

## Measurements of Cross Sections and Charged Pion Spectra in Proton-Carbon Interactions at 31 GeV/c

L. S. Esposito\*, on behalf of the NA61/SHINE Collaboration

*ETH, Institute for Particle Physics,  
Zurich, Switzerland*

*\*E-mail: lullo@cern.ch*

The NA61 Collaboration:

N. Abgrall<sup>23</sup>, A. Aduszkiewicz<sup>4</sup>, B. Andrieu<sup>12</sup>, T. Anticic<sup>14</sup>, N. Antoniou<sup>19</sup>, J. Argyriades<sup>23</sup>,  
A. G. Asryan<sup>16</sup>, B. Baatar<sup>9</sup>, A. Blondel<sup>23</sup>, J. Blumer<sup>11</sup>, M. Bogusz<sup>25</sup>, L. Boldizar<sup>10</sup>,  
A. Bravar<sup>23</sup>, W. Brooks<sup>18</sup>, J. Brzychczyk<sup>7</sup>, A. Bubak<sup>24</sup>, S. A. Bunyatov<sup>9</sup>, O. Busygina<sup>6</sup>,  
T. Cetner<sup>25</sup>, K.-U. Choi<sup>13</sup>, P. Christakoglou<sup>19</sup>, P. Chung<sup>17</sup>, T. Czopowicz<sup>25</sup>, N. Davis<sup>19</sup>,  
F. Diakonos<sup>19</sup>, S. Di Luise<sup>1</sup>, W. Dominik<sup>4</sup>, J. Dumarchez<sup>12</sup>, R. Engel<sup>11</sup>, A. Ereditato<sup>21</sup>,  
L. S. Esposito<sup>1</sup>, G. A. Feofilov<sup>16</sup>, Z. Fodor<sup>10</sup>, A. Ferrero<sup>23</sup>, A. Fulop<sup>10</sup>, X. Garrido<sup>11</sup>,  
M. Gaździcki<sup>8,2</sup>, M. Golubeva<sup>6</sup>, K. Grebieszko<sup>25</sup>, A. Grzeszczuk<sup>24</sup>, F. Guber<sup>6</sup>, H. Hakobyan<sup>18</sup>,  
T. Hasegawa<sup>5</sup>, S. Igolkin<sup>16</sup>, A. S. Ivanov<sup>16</sup>, Y. Ivanov<sup>18</sup>, A. Ivashkin<sup>6</sup>, K. Kadija<sup>14</sup>,  
A. Kapoyannis<sup>19</sup>, N. Katryńska<sup>a,7</sup>, D. Kielczewska<sup>4</sup>, D. Kikola<sup>25</sup>, J.-H. Kim<sup>13</sup>, M. Kirejczyk<sup>4</sup>,  
J. Kisiel<sup>24</sup>, T. Kobayashi<sup>5</sup>, O. Kochebina<sup>16</sup>, V. I. Kolesnikov<sup>9</sup>, D. Kolev<sup>3</sup>, V. P. Kondratiev<sup>16</sup>,  
A. Korzenev<sup>23</sup>, S. Kowalski<sup>24</sup>, S. Kuleshov<sup>18</sup>, A. Kurepin<sup>6</sup>, R. Lacey<sup>17</sup>, J. Lagoda<sup>15</sup>,  
A. Laszlo<sup>10</sup>, V. V. Lyubushkin<sup>9</sup>, M. Mackowiak<sup>25</sup>, Z. Majka<sup>7</sup>, A. I. Malakhov<sup>9</sup>, A. Marchionni<sup>1</sup>,  
A. Marcinek<sup>7</sup>, I. Maris<sup>11</sup>, V. Marin<sup>6</sup>, T. Matulewicz<sup>4</sup>, V. Matveev<sup>6</sup>, G. L. Melkumov<sup>9</sup>,  
A. Mereaglia<sup>1</sup>, M. Messina<sup>21</sup>, St. Mrówczyński<sup>8</sup>, S. Murphy<sup>23</sup>, T. Nakadaira<sup>5</sup>,  
P. A. Naumenko<sup>16</sup>, K. Nishikawa<sup>5</sup>, T. Palczewski<sup>15</sup>, G. Palla<sup>10</sup>, A. D. Panagiotou<sup>19</sup>, W. Peryt<sup>25</sup>,  
O. Petukhov<sup>6</sup>, R. Płaneta<sup>7</sup>, J. Pluta<sup>25</sup>, B. A. Popov<sup>9,12</sup>, M. Posiadła<sup>4</sup>, S. Puławski<sup>24</sup>,  
W. Rauch<sup>2</sup>, M. Ravonel<sup>23</sup>, R. Renfordt<sup>22</sup>, A. Robert<sup>12</sup>, D. Röhrich<sup>20</sup>, E. Rondio<sup>15</sup>, B. Rossi<sup>21</sup>,  
M. Roth<sup>11</sup>, A. Rubbia<sup>1</sup>, M. Rybczyński<sup>8</sup>, A. Sadovsky<sup>6</sup>, K. Sakashita<sup>5</sup>, T. Sekiguchi<sup>5</sup>,  
P. Seyboth<sup>8</sup>, M. Shibata<sup>5</sup>, A. N. Sissakian<sup>b,9</sup>, E. Skrzypczak<sup>4</sup>, M. Słodkowski<sup>25</sup>, A. S. Sorin<sup>9</sup>,  
P. Staszal<sup>7</sup>, G. Stefanek<sup>8</sup>, J. Stepaniak<sup>15</sup>, C. Strabel<sup>1</sup>, H. Ströbele<sup>22</sup>, T. Susa<sup>14</sup>, P. Szaffik<sup>24</sup>,  
M. Szuba<sup>11</sup>, M. Tada<sup>5</sup>, A. Taranenko<sup>17</sup>, R. Tsenov<sup>3</sup>, R. Ulrich<sup>11</sup>, M. Unger<sup>11</sup>, M. Vassiliou<sup>19</sup>,  
V. V. Vechernin<sup>16</sup>, G. Vesztergombi<sup>10</sup>, A. Wilczek<sup>24</sup>, Z. Włodarczyk<sup>8</sup>, A. Wojtaszek<sup>8</sup>,  
J.-G. Yi<sup>13</sup>, I.-K. Yoo<sup>13</sup>, W. Zipper<sup>24</sup>

<sup>1</sup>ETH, Zurich, Switzerland

<sup>2</sup>Fachhochschule Frankfurt, Frankfurt, Germany

<sup>3</sup>Faculty of Physics, University of Sofia, Sofia, Bulgaria

<sup>4</sup>Faculty of Physics, University of Warsaw, Warsaw, Poland

<sup>5</sup>High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

<sup>6</sup>Institute for Nuclear Research, Moscow, Russia

<sup>7</sup>Jagiellonian University, Cracow, Poland

- <sup>8</sup>Jan Kochanowski University in Kielce, Poland  
<sup>9</sup>Joint Institute for Nuclear Research, Dubna, Russia  
<sup>10</sup>KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary  
<sup>11</sup>Karlsruhe Institute of Technology, Karlsruhe, Germany  
<sup>12</sup>LPNHE, University of Paris VI and VII, Paris, France  
<sup>13</sup>Pusan National University, Pusan, Republic of Korea  
<sup>14</sup>Rudjer Boskovic Institute, Zagreb, Croatia  
<sup>15</sup>Soltan Institute for Nuclear Studies, Warsaw, Poland  
<sup>16</sup>St. Petersburg State University, St. Petersburg, Russia  
<sup>17</sup>State University of New York, Stony Brook, USA  
<sup>18</sup>The Universidad Tecnica Federico Santa Maria, Valparaiso, Chile  
<sup>19</sup>University of Athens, Athens, Greece  
<sup>20</sup>University of Bergen, Bergen, Norway  
<sup>21</sup>University of Bern, Bern, Switzerland  
<sup>22</sup>University of Frankfurt, Frankfurt, Germany  
<sup>23</sup>University of Geneva, Geneva, Switzerland  
<sup>24</sup>University of Silesia, Katowice, Poland  
<sup>25</sup>Warsaw University of Technology, Warsaw, Poland  
<sup>a</sup>Present affiliation: University of Wrocław, Wrocław, Poland  
<sup>b</sup>deceased

As neutrino long baseline experiments enter a new domain of precision, the careful study of systematic errors due to poor knowledge of production cross sections for pions and kaons require more dedicated measurements for precise neutrino flux predictions. The cosmic ray experiments require dedicated hadron production measurements to tune simulation models used to describe air shower profiles. Among other goals, the NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) experiment at the CERN SPS aims at precision measurements (5% and below) for both neutrino and cosmic ray experiments: those will improve the prediction of the neutrino flux for the T2K experiment at J-PARC and the prediction of muon production in the propagation of air showers for the Auger and KASCADE experiments. NA61/SHINE took data during a pilot run in 2007 and in 2009 and 2010 with different carbon targets. The NA61/SHINE set-up and spectra for positive and negative pions obtained with the 2007 thin (4% interaction length) carbon target data are presented.<sup>1</sup>

*Keywords:* p+C interaction, inelastic cross section, inclusive pion spectra

## 1. Physics motivation

The NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) experiment at the CERN SPS pursues a rich physics program in various fields.<sup>2-5</sup> First, precise hadron production measurements are performed for improving calculations of the neutrino flux in the T2K neutrino oscillation experiment,<sup>6</sup> as well as for more reliable simulations of cosmic-ray air showers in the Pierre Auger and KASCADE experiments.<sup>7,8</sup> Second, p+p, p+Pb and nucleus+nucleus collisions will be studied extensively at SPS energies. This article presents first NA61/SHINE results on charged pion spectra in p+C interactions at 31 GeV/c which are needed for an accurate neutrino flux prediction in the T2K experiment. The results are based on the data collected during the first NA61/SHINE run in 2007.

T2K is a long baseline neutrino experiment in Japan, which uses a high inten-

sity neutrino beam produced at J-PARC<sup>a</sup>. It aims to precisely measure the  $\nu_\mu \rightarrow \nu_e$  appearance and  $\nu_\mu$  disappearance.<sup>6</sup> In order to generate the neutrino beam a high intensity 30 GeV (kinetic energy) proton beam impinging on a 90 cm long graphite target is used, where  $\pi$  and K mesons decaying into (anti)neutrinos are produced. The neutrino fluxes and spectra are then measured both at the near detector complex, 280 m from the target, and by the Super-Kamiokande (SK) detector located 295 km away from the neutrino source and 2.5 degrees off-axis. Neutrino oscillations are probed by comparing the neutrino flux measured at SK to the predicted one. In order to predict the flux at SK one uses the near detector measurements and extrapolates them to SK with the help of Monte Carlo simulations. Up to now, these Monte Carlo predictions are based on hadron production models only. For more precise predictions, which would allow the reduction of systematic uncertainties to the level needed for the T2K physics goals, measurements of pion and kaon production off carbon targets are essential.<sup>2-4</sup> The purpose of the NA61/SHINE measurements for T2K is to provide this information at exactly the proton extraction energy of the J-PARC Main Ring synchrotron, namely 30 GeV kinetic energy (approximately 31 GeV/c momentum). Presently, the T2K neutrino beam-line is set up to focus positively charged hadrons, in such a way that it produces a  $\nu_\mu$  beam. Spectra of positively charged pions presented in this paper constitute directly an essential ingredient in the neutrino flux calculation.

## 2. The NA61/SHINE detector

The NA61/SHINE experiment is a large acceptance hadron spectrometer in the North Area H2 beam-line of the CERN SPS. The schematic layout is shown in Fig. 1 together with the overall dimensions.

The main components of the current detector were constructed and used by the NA49 collaboration.<sup>9</sup> A set of scintillation and Cherenkov counters as well as beam position detectors (BPDs) upstream of the spectrometer provide timing reference, identification and position measurements of the incoming beam particles. The main tracking devices of the spectrometer are large volume Time Projection Chambers (TPCs). Two of them, the vertex TPCs (VTPC-1 and VTPC-2 in Fig. 1), are located in a free gap of 100 cm between the upper and lower coils of the two superconducting dipole magnets. Their maximum combined bending power is 9 Tm. In order to optimize the acceptance of the detector at 31 GeV/c beam momentum, the magnetic field used during the 2007 data taking period was set to a bending power of 1.14 Tm. Two large TPCs (MTPC-L and MTPC-R) are positioned downstream of the magnets symmetrically to the beam line. The TPCs are filled with Ar:CO<sub>2</sub> gas mixtures in proportions 90:10 for VTPCs and 95:5 for MTPCs. The particle identification capability of the TPCs based on measurements of the specific energy loss,  $dE/dx$ , is augmented by time-of-flight measurements using Time-of-Flight (ToF)

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<sup>a</sup>Japan Proton Accelerator Research Complex organized jointly by JAEA and KEK in Tokai, Japan

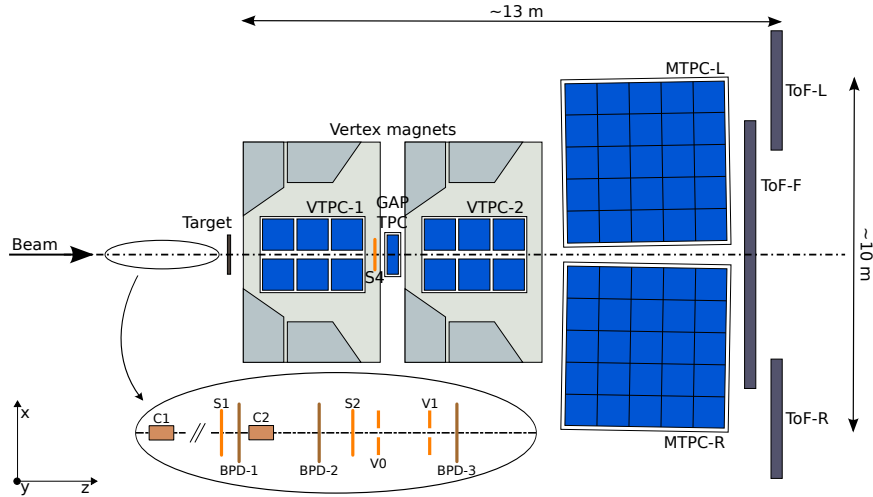


Fig. 1. (Color online) The layout of the NA61/SHINE experiment at the CERN SPS (top view, not to scale). The chosen right-handed coordinate system is shown on the plot. The incoming beam direction is along the  $z$  axis. The magnetic field bends charged particle trajectories in the  $x - z$  (horizontal) plane. The drift direction in the TPCs is along the  $y$  (vertical) axis.

detectors. The ToF-L and ToF-R arrays of scintillator pixels have a time resolution of better than 90 ps.<sup>9</sup> Before the 2007 run the experiment was upgraded with a new forward time-of-flight detector (ToF-F) in order to extend the acceptance. The ToF-F consists of 64 scintillator bars with photomultiplier (PMT) readout at both ends resulting in a time resolution of about 115 ps. The target under study is installed 80 cm in front of the VTPC-1. The results presented here were obtained with an isotropic graphite target of dimensions  $2.5(W) \times 2.5(H) \times 2(L)$  cm and with a density of  $\rho = 1.84 \text{ g/cm}^3$ . The target thickness along the beam is equivalent to about 4% of a nuclear interaction length ( $\lambda_I$ ).

### 3. Analysis techniques

This section presents the procedures used for data analysis to extract pion cross sections. Crucial for this analysis is the identification of the produced pions. Depending on the momentum interval, different approaches have been adopted, which lead also to different track selection criteria. The calibrated  $dE/dx$  distributions as a function of particle momentum for positively and negatively charged particles are presented in Fig. 2.

The task is facilitated for the negatively charged pions, by the observation that more than 90% of primary negatively charged particles produced in p+C interactions at this energy are  $\pi^-$ , and thus the analysis of  $\pi^-$  spectra can also be carried out without additional particle identification.

In the low momentum region (less than about 1 GeV/c), it is sufficient to distinguish pions from electrons/positrons, kaons and protons by means of particle

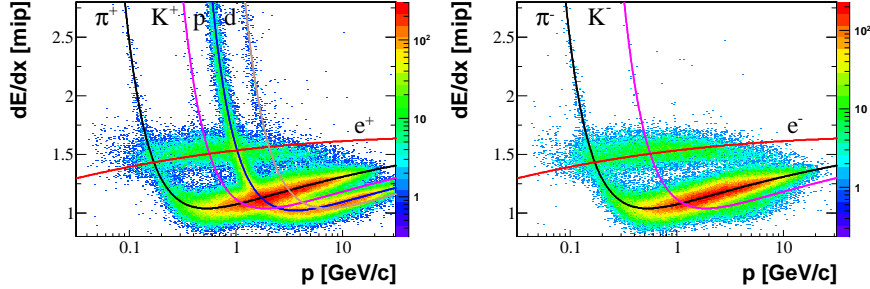


Fig. 2. (Color online) Specific energy loss in the TPCs for positively (*right*) and negatively (*left*) charged particles as a function of momentum. Curves show parameterizations of the mean  $dE/dx$  calculated for different particle species.

identification via measurements of specific energy loss ( $dE/dx$ ) in the TPCs. A reliable identification of  $\pi^+$  mesons was not possible at momenta above 1 GeV/c where the Bethe-Bloch (BB) curves for pions, kaons and protons cross each other. On the other hand, for  $\pi^-$  mesons, where the contribution of  $K^-$  and antiprotons is almost negligible, the  $dE/dx$  analysis could be extended in momentum up to 3 GeV/c allowing consistency checks with the other analysis methods in the region of overlap.

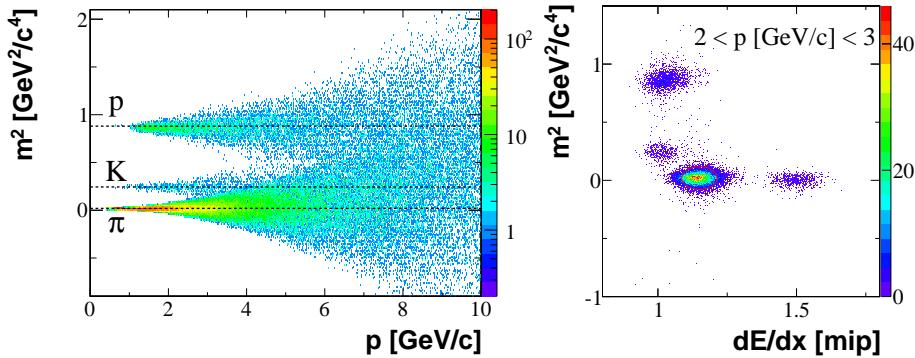


Fig. 3. (Color online) *Right*: Mass squared, derived from the ToF-F measurement and the fitted path length and momentum, versus momentum  $p$ . The lines show the expected mass squared values for different particles. *Left*: Example of two-dimensional  $m^2-dE/dx$  plots for positively charged particles in the momentum range 2-3 GeV/c.  $2\sigma$  contour around fitted pion peaks are shown.

High purity particle identification can be performed by combining the *tof* and  $dE/dx$  information. Moreover, in the momentum range 1-4 GeV/c, where  $dE/dx$  bands for different particle species overlap, particle identification is in general only possible using the *tof* method, see Figs. 3. The ToF-F detector was designed to cover the necessary acceptance in momentum and polar angle required by the T2K

experiment, although limited to particle momenta above about 0.8 GeV/c.

Indeed, three analysis methods were applied to obtain pion spectra:

- (1) analysis of  $\pi^-$  mesons via measurements of negatively charged particles (*h<sup>-</sup> analysis*)<sup>10</sup>
- (2) analysis of  $\pi^+$  and  $\pi^-$  mesons identified via  $dE/dx$  measurements in the TPCs (*dE/dx analysis at low momentum*)<sup>11</sup> and
- (3) analysis of  $\pi^+$  and  $\pi^-$  mesons identified via time-of-flight and  $dE/dx$  measurements in the ToF-F and TPCs, respectively (*tof - dE/dx analysis*).<sup>12</sup>

Each analysis yields fully corrected pion spectra with independently calculated statistical and systematic errors. The spectra were compared in overlapping phase-space domains to check their consistency. Complementary domains were combined to reach maximum acceptance.

The agreement between the spectra obtained by different methods is, in general, better than 10%. Note, that data points in the same  $(p, \theta)$  bin from different analysis methods are statistically correlated as they result from the analysis of the same data set. In order to obtain the final spectra consisting of statistically uncorrelated points the measurement with the smallest total error was selected.

The analysis was based on a sample of 521 k events selected from the total sample of 667 k of registered and reconstructed events. This criterion essentially removes a contamination by interactions upstream of the target. For the event sample with the target removed, the selection reduces the number of events from 46 k to 17 k.

## 4. Results

This section presents results on inelastic and production cross sections as well as on differential spectra of  $\pi^+$  and  $\pi^-$  mesons in p+C interactions at 31 GeV/c.

### 4.1. Inelastic and production cross sections

The total inelastic cross section is measured to be<sup>13</sup>

$$\sigma_{inel} = 257.2 \pm 1.9 \pm 8.9 \text{ mb} .$$

The production cross section was calculated from the inelastic cross section by subtracting the quasi-elastic contribution.<sup>14</sup> The result is:<sup>13</sup>

$$\sigma_{prod} = 229.3 \pm 1.9 \pm 9.0 \text{ mb} .$$

The production cross section is compared to previous measurements in Fig. 4.

### 4.2. Spectra of $\pi^+$ and $\pi^-$ mesons

The  $\pi^+$  and  $\pi^-$  spectra presented in this section refer to pions produced in strong and electromagnetic processes in p+C interactions at 31 GeV/c.

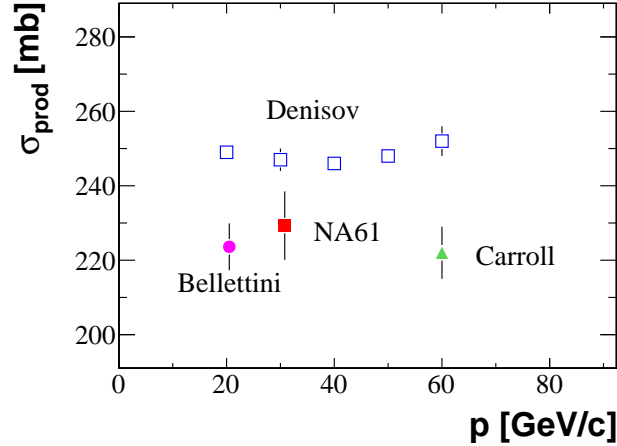


Fig. 4. (Color online) Beam momentum dependence of the production cross section for p+C interactions. The NA61/SHINE result (filled square) is compared with previous measurements: Bellettini et al. (circle),<sup>15</sup> Carroll et al. (triangle)<sup>16</sup> and Denisov et al. (open squares).<sup>17</sup> For the NA61/SHINE point, the error bar indicates statistical and systematic uncertainties added in quadrature. The result from Ref.<sup>15</sup> was recalculated by subtracting from the measured inelastic cross section a quasi-elastic contribution at 20 GeV/c of  $(30.4 \pm 1.9)$  (sys) mb.

The spectra are presented as a function of particle momentum in ten intervals of the polar angle. Both quantities are calculated in the laboratory system. The chosen binning takes into account the available statistics of the 2007 data sample, detector acceptance and particle production kinematics.

The final spectra are plotted in Figs. 5 and 6. For the purpose of a comparison of the data with model predictions the spectra were normalized to the mean  $\pi^\pm$  multiplicity in all production interactions by dividing by  $\sigma_{prod}$ . This avoids uncertainties due to the different treatment of quasi-elastic interactions in models as well as problems due to the absence of predictions for inclusive cross sections.

## 5. Conclusion

This work presents inelastic and production cross sections as well as positively and negatively charged pion spectra in p+C interactions at 31 GeV/c on the 2007 thin (4% interaction length) carbon target. These data are essential for precise predictions of the neutrino flux for the T2K long baseline neutrino oscillation experiment in Japan. Furthermore, they provide important input to improve hadron production models needed for the interpretation of air showers initiated by ultra high energy cosmic particles.

A much larger data set with both the thin and the T2K replica carbon targets was recorded in 2009 and 2010 and is presently being analysed. This will lead to results of higher precision for pions and extend the measurements to other hadron species such as charged kaons, protons,  $K_S^0$  and  $\Lambda$ . Analysis of the data collected

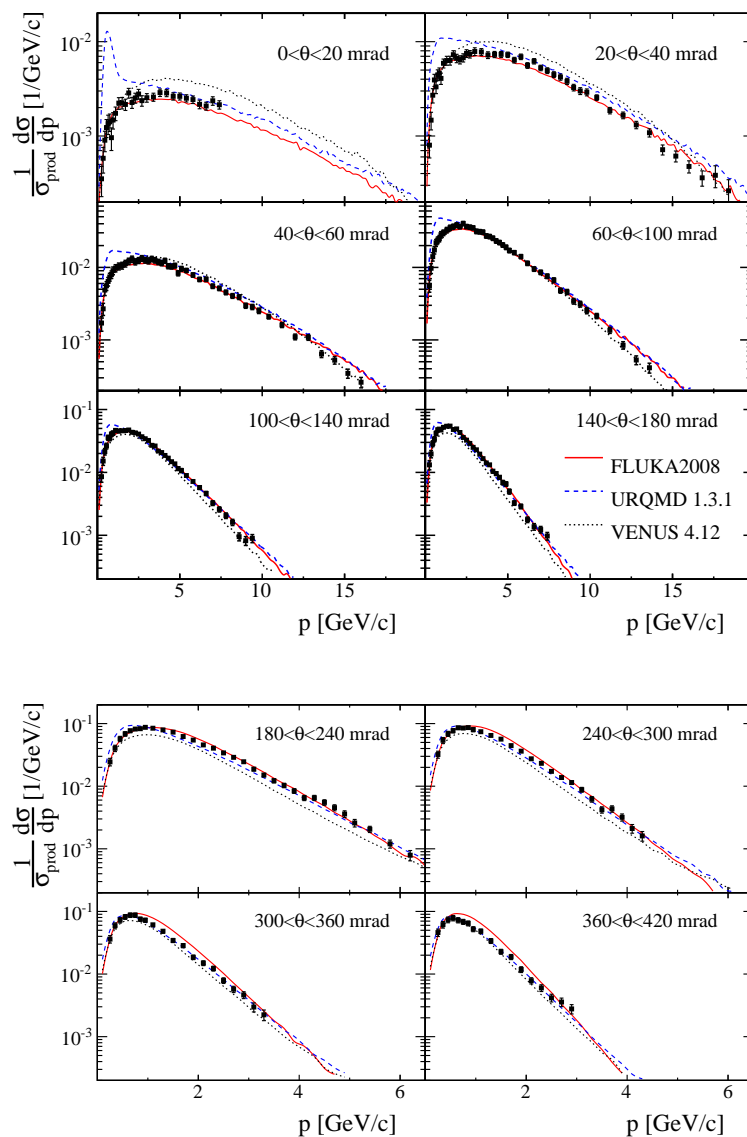


Fig. 5. (Color online) Laboratory momentum distributions of  $\pi^+$  mesons produced in production p+C interactions at 31 GeV/c in different intervals of polar angle ( $\theta$ ). The spectra are normalized to the mean  $\pi^+$  multiplicity in all production p+C interactions. Error bars indicate statistical and systematic uncertainties added in quadrature. The overall uncertainty (2.3%) due to the normalization procedure is not shown. Predictions of hadron production models, FLUKA2008<sup>18</sup> (solid line), URQMD1.3.1<sup>19</sup> (dashed line) and VENUS4.12<sup>20</sup> (dotted line) are also indicated.



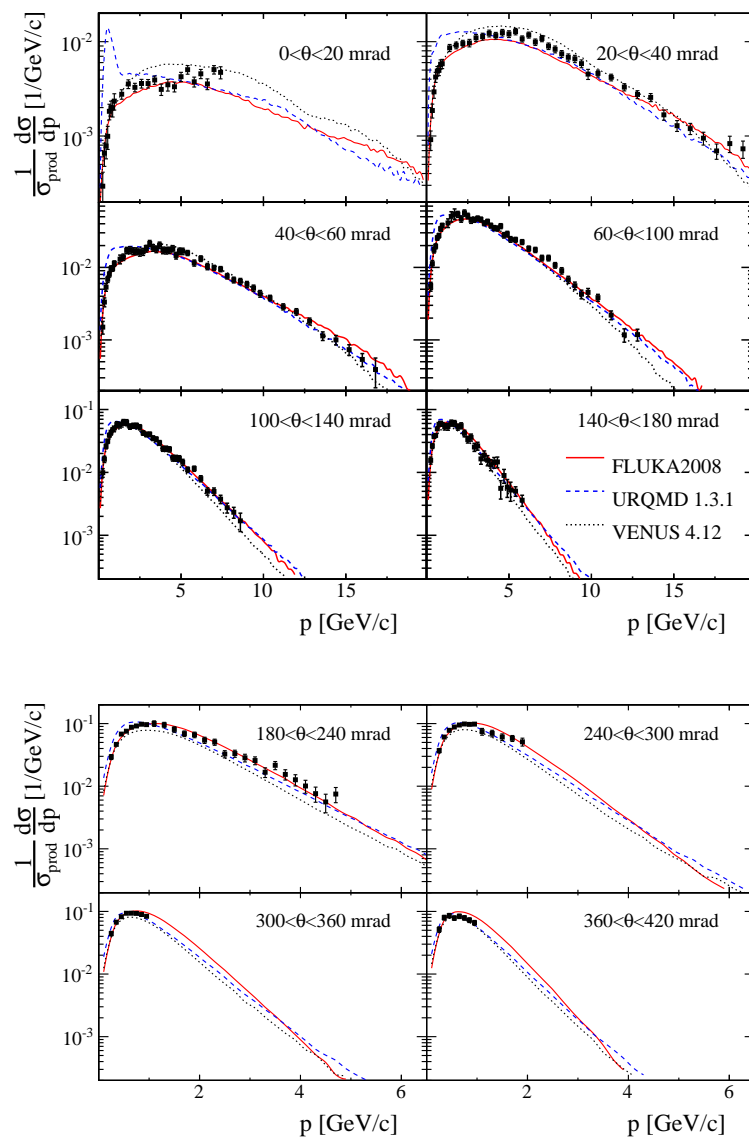


Fig. 6. (Color online) Laboratory momentum distributions of  $\pi^-$  mesons produced in production p+C interactions at 31 GeV/c in different intervals of polar angle ( $\theta$ ). The spectra are normalized to the mean  $\pi^-$  multiplicity in all production p+C interactions. Error bars indicate statistical and systematic uncertainties added in quadrature. The overall uncertainty (2.3%) due to the normalization procedure is not shown. Predictions of hadron production models, FLUKA2008<sup>18</sup> (solid line), URQMD1.3.1<sup>19</sup> (dashed line) and VENUS4.12<sup>20</sup> (dotted line) are also indicated.

with the T2K replica target during the 2007 run is in progress.<sup>21</sup> The new data will allow a further significant reduction of the uncertainties in the prediction of the neutrino flux in the T2K experiment.

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