Status of the NA61 (SHINE) experiment at CERN

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Abstract

A precise measurement of the hadron production from interactions of 30 GeV protons on carbon target is performed by NA61 (SHINE) experiment at the CERN SPS. The inclusive spectra of pions and kaons on the carbon target obtained from NA61 measurements constrain the neutrino flux in the T2K long baseline neutrino oscillation experiment at J-PARC, Japan. The article presents description of the NA61 apparatus together with the preliminary results from the pilot 2007 run.

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1 Introduction

The physics program of the NA61 (SHINE) (SHINE = SPS Heavy Ion and Neutrino Experiment) experiment at CERN SPS consists of three subjects (see references: [1, 2, 3, 4] for details).

In the first stage of data taking (2007-2009) measurements of hadron production in proton - nucleus interactions needed for neutrino (T2K) and cosmic-ray (Pierre Auger and KASCADE) experiments is performed.

In the second stage (2009-2010) hadron production in proton - proton and proton - nucleus interactions as a reference data for a better understanding of nucleus - nucleus reactions will be studied.

In the third stage (2009-2013) energy dependence of hadron production properties will be measured in nucleus - nucleus collisions as well as proton - proton, proton - lead interactions. The aim is to identify the properties of the onset of deconfinement and find evidence for the critical point of strongly interacting matter.

The experiment was approved at CERN in June 2007. The first pilot run was performed during October 2007. The aims of this run were [2]:

- to set up and test the NA61 (SHINE) apparatus,
- to take pilot physics data on the interactions of 30 GeV protons on two carbon targets with different geometry.

This article reports on the data taken in 2007 October run for the T2K neutrino oscillation experiment.

2 The T2K experiment

The T2K experiment will study neutrino oscillations using off-axis neutrino beam from the J-PARC accelerator and the Super-Kamiokande detector [5, 6]. The first phase of the T2K experiment (2009-2014) is aimed at:

- an order of magnitude better determination of the atmospheric parameters $\Delta \sin^2 2\theta_{23} = 0.01$ and $\Delta m^2_{23} = 10^{-4} eV^2$ by measuring the $\nu_\mu \rightarrow \nu_x$ disappearance,
- search for the $\nu_\mu \rightarrow \nu_e$ oscillations with the sensitivity to $\sin^2 2\theta_{13}$ down to 0.008 (90%CL).

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 the line 2.5 degrees of the beam axis.

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

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

If the neutrino source was point-like and isotropic, the $R_{\nu_\mu,\nu_e}$ ratios would be given by the ratio of the distances from the neutrino source squared and energy independent. However the neutrinos are born along the 94 m decay pipe which means that they constitute a
Figure 1: Simulation of J-PARC neutrino beam. The plots show meson production angles versus energies for pions and kaons whose daughter neutrinos pass through the Super-Kamiokande detector (see [7]).

point-like source only for the far detector. In addition near and far detectors see quite different solid angles. These effects lead to different energy spectra at the near and far detectors. Knowledge of $R_{\nu_\mu,\nu_e}$ is based only on Monte Carlo predictions (see Fig. 2) in which many hadron production models are used. Studies show that these models may result in up to 20% differences on the calculation of $R_{\nu_\mu}$ [2, 8]. In the same reports it has been proved that to achieve T2K physics goals $R_{\nu_\mu,\nu_e}$ should be known on 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. For this purpose the NA61 (SHINE) experiment has been proposed.

Figure 2: Ratio of neutrino fluxes $R_{\nu_\mu,\nu_e}$ for $\nu_\mu$ and $\nu_e$, respectively. Clear energy dependence can be seen. Results are obtained from the T2K neutrino beam simulation.

3 The NA61 (SHINE) detector

The NA61 (SHINE) experiment is a large acceptance hadron spectrometer at the CERN SPS. The layout of the NA61 (SHINE) set-up is shown in Fig. 3. 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 (1.5 and 1.1T, respectively). Two others (MTPC-L and MTPC-R) are positioned downstream of the magnets symmetrically to the beam line. TPCs are filled with mixtures of
Figure 3: The layout of the NA61 (SHINE) set-up (top view, not in scale) with the basic upgrades indicated in red.

$Ar + CO_2$ (90:10) for VTPCs and (95:5) for MTPCs.

Two time-of-flight detectors (ToF-L/R) were inherited from NA49 and are able to provide a time measurement resolution of $\sigma \approx 100 \text{ps}$. For the pilot 2007 run [4] a new forward time-of-flight detector (ToF-F) was constructed in order to extend the acceptance of the NA61 (SHINE) set-up for pion and kaon identification as required for T2K measurements. The ToF-F wall is installed downstream of the MTPC-L and MTPC-R (red line on Fig. 3), closing the gap between the ToF-L and ToF-R walls. The ToF-F time resolution is $\sigma \approx 120 \text{ps}$. The most downstream component of the NA61 (SHINE) apparatus is Projectile Spectator Detector (PSD) designed for heavy ion physics. It will be used to measure energy of the beam particles which do not interact with nucleons in the target.

4 Beam counters and Beam Position Detectors

NA61 is located in the North experimental area on the H2 beam line. The primary proton beam is extracted from the SPS towards the North area. Proton beam together with the production target creates secondary hadron beam which is coming to the H2 beam line. The secondary beam contains a mixture of particles types: 87.3% pions, 14.1% protons and 1.6% kaons.

Figure 4: Schematic layout of the beam counters together with the three Beam Position Detectors (BPD).
Table 1: Preliminary results of event cuts applied on all thin target data. The fraction of events passing the cuts is presented.

| Cut                  | Result |
|----------------------|--------|
| BPD position         | 78%    |
| vertex.iflag = 0     | 60%    |
| z-vertex position    | 41%    |

The purpose of the beam instrumentation (see Fig. 4) is to tag the presence of the valid beam particle and to provide a precise timing information. The S1 counter is placed 32 m upstream from the target. This counter defines the timing of the experiment. For proton beam a 5 mm thick scintillator equipped with four photomultipliers was used. The S2 is additional scintillator. A differential Cherenkov counter (C1) and threshold Cherenkov counter (C2) are applied to select protons from the secondary hadron beam. The beam definition is completed by V0 and V1, two scintillators with a hole, required to be in anticoincidence with S1, S2 and C1 and C2. These counters allow to select beam particles hitting the target.

The transverse positions of the incoming beam particles are measured by three Beam Position Detectors (BPDs). These counters are proportional chambers (48x48 mm$^2$) with cathode strip readout. The chambers are operated with an Ar + CO$_2$ mixture (90:10).

The interactions in the target are selected by anticoincidence of the incoming beam particle with small ($\phi = 2 \text{cm}$) scintillation counter (S4) placed on the beam line between two vertex magnets.

5  Carbon targets used in 2007 run

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

- a 2 cm long target (about 4% of nuclear interaction length, $\lambda_f$) with density $\rho = 1.84 \frac{g}{cm^3}$, so called thin target,
- a 90 cm long cylinder (about 1.9 $\lambda_f$) of 2.6 cm diameter, so called T2K replica target, with density $\rho = 1.83 \frac{g}{cm^3}$.

In 2007 run about 670 k events with the thin target, 230 k events with the T2K replica target and 80 k events without target (empty target events) were reconstructed.

The data from the T2K replica target will allow to predict the $\nu$ flux of the T2K experiment. They will be used also for studies of secondary interactions in the target.

The thin target will be used for the determination of inclusive cross sections for the reactions:

\[
p + C \rightarrow \pi^+(\pi^-) + X, \]
\[
p + C \rightarrow K^+(K^-, K^0_s) + X.
\]

6  Event selection

A proper event selection is needed in order to reduce the background coming from non-target interactions. A preliminary list of the event cuts for the thin target data together with their
impact on the event sample is presented in the Table [6]. The first cut requires that the particle was measured by each of the BPDs. The aim of this cut is to select well defined beam tracks. The second variable checks the flag set in each event during reconstruction. If the fit to determine the z-position of the main vertex has converged the \texttt{vertex.iflag} is set to 0. In case of any problems with the fit the flag is set to non-zero values. The third position in the Table [6] requires that the fitted z-vertex position is close to the nominal one.

7 Methods of Particle Identification

In NA61 (SHINE) experiment particle identification is possible using ionization measurements in active volume of the TPCs and time-of-flight measurements in ToF counters.

The energy loss distribution is described by the Landau distribution. Therefore in order to avoid large fluctuations in energy deposits the truncated mean technique is used in quantifying $\frac{dE}{dx}$. In this method, the highest and lowest measurements are rejected for each track. The accepted measurements follow approximately Gaussian distribution. For all data collected during run in 2007 the (0:50) truncation was applied, which means that only the 50% smallest clusters are kept for the determination of the $\frac{dE}{dx}$.

The optimization of the parameters required for the determination of energy loss in the TPCs was performed using the method developed by NA49 and described in detail in [10, 11]. Corrections for the following effects were applied during the calibration of the NA61 data:

- signal loss due to threshold cuts; corrections were obtained using Monte Carlo calculations for gas mixture used in NA61,
- time dependence of the TPC gas pressure,
- residual time dependence of the measurements (day/night),
- charge absorption during the drift,
- differences in the TPC sector gain factors,
- differences in the amplification of the preamplifiers and edge effects at sectors boundaries.

Preliminary distributions of corrected dE/dx values for particles with momentum chosen around 5 and 15 GeV/c are presented in Fig. [5]. Estimated resolution of dE/dx measurements
Figure 6: Preliminary plots of the reconstructed $dE/dx$ values versus momenta for positively and negatively charged particles, respectively, together with the Bethe-Bloch curves for positrons (electrons), pions, kaons, (anti)protons and deuterons.

of 4-5% can be achieved for particles passing through both the vertex and the main TPC chambers.

Scatter plots of the energy loss $dE/dx$ value of the track (in MIP units) versus the particle momentum in the laboratory frame is shown in Fig. 6 for positively and negatively charged particles. Here we present preliminary results obtained with the thin target.

For particles reaching the ToF detectors $dE/dx$ information from the TPCs is available together with the time-of-flight. Example of combined analysis is demonstrated on preliminary plots in Fig. 7, where particles separation in various momentum ranges is possible thanks to $dE/dx$ signal and the mass squared obtained from the forward ToF counters.

Comparison of Fig. 1 and Fig. 7 (lower) proves that $\pi^+$ and $K^+$ detected in NA61 (SHINE) apparatus have momenta and production angles in the same range as needed for T2K neutrino oscillation experiment.

All presented plots show only raw results, without any corrections applied for acceptance, reconstruction efficiency or trigger normalization.

8 Conclusions

In the 2007 NA61 (SHINE) run the first physics data on interactions of 30 GeV protons on the thin and T2K replica carbon target were registered. The NA61 (SHINE) apparatus together with new ToF-F counters were running successfully. All collected data were reconstructed and calibrated in order to obtain preliminary uncorrected particle spectra presented in this article.

In 2008 the NA61 (SHINE) Collaboration planned to increase the statistics of data needed for T2K neutrino oscillation experiment. The data taking was planned to last from September 4 to October 30. Unfortunately, it was stopped on October 6, because of the changes in accelerator schedule caused by the LHC incident [12]. During this shorter run installation and commissioning of the new TPC read-out electronics together with new DAQ (Data Acquisition) was successfully performed. This upgrade permits an increase of the data rate by a factor of 10 in comparison to the NA61 rate from 2007 year run.

Due to early run stop the physics data with the full detector upgrade were not registered. Thus, during 2009 run three weeks of data taking for T2K experiment are planned.
Figure 7: Preliminary results of the combined dE/dx andToF analysis in selected particle momentum bins.

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