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Conference Paper

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Publication date:
2016-04

Permanent link:
https://doi.org/10.3929/ethz-b-000117308

Originally published in:
Nuclear and Particle Physics Proceedings 273-275, https://doi.org/10.1016/j.nuclphysbps.2015.10.026

Available online at www.sciencedirect.com

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Nuclear and Particle Physics Proceedings 273–275 (2016) 2672–2674

www.elsevier.com/locate/nppp

Constraints on the T2K neutrino flux prediction from hadron production measurements at NA61/SHINE

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Abstract

New measurements of hadron production with a proton beam on a 2 cm carbon target at 31 GeV/c performed by the NA61/SHINE collaboration are shown. The inelastic and production cross section are presented. Multiplicities of $\pi^{\pm}$, $K^{\pm}$, K^0_S, proton and Λ are shown. These measurements are fundamental to reduce the uncertainties on the neutrino flux at the T2K experiment. The procedure used to tune the T2K flux prediction with the measured spectra is explained as well.

Keywords: NA61/SHINE, T2K, neutrino flux, neutrino oscillations

1. The T2K experiment

T2K (Tokai-to-Kamioka) is an off-axis long-baseline neutrino experiment in Japan that aims to precisely measure the parameters of the PMNS matrix and to look for the first indication of CP violation in the lepton sector by measuring ν_μ disappearance and ν_e appearance in a ν_μ beam.

The T2K experiment [3] is composed of three main components: the beam source, a near detector and a far detector. A muon neutrino beam is produced at the J-PARC Main Ring (MR) accelerator that provides a 30 GeV proton-beam interacting on a long carbon target ($1.9\lambda_L$). The collisions produce hadrons, mainly charged pions and kaons, that further decay into ν_μ with a contamination of ν_e below 1%. The neutrino beam is directed 2.5° off the axis between the target and the far detector 295 km away. This configuration produces a narrow-band beam with a peak energy of about 0.6 GeV which is exactly on the first $\nu_\mu \rightarrow \nu_e$ oscillation maximum. With this setup, the background to the ν_e appearance signal is dramatically reduced.

The near detector complex is located 280 m downstream of the target and consists of several detectors embedded in magnet (0.2T). The far detector, Super-Kamiokande (SK) [4], is a water Cherenkov detector located 295 km away from the neutrino production point. Precise measurements of the neutrino oscillation parameters θ_{23}, Δm^2_{32} for normal hierarchy (Δm^2_{13} for inverted hierarchy) and θ_{13} are performed by comparing the measured neutrino flux at the near detector and at the far detector. ν_μ disappearance and ν_e appearance in a ν_μ beam are measured [1, 2]. Thanks to the relatively large θ_{13}, T2K aims to look for first hints of CP violation in the leptonic sector. The largest uncertainty on the neutrino flux is given by the poor knowledge of the hadron production. The NA61/SHINE experiment at the CERN SPS measures the hadronic production with a proton beam of the same momentum as in T2K on a graphite target [5]. All the T2K phase space is covered (Fig.1), allowing a sensible reduction of the uncertainty on the neutrino flux from $\sim 30\%$ to about 12% in the region of interest.

2. The NA61/SHINE experiment

NA61/SHINE is a fixed target experiment at the CERN SPS. Interactions of incoming 31 GeV/c protons on Carbon are measured with a thin target, 4% of the nuclear interaction length, in order to study the

http://dx.doi.org/10.1016/j.nuclphysbps.2015.10.026

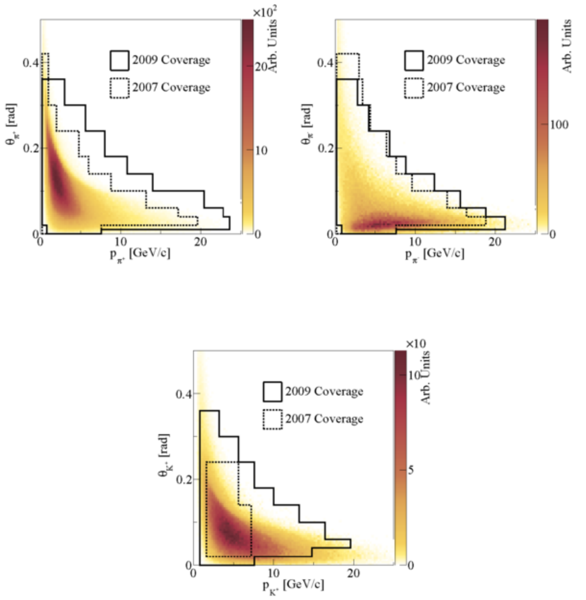

Figure 1: The p-θ phase space of π^+, π^-, K^+ contributing to the flux expected at the T2K far detector. The region covered by the NA61/SHINE measurement is overlaid for the 2009 (solid line) and 2007 (dashed line) measurement.

primary interactions. The setup is composed by three beam position detectors, five time projection chambers and three time of light (ToF) detectors with a time resolution $\Delta t < 120\ ps$. A very good particle identification ($\sigma(dE/dx)/ < dE/dx > \sim 0.04$) allows to precisely measure the hadrons produced in the interactions. A scintillator is used to trigger the interaction of the proton beam in the target. In 2007 a low statistic pilot run has been conducted with the thin [7, 8] and a replica target [9]. The measured spectra were used to tune the T2K neutrino flux. The detector undergone many updates in 2008: new trigger logics, DAQ upgrade and new TPC readout. The extension of the wall of the Time of Fight detector and the usage of the GAP TPC detector for the reconstruction of the forward-going tracks improved the coverage in the $\{p, \theta\}$ phase space, where p is the hadron momentum and θ is the polar angle. A new data-taking was performed in 2009 with both targets, increasing the statistics approximately by a factor of 10.

New results on multiplicities of charged hadrons as well as the total p+C production cross section are shown in the next sections.

3. Production cross section

The hadron production cross section has been measured. It is needed to normalize the measured hadron spectra. The trigger cross section is computed by measuring the probability to have an interaction in the target. The rate of interactions in the surrounding material is measured with special runs without the target inserted and then subtracted from the total trigger cross section. The production cross section is obtained applying corrections due to elastic and quasi-elastic events, estimated with FTF_BIC physics list of GEANT4. The measured production cross section is:

$$\sigma_{prod} = 233.5 \pm 2.7 \text{ (stat)} \pm 2.4 \text{ (det)} \pm 3.6 \text{ (mod) mb}$$

The comparison with the production cross section measured by NA61/SHINE using the 2007 pilot run data set as well as with the other experiments is shown in Fig. 2.

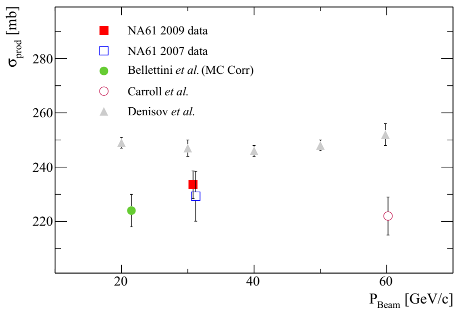

Figure 2: A comparison of the measured production cross sections with previously published results at different momenta. Carroll et al. (pink empty circle) [10], Denisov et al. measurements (grey triangles) [11] and Bellettini et al. (green full circle) [12], that measured the inelastic cross section and the quasi-elastic component has been estimated with MC and subtracted. NA61/SHINE measurements with 2007 (blue empty square) and 2009 (red full square) data samples are shown as well.

4. Charged hadrons

The charged hadrons ($\pi^\pm, K^\pm$ and p) multiplicities have been measured. The combination of the energy loss dE/dx measured in the TPCs and the information on the mass from the ToF allows to separate the detected particles very well. A maximum likelihood fit of the raw yields is performed in each p-θ bin and the obtained multiplicities are corrected for geometrical acceptance, reconstruction efficiency, contamination of other particles, secondary interactions. The biggest source of uncertainty for protons and pions comes from the feed-down contamination due to decays of neutral strange particles. Both statistical and systematic uncertainties are reduced by approximately a factor of 2-3. Positively charged pions spectra are shown in Fig. 3 as an example.

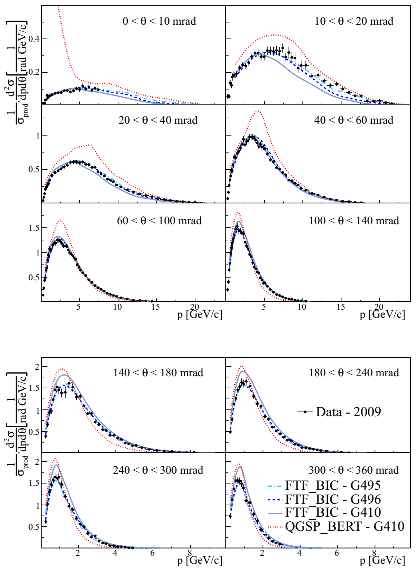

Figure 3: Distribution of π^+ multiplicities produced in p-C interactions at 31 GeV/c in different intervals of polar angle θ. Error bars indicate statistical uncertainty. Data points are overlapped by the Geant4 physics list FTF_BIC predictions for different releases of the software as well as the QGSP_BERT physics list.

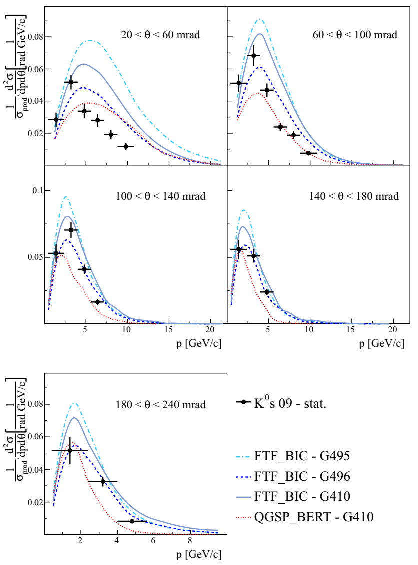

Figure 4: Distribution of K^0_S multiplicities produced in p-C interactions at 31 GeV/c in different intervals of polar angle θ. Error bars indicate the statistical uncertainty. Data points are overlapped by the prediction of different versions of the FTF_BIC and QGSP_BERT physics lists for different releases of the Geant4 software.

5. Neutral strange particle spectra

Since the main systematic uncertainty for pions and protons spectra is from feed-down $\Lambda^0 \rightarrow p + \pi^-$ and $K^0_S \rightarrow \pi^+ + \pi^-$, the spectra of both Λ^0 and K^0_S are measured and used to constrain the systematic uncertainties. Furthermore most of the T2K ν_e flux at high energy is produced by $K^0_L \rightarrow \pi^- \nu_e e^+$ and the measured K^0_S spectra can be used to constrain this component. An invariant mass fit is performed on the raw yields of the tracks that fulfill the V^0 topology. The bin by bin systematic uncertainties are within 10-20%. The measured K^0_S spectra are shown in Fig. 4.

6. Tuning of the T2K neutrino flux

The T2K flux is estimated with MC simulations of the secondary beam line: proton interactions in the target are simulated with the Fluka generator while the Geant3 interfaced with the GCALOR generator is used to estimate the propagation in the beam-line. Weights are computed for each specie i by the ratio between the external data (priority is given to NA61/SHINE measurements) and T2K MC expectation in each p-θ bin:

$$W(p_i, \theta_i, p_0, A) = \frac{\left[\frac{dn_i}{dp_i}(p_i, \theta_i, p_0, A)\right]_{data}}{\left[\frac{dn_i}{dp_i}(p_i, \theta_i, p_0, A)\right]_{MC}} \quad (1)$$

where p_0 and A are respectively the momentum of the interaction and the atomic number. The interactions that occur in different materials, not covered by external data, are re-weighted accordingly to eq. 1 using the scaling hypothesis in momentum and/or in target. A detailed description of the procedure is given in [6].The procedure has been successfully tested with the 2007 pilot run. After the flux tuning, the total uncertainty, still dominated by the hadron production, is reduced down to about 12%. In the next future also the 2009 run data will be used to tune the T2K neutrino flux, further reducing the total flux systematic uncertainty.

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