MEASUREMENTS OF HADRON PRODUCTION FOR NEUTRINO PHYSICS WITHIN NA61/SHINE EXPERIMENT AT CERN SPS*

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NA61/SHINE, a fixed target experiment at CERN SPS, performs in its first stage of data taking (years 2007 and 2009) measurements of hadron production in hadron–nucleus interactions. Such data are needed for neutrino (T2K) and cosmic-ray (Pierre Auger and KASCADE) experiments. The NA61/SHINE apparatus offers the unique possibility of accurate measurement of hadron production, including good particle identification. For precise predictions of the T2K neutrino beam parameters the measurements are performed for 30 GeV proton interactions on thin carbon target as well as on the replica of the actual target of the T2K experiment. The preliminary results on π^+ and π^- multiplicities from the 2007 pilot run are presented.

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1. Introduction

The NA61/SHINE (SHINE — SPS Heavy Ion and Neutrino Experiment) experiment at the CERN SPS combines a rich physics program in three different fields: neutrino experiment calibration, cosmic-ray simulations, and the behavior of strongly interacting matter at high density (see references [1–4] for details). In this article we present a study of the pion production in the phase space region important for the T2K neutrino beam. The NA61 detector is based on large volume Time Projection Chambers (TPCs) of the NA49 experiment. Preliminary pion results obtained from the data taken during the first pilot run in October 2007 are shown.

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2. NA61/SHINE program for the T2K neutrino oscillation experiment

The T2K experiment will study neutrino oscillations using an off-axis neutrino beam from the J-PARC accelerator to the Super-Kamiokande detector [5–7].

The beam neutrinos come from decays of pions and kaons produced in the interactions of the 30 GeV protons on a carbon target (see Fig. 1). The neutrino interactions will be measured in the near detector (ND280) at a distance of 280 m from the target and the Super-Kamiokande (SK) detector located at a distance of 295 km from the neutrino source. Both detectors are situated along a line 2.5 degrees off the beam axis.

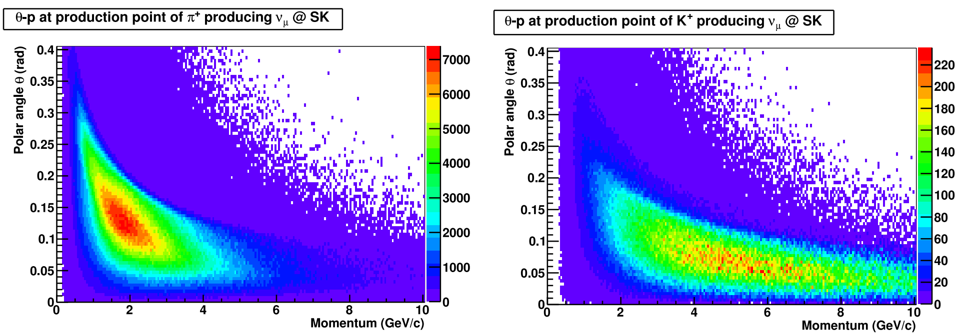

Fig. 1. Simulation of the J-PARC neutrino beam. The plots show meson production angles *versus* energies of pions and kaons whose daughter neutrinos pass through the Super-Kamiokande detector (see [3]).

Neutrino oscillations will be probed by comparing interaction rates at Super-Kamiokande with predictions with and without oscillations. The expected neutrino fluxes at SK, $\Phi^{\mathrm{SK}}_{\nu_e}$ and $\Phi^{\mathrm{SK}}_{\nu_\mu}$ will be obtained from $\Phi^{\mathrm{ND}}_{\nu_e}$ and $\Phi^{\mathrm{ND}}_{\nu_\mu}$, measured in the near detector multiplied by the so-called far-to-near ratios, denoted R_{ν_μ} and R_{ν_e}, respectively:

$$\Phi^{\mathrm{SK}}_{\nu_\mu,\nu_e}(E_\nu) = R_{\nu_\mu,\nu_e}(E_\nu)\,\Phi^{\mathrm{ND}}_{\nu_\mu,\nu_e}(E_\nu)\,. \tag{1}$$

Knowledge of R_{ν_μ,ν_e} is based only on Monte Carlo predictions in which many hadron production models are used. Studies show that these models may result in up to 20% differences on the calculation of R_{ν_μ} [2, 8]. In the same reports it was shown that to achieve the T2K physics goals, R_{ν_μ,ν_e} should be known at the level of $\delta(R_{\nu_\mu,\nu_e}) \approx 2-3\%$, which requires precise information on the pion and kaon production on the T2K target. The NA61/SHINE experiment was proposed to provide this information.

3. The NA61/SHINE detector

The NA61/SHINE experiment is a large acceptance hadron spectrometer at the CERN SPS. The layout of the detector is shown in Fig. 2.

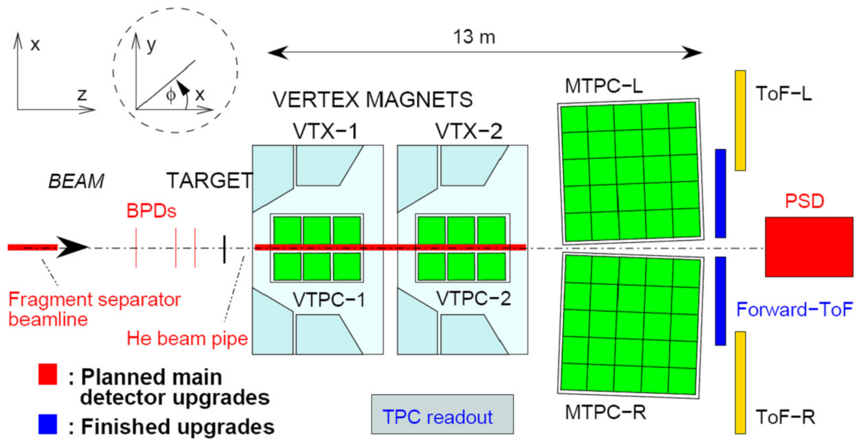

Fig. 2. The layout of the NA61/SHINE set-up (top view, not in scale).

The main components of the current detector were constructed and used by the NA49 experiment [9]. The main tracking devices are four large volume Time Projection Chambers (TPCs). Two of them, the vertex TPCs (VTPC-1 and VTPC-2), are located in the magnetic field of two superconducting dipole magnets (a maximum combined bending power of 9 Tm). Two others MTPC-L and MTPC-R are positioned downstream. Two time-of-flight detectors (ToF-L/R) were inherited from NA49 and are able to provide a time measurement resolution of $\sigma \approx 60$ ps. In 2007 the experiment has been updated with a new forward time-of-flight detector (ToF-F) in order to extend the acceptance for pion and kaon identification as required for T2K measurements [4]. The ToF-F wall is installed downstream of the main TPCs, closing the gap between the ToF-L and ToF-R walls. The ToF-F time resolution is $\sigma \approx 120$ ps. The most downstream component of the apparatus is the Projectile Spectator Detector (PSD) designed for heavy ion physics. A major enhancement for the detector performance, *i.e.* the TPC readout and DAQ upgrade, was achieved in the 2008 run, which allowed to increase the speed of the data reading by a factor of about 10 compared to the old set-up.

Two carbon, isotropic graphite targets were used during 2007 run:

- a 2 cm long target (about 4% of nuclear interaction length, λ_{I}) with density $\rho = 1.84\,\mathrm{g/cm^3}$, so called thin target,
- a 90 cm long cylinder of 2.6 cm diameter (about 1.9 λ_{I}), so called T2K replica target.

In this article only the results of the measurements on the thin target are shown.

4. Methods of particle identification

The identification of pions produced in proton interactions was possible using energy loss measurements (dE/dx) in active volume of the TPCs and time-of-flight information from the ToF detectors. In order to obtain pion yields, three different analyses were developed. They are based on:

1. Energy loss measurement for particles with momenta below 1 GeV/c, which is described in greater detail in Sec. 5.
2. Combined energy loss and time-of-flight measurement (dE/dx + ToF) was used to perform identification of pions with momenta between 1 and 6 GeV/c. For particles with momentum $p > 6$ GeV/c particle identification was based only on energy loss measurement [10].
3. Analysis of negatively charged particles further referred to as h^-, is based on the theoretical and experimental premises that negative particles produced by 30 GeV protons consist mainly of negative pions with an admixture of electrons, negative kaons and a negligible fraction of antiprotons. This procedure allows to obtain spectra of π^- mesons in a broad momentum range. (For more details see Ref. [11].)

The NA61 Monte Carlo chain (Venus generator for primary interactions, default GHEISHA model from GEANT 3.21 for secondary interactions) is used to calculate most of the corrections like for geometrical acceptance of the detector (except dE/dx + ToF analysis), reconstruction efficiency, weak decays and non vertex particles (*e.g.* from weak decays and secondary interactions in the detector material). For dE/dx + ToF analysis a flat space simulation is applied in order to calculate geometrical acceptance.

5. Particle identification based on the energy loss measurement for momenta below 1 GeV/c

The particles with momenta below 1 GeV/c are deflected in the magnetic field and in the most part do not reach the ToF detectors. They require a dedicated particle identification, because the energy loss strongly depends on their momenta. The region below 1 GeV/c was divided into 0.1 GeV/c momentum bins and 20 mrad bins in production angle (θ). In selected cells of phase space (cell $\equiv (\Delta p, \Delta\theta)$) preliminary particle identification was performed. First probability functions have been calculated for every $(\Delta p, \Delta\theta)$ cell. For every particle identification hypothesis, j, a probability density function was constructed, $f_j(dE/dx)$, using the dE/dx values from the Bethe–Bloch curves, experimental uncertainty of the energy loss measurement and assuming equal yields of all particles. For that study we select

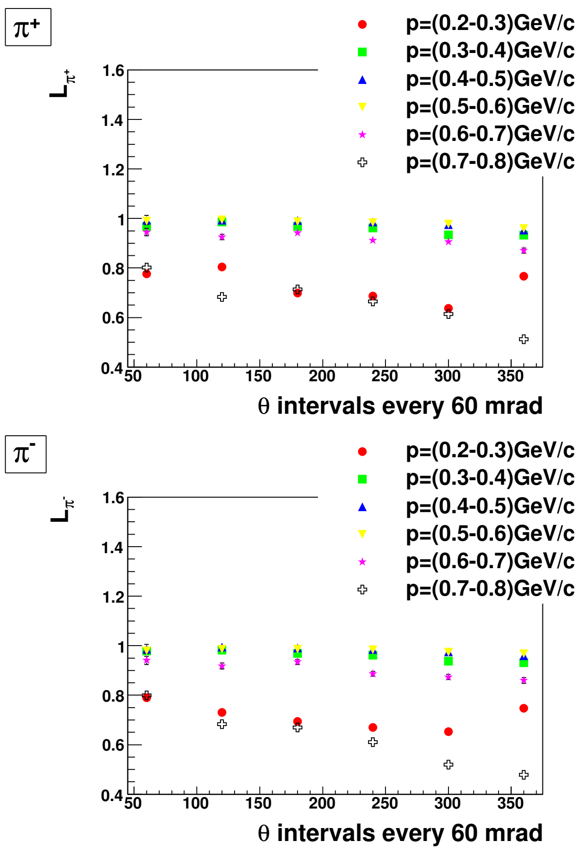

Fig. 3. Fractions of π^+ (left) and π^- (right) particles in the dE/dx bins for which their relative probability is larger than $\geq 95\%$.

dE/dx bins in which relative probability for a given particle hypothesis is $\geq 95\%$. We then determine which fraction, L_j, of all particle j tracks should have dE/dx in the selected 95% bins. The L_{π^+} for π^+ and L_{π^-} for π^- in selected $(\Delta p, \Delta\theta)$ cells are presented in Fig. 3.

It is seen that for momentum range $p = [0.3\text{–}0.7]\,\mathrm{GeV}/c$ pions are almost completely separated. For $p \leq 0.3\ \mathrm{GeV}/c$ pions are more difficult to distinguish from electrons (positrons) whereas for $p \geq 0.7\,\mathrm{GeV}/c$ an overlap with kaon hypothesis makes the separation difficult.

In order to obtain identified pion spectra one takes all the tracks from 95% bins and corrects their rate by L_π fraction in every $(\Delta p, \Delta\theta)$ cell.

In the analysis a small dependence of the energy loss measurements on the production angle (θ) has been found out. The few % shifts in dE/dx values were applied for all the data tracks. The shifts are independent of the track momentum. It is seen in Figs. 4, and 5 that dE/dx resolution has improved. The points corresponding to electrons and pions are better separated.

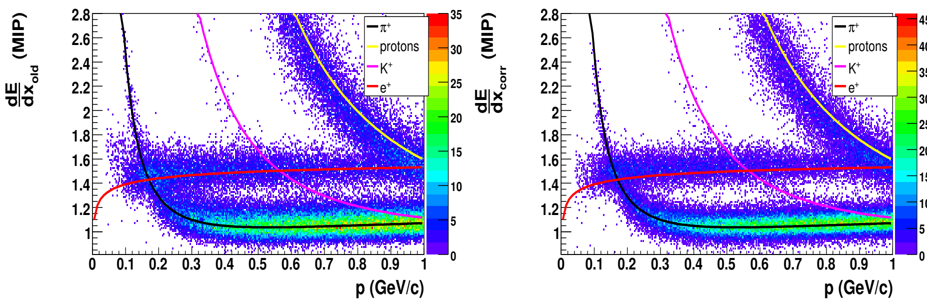

Fig. 4. Energy loss measurements *versus* particle momentum for positively charged particles before (left) and after (right) applying angular corrections.

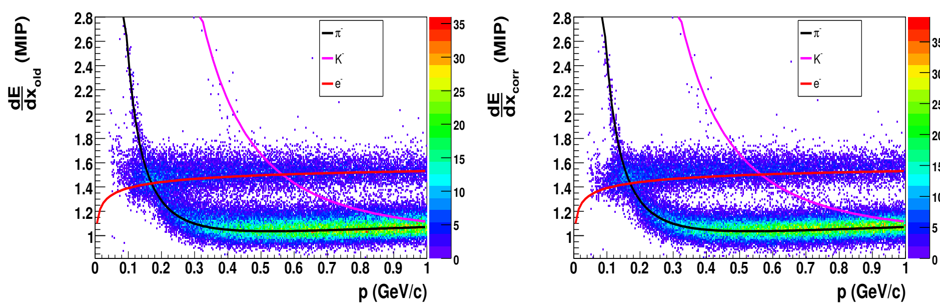

Fig. 5. Energy loss measurements *versus* particle momentum for negatively charged particles before (left) and after (right) applying angular corrections.

6. Preliminary results

In Figs. 6 and 7 we display mean multiplicity per event in inelastic collisions of 30 GeV protons on thin carbon target. In order to determine the correct number of inelastic interactions among all triggered events some corrections have to be applied (see [12]). First, one has to subtract the contribution of large angle coherent elastic scatterings which pass the trigger conditions. Secondly, one needs to take into account a loss of inelastic triggers due to a fact that secondary particle acted as primary proton on the trigger counters. One also has to estimate the rate of the events which take place outside of the carbon target. The π^+ multiplicities obtained from dE/dx analysis with those derived from the combined energy loss *versus* time-of-flight measurements are shown in Fig. 6).

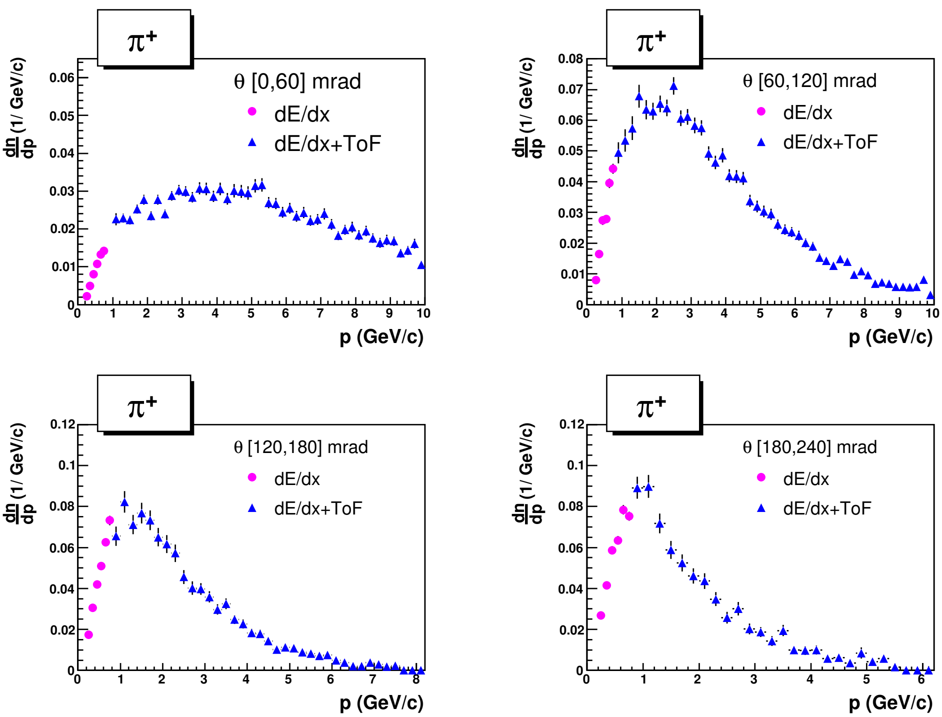

Fig. 6. Mean multiplicity of π^+ *versus* momentum in different (θ) angle intervals comparison of dE/dx (circles) and dE/dx + ToF (triangles) analyses.

Fig. 7 illustrates π^- multiplicities obtained from dE/dx, h^- analyses and those derived from the combined energy loss *versus* time-of-flight measurements. Only statistical errors are shown. Systematical uncertainties are estimated to be below 20% maximum.

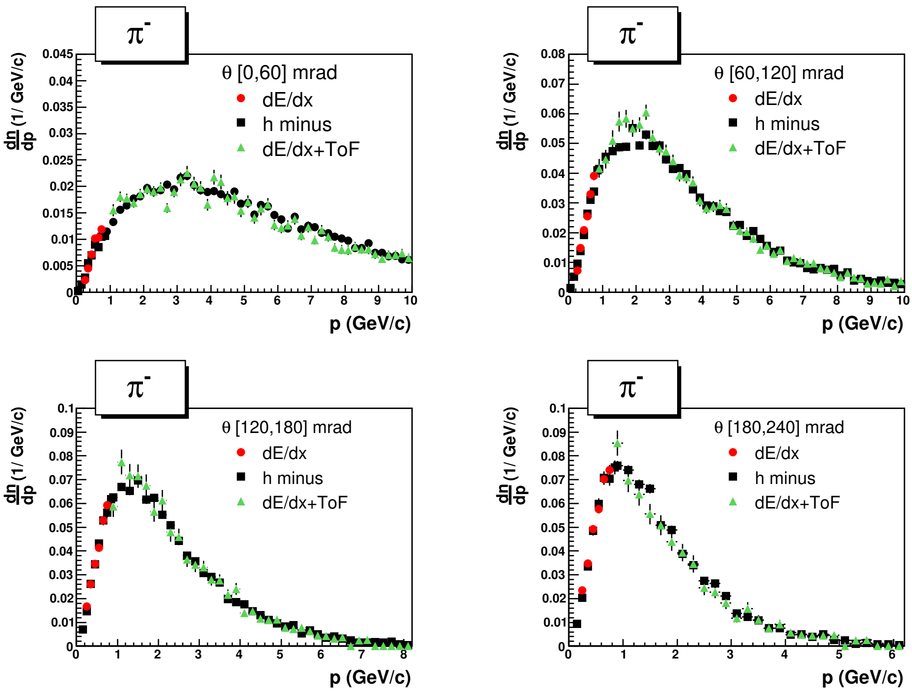

Fig. 7. Mean multiplicity of π^- *versus* momentum in different (θ) angle intervals comparison of dE/dx (circles), dE/dx + ToF (triangles) and h^- (squares) analyses.

7. Conclusions

In the 2007 data taking the first physics data on interactions of 30 GeV protons on the thin and T2K replica carbon target were registered. Preliminary spectra of π^+ and π^- mesons were obtained using different methods: dE/dx, dE/dx + ToF and h^-. The measurements obtained with the T2K replica target are currently being analysed. The work to minimize systematic biases is in progress. The dependence on the details of the MC generators is also under study. In year 2009 three weeks were dedicated for T2K measurements. We registered 4.4 milion interactions for the thin target and 2 milion interactions (after preliminary quality cuts) for the T2K replica target. Collected data are currently being calibrated and will be used to increase the limited statistics from 2007 pilot run.

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