multiplicities obtained with data 2009 as a function of momentum in different intervals of θ is shown in Fig. 5. Comparison to GEANT4 models shows that none of them can satisfactory describe the data.

Cross section of neutral particles K_S^0 and Λ

Understanding of the neutral strange particle production in NA61/SHINE is of great interest for two reasons. First, it allows to decrease the systematic uncertainty associated with the charged particle production, namely pions [4] and protons. Second, the measurement of the K_S^0 production will improve our knowledge of the ν_e flux at the T2K experiment coming from the three body decay of the $K_L^0 \to \pi^0 e^\pm \nu_e(\overline{\nu}_e)$ [1].

The technique used for the analysis of the 2009 data have been already tested on the 2007 data [13]. We reconstruct K_S^0 and Λ in so-called V^0 mode: decay into two charged particle of opposite signs $K_S^0 \to \pi^+ + \pi^-$ and $\Lambda \to p + \pi^-$. Particle yields have been extracted in the analysis of invariant mass spectra applying corresponding mass hypotheses for daughter tracks. The main background sources were associated with converted photons and the combinatorial background which is mainly due to particles produced in the primary interaction. Selection cuts have been applied on the following variables: the number of clusters for daughter tracks, the impact parameter
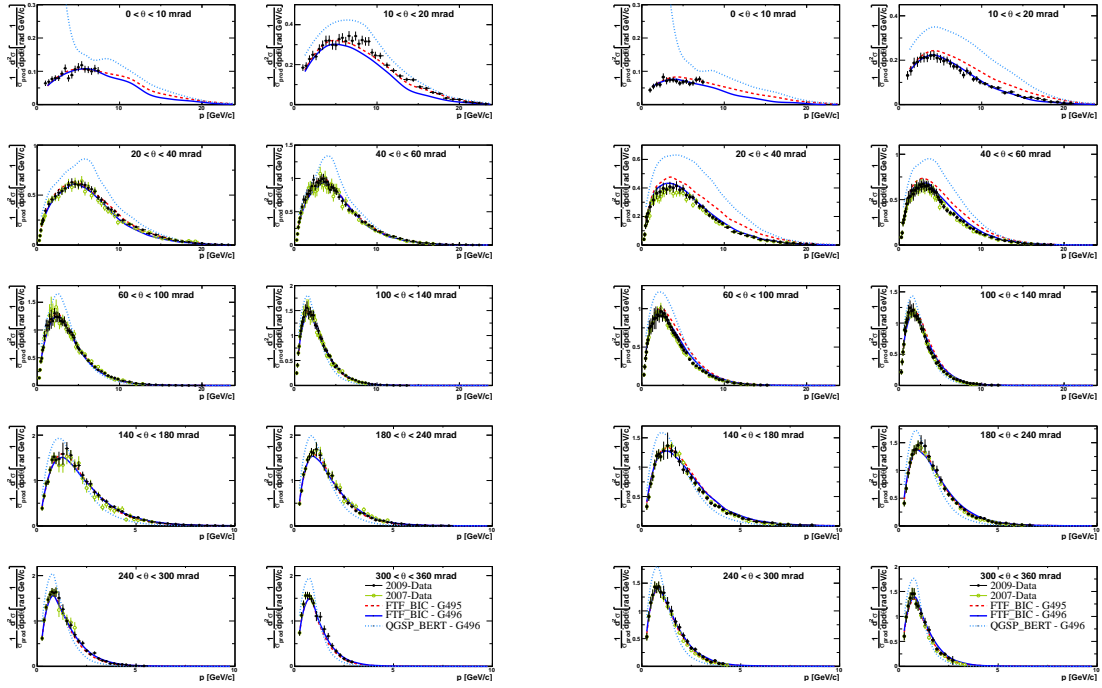
Figure 3: Laboratory momentum distributions of the π^+ and π^- multiplicities produced in p-C interactions at 31 GeV/c in different intervals of polar angle θ. Error bars indicate statistical uncertainty. Data points are overlapped by various model predictions [11, 12].
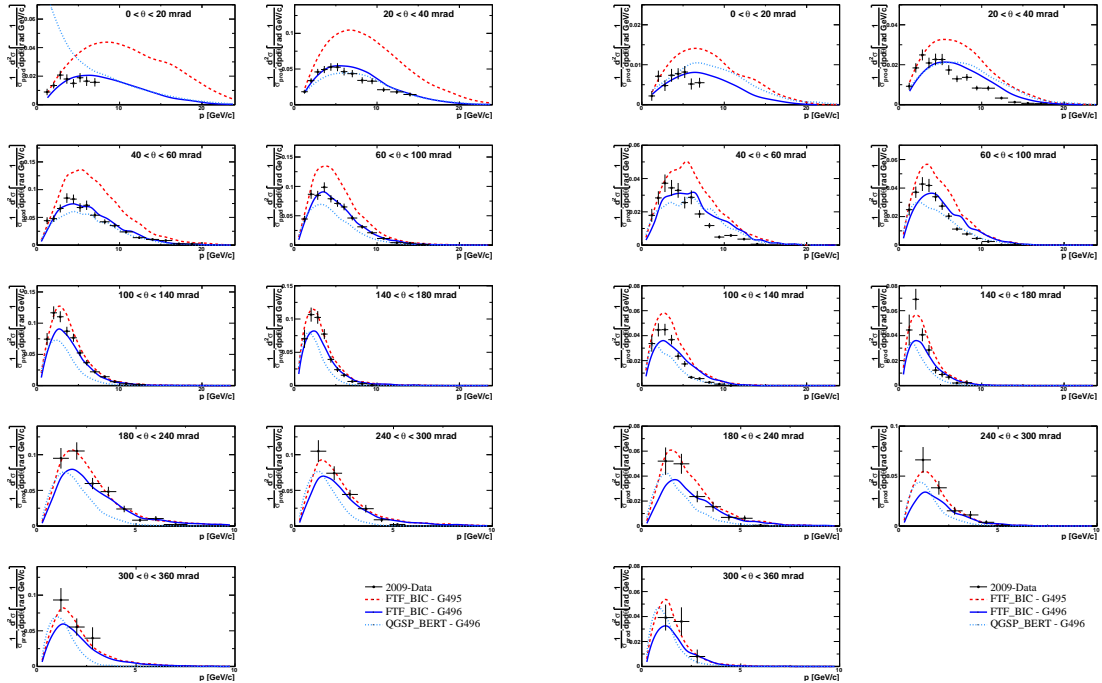

Figure 4: Laboratory momentum distributions of the K^+ and K^- multiplicities produced in p-C interactions at 31 GeV/c in different intervals of polar angle θ. Error bars indicate statistical uncertainty. Data points are overlapped by various model predictions [11, 12].
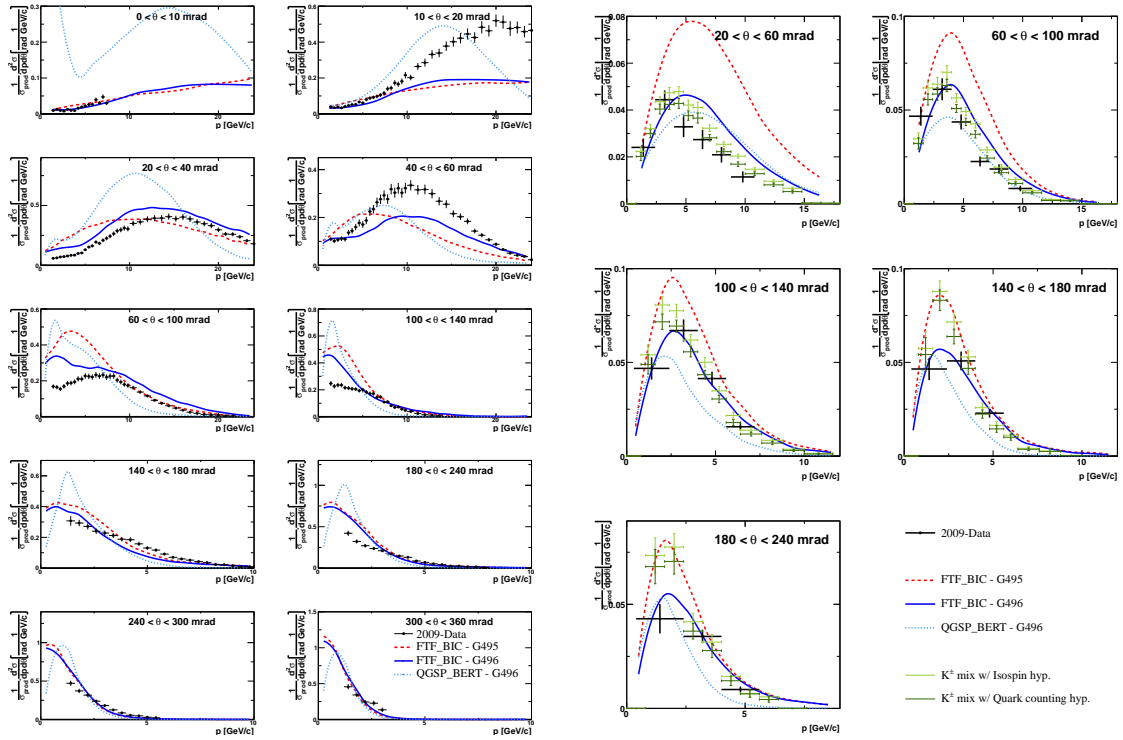
Figure 5: Laboratory momentum distributions of the proton multiplicities produced in p-C interactions at 31 GeV/c in different intervals of polar angle θ. Error bars indicate statistical uncertainty. Data points are overlapped by various model predictions [11, 12].

Figure 6: Laboratory momentum distributions of the K_S^0 multiplicities produced in p-C interactions at 31 GeV/c in different intervals of polar angle θ. Error bars indicate statistical uncertainty. Data points are overlapped by various model predictions [11, 12].

of the V^0 track in the primary vertex, the distance of closest approach between daughter tracks, the distance between primary and decay vertices, the cosine of the angle between the trajectory of V^0 and daughter particle in the center-of-mass system of V^0, the energy loss in TPC by daughter tracks, and finally V^0 satisfying the hypothesis of K_S^0 were removed from the analysis of Λ and vice versa. Multiplicities of K_S^0 are shown in Fig. 6 together with a prediction of several models. Analysis of Λ is in progress.

Being able to measure simultaneously K^+, K^- and K_S^0 we can provide a test for several hypotheses predicting a relative yield of charged and neutral kaons. These hypotheses derived from the isospin symmetry and/or some basic assumption on parton distributions in nucleon [14]. The comparison of the measured differential multiplicity of K_S^0 to the prediction obtained with the charged kaons is shown in Fig. 6. A reasonable agreement is observed for prediction of 'isospin' and 'quark-counting' hypotheses presented in the figure. However more certain statement would require a higher statistical precision for K_S^0.

Analysis for the T2K replica-target

First physics results from the analysis of the replica-target data taken in 2007 have been published [9]. A dedicated reconstruction method has been developed to provide results in a form that

is of direct interest for T2K. Yields of positively charged pions are reconstructed at the surface of the T2K replica target in bins of the laboratory momentum and polar angle as a function of the longitudinal position along the target. By parametrizing hadron yields on a surface of the target one predicts up to 90% of the flux for both ν_μ and ν_e components while only 60% of neutrinos coming from the primary interaction vertex. Two methods (constraint of hadroproduction data at primary interaction and on a target surface) are consistent within their uncertainties achieved on statistics of pilot run 2007. The ultimate precision will come from the analysis of the replica-target data 2009 and 2010.

Data taking for the Fermilab neutrino beam

Following discussion initiated at NUFACT 2011 a group from 10 US institutions expressed their interest in possibility of collecting data relevant for NuMI experiments (MINERvA, NOvA, MINOS+), Booster experiments (MiniBooNE, MicroBooNE) and LBNE [18]. An important pilot run with a proton beam of 120 GeV and a thin graphite target took place in July 2012. It resulted to 3.5 millions of recoded events. An experience with these pilot data gives a basis to estimate an amount of efforts needed to complete the Fermilab's neutrino program in NA61. A complete data taking is expected after the 2013/2014 shutdown of the CERN accelerator complex.

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