PROCEEDINGS OF SCIENCE

Results from Pion-Carbon Interactions Measured by NA61/SHINE for Improved Understanding of Extensive Air Showers

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The interpretation of extensive air shower measurements, produced by ultra-high energy cosmic rays, relies on the correct modeling of the hadron-air interactions that occur during the shower development. The majority of hadronic particles are produced at equivalent beam energies below the TeV range. NA61/SHINE is a fixed target experiment using secondary beams produced at CERN at the SPS. Hadron-hadron interactions have been recorded at beam momenta between 13 and 350 GeV/c with a wide-acceptance spectrometer. In this contribution we present measurements of the spectra of charged pions and the ρ^0 production in pion-carbon interactions, which are essential for modeling of air showers.

The 34th International Cosmic Ray Conference
30 July – 6 August, 2015
The Hague, The Netherlands

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PoS(ICRC2015)330

1. Introduction

When cosmic rays collide with the nuclei of the atmosphere, they initiate extensive air showers (EAS). The interpretation of EAS data relies to a large extent on the understanding of these air showers, specifically on the correct modeling of hadron-air interactions that occur during the shower development. Experiments such as the Pierre Auger Observatory [9], KASCADE-Grande [10], IceTop [11] or the Telescope Array [12] use models for the interpretation of measurements. However, there is mounting evidence that current models give a poor description of muon production in air showers (see e.g. [13, 14, 15]).

Unfortunately, there exist no comprehensive and precise particle production measurements for the most numerous projectile in air showers, the π-meson. Therefore, new data with pion beams at 158 and 350 GeV/c on a thin carbon target (as a proxy for nitrogen) were collected by the NA61/SHINE experiment at the CERN SPS.

Preliminary spectra of unidentified hadrons have been previously derived from this data set and the spectra revealed discrepancies between the data and predictions from generators for hadronic interactions [16, 17, 18].

In this contribution we will present the measurement of the production spectra of identified charged pions and ρ^0 production in π^-+C interactions at 158 and 350 GeV/c.

2. The NA61/SHINE Experiment

NA61/SHINE[1] [1] is a multi-purpose fixed target experiment to study hadron production in hadron-nucleus and nucleus-nucleus collisions at the CERN Super Proton Synchrotron (SPS). Among its physics goals are precise hadron production measurements for improving calculations of the neutrino beam flux in the T2K neutrino oscillation experiment [2] as well as for more reliable simulations of hadronic interactions in air showers. Moreover, p+p, p+Pb and nucleus+nucleus collisions are measured to study the properties of the onset of de-confinement and search for the critical point of strongly interacting matter (see e.g. Ref. [3]).

The NA61/SHINE Collaboration uses large time-projection-chambers (TPCs) inherited from the NA49 experiment [4] to measure the charge and momentum of particles. The momentum resolution, $\sigma(1/p) = \sigma(p)/p^2$, is about $10^{-4}\,(\mathrm{GeV}/c)^{-1}$ at full magnetic field and the tracking efficiency is better than 95%. A set of scintillation and Cherenkov counters as well as beam position detectors upstream of the spectrometer provide timing reference, identification and position measurements of the incoming beam particles. Particle identification is achieved by measuring the energy loss along the tracks in the TPCs and by determining their velocity from the time of flight provided by large scintillator walls placed downstream of the TPCs. The centrality of nucleus-nucleus collisions can be estimated using the measurement of the energy of projectile spectators with a calorimeter [5] located behind the time of flight detectors. For nucleon-nucleus collisions, the centrality is determined by counting low momentum particles from the target (so called ‘gray protons’) with a small TPC around the target [6].

Data taking with the NA61/SHINE experiment started in 2007. After a first run with proton on carbon at 31 GeV/c, the data acquisition system was upgraded during 2008 to increase the event

[1] SHINE = SPS Heavy Ion and Neutrino Experiment

recording rate by a factor of ≈10 [7]. In the last years, a wealth of data has been recorded by the experiment at beam momenta ranging from 13 to 350 GeV/c with various beam particles and targets. In this paper we present results obtained from a special run with negative pions as beam particles and carbon as the target. Since pions are the most numerous particles in an air shower, this data will help to improve the interpretation of air showers at ultra-high energies.

3. Production of Charged Pions

For each track detected in the TPCs of NA61, the particle type can be estimated by using the truncated mean of the energy that is deposited per unit track length ($\mathrm{d}E/\mathrm{d}x$) along the particle trajectory. An example of a $\mathrm{d}E/\mathrm{d}x$-distribution in a specific bin in momentum p and transverse momentum p_T is shown in Fig. 1. As can be seen, the distribution can be well described by the sum of the energy loss distributions of electrons, protons, pions and kaons (see Ref. [8] for details) and given the fitted fraction of each particle type, the corresponding number, Δn, of produced tracks within each p/p_T-bin can be reconstructed.

This number is then corrected for the detector acceptance, selection efficiency, feed-down from weak decays and re-interactions in the target. The latter two corrections are currently estimated using model predictions (EPOS1.99, QGSJETII-04, DPMJET3.06) and they are typically well below 5%, but can reach up to 20% at low particle momenta. Overall, the systematic uncertainty of the corrected number of tracks, $\Delta n'$, is estimated to be ≤7%.

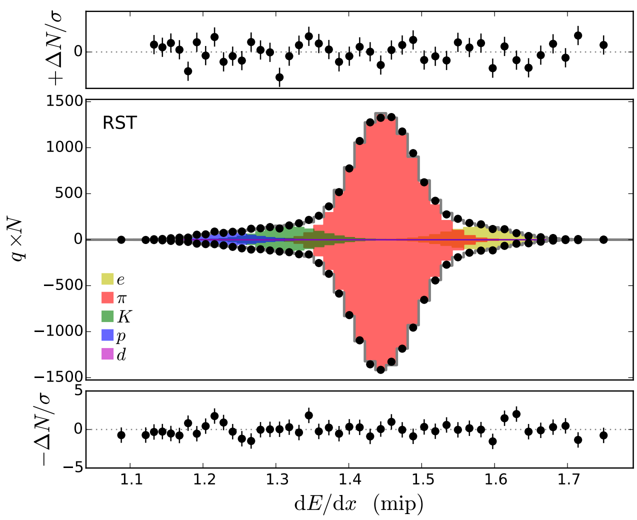

Figure 1: Example of a $\mathrm{d}E/\mathrm{d}x$ fit ($\langle p\rangle = 28.4$ GeV/c, $0 < p_\mathrm{T} < 0.1$ GeV/c). The middle panel shows the energy deposit of positively and negatively charged tracks. The fitted particles are indicated by colored histograms. Residuals to the fit are shown in the upper and lower panels.

The average multiplicity of particles produced within a p/p_T-bin is then obtained by dividing $\Delta n'$ by the total number of recorded events in which an interaction occurred, N_prod. N_prod is estimated by extrapolating the number of recorded interaction triggers to full phase space. The correction amounts to $(92.5 \pm 3.5)\%$ at 158 GeV/c and $(92.5 \pm 4.0)\%$ at 350 GeV/c, where the uncertainty was derived by running different generators to evaluate the correction.

The measured average multiplicities of charged pions are shown in Fig. 2 and the measurements are compared to predictions of pion production in π^-+C at 158 GeV/c from hadronic interaction models in Fig. 3. As can be seen, none of the generators describes the data well.

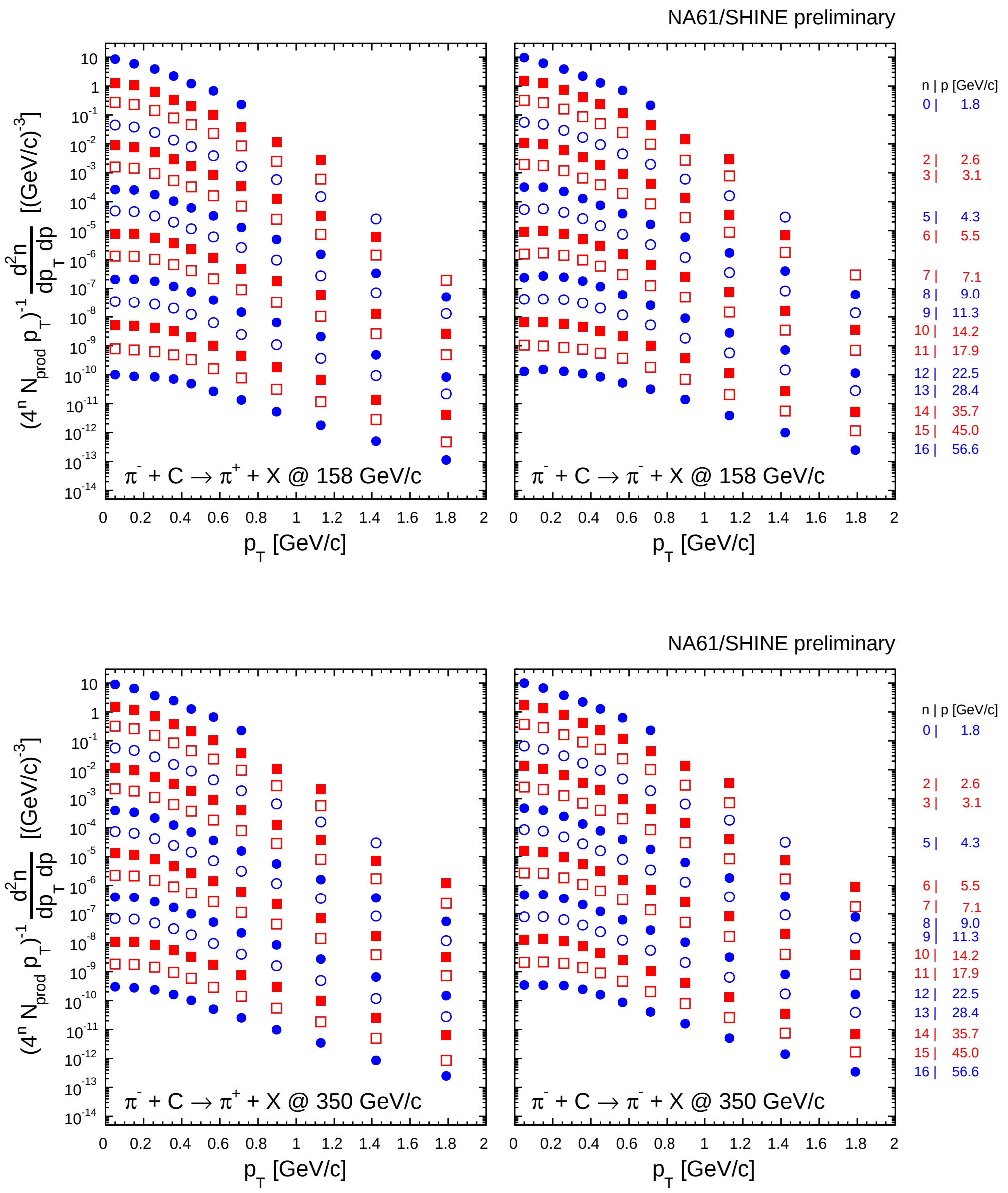

Figure 2: Inclusive production of charged pions in π^-+C interactions at beam energies of 158 and 350 GeV/c. For better visibility, the spectra from the nth momentum bin are multiplied by a factor of $^1/_{4^n}$. The momentum increases from top to bottom as indicated in the legend on the right.

4. Production of ρ^0 Mesons

The measurement of resonances in π+C is useful to constrain the production of ρ^0 meson, which is important to predict the number of muons observed in air showers as the baryon fraction (see e.g. Ref. [19]).

In the inclusive $\pi^+\pi^-$ mass spectra there is a large combinatorial background, which dominates over the effective mass distributions of individual resonances. The method used to estimate

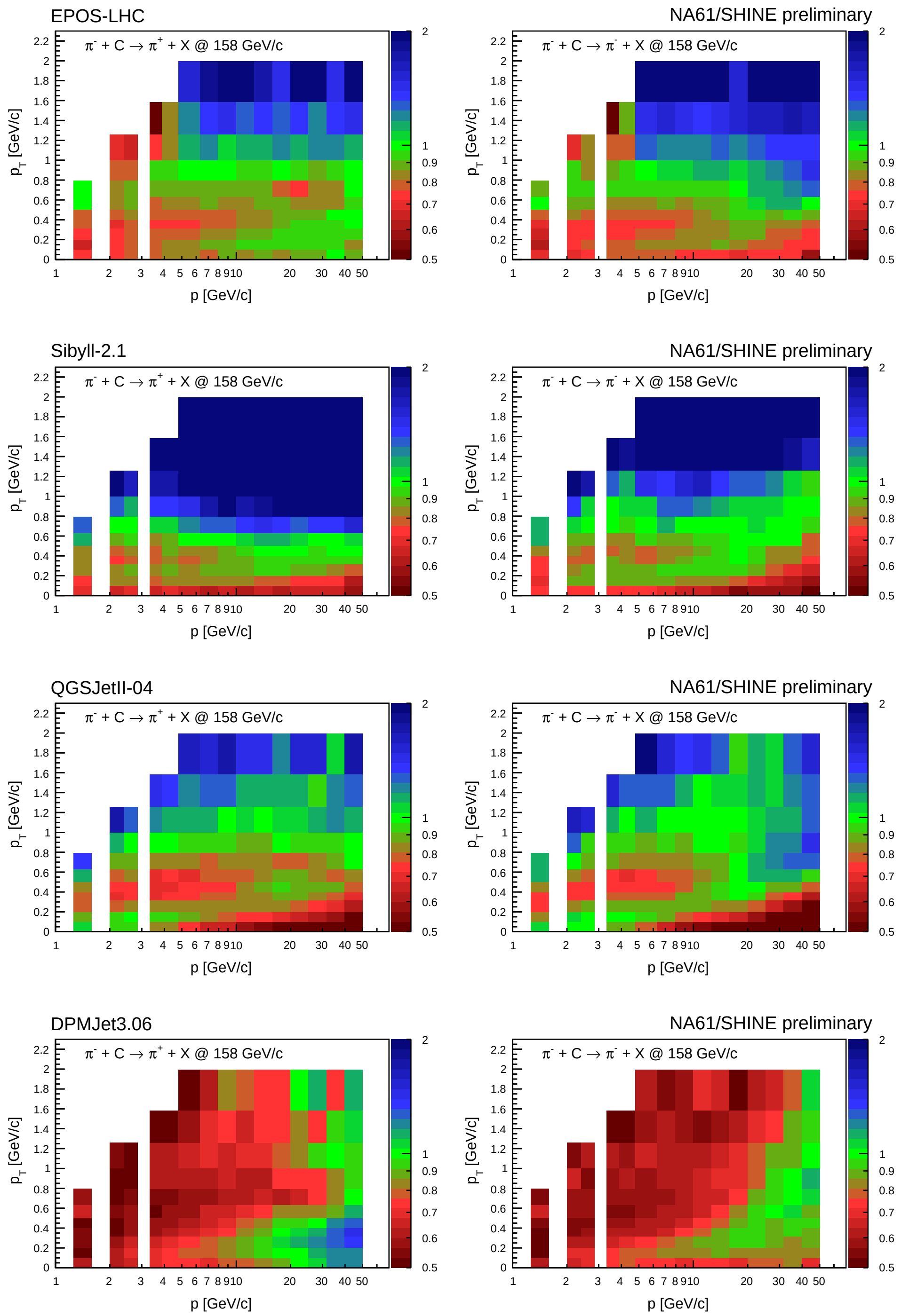

Figure 3: Comparison of the measured production spectra of charged pions to predictions from hadronic interaction models used for the interpretation of cosmic ray data [25, 23, 24, 22]. The colors denote the ratio of data to simulation and the color scale is truncated at 0.5 and 2. The two empty p-bins at $p \lesssim 2\,\mathrm{GeV}/c$ and $p \gtrsim 3\,\mathrm{GeV}/c$ are momenta excluded from the analysis due to the ambiguity with the energy deposit distributions of other particles types.

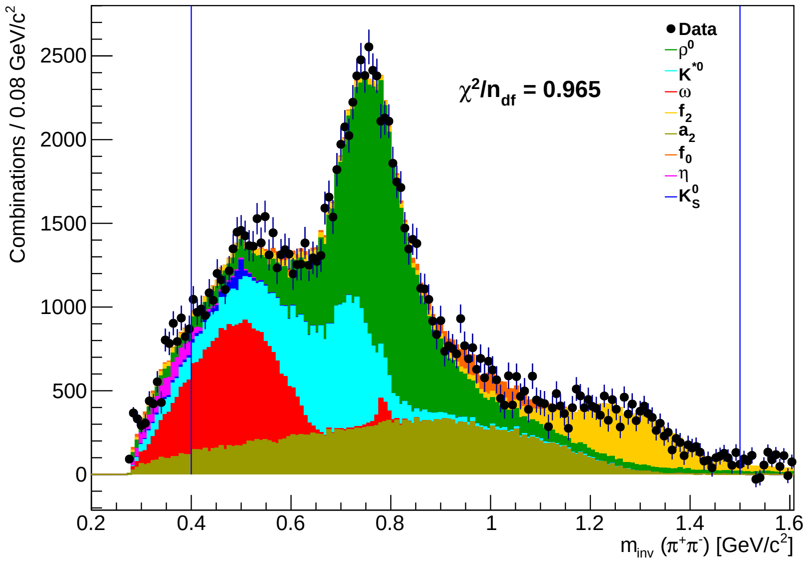

Figure 4: $\pi^+\pi^-$ mass distribution in π^-+C interactions at 158 GeV/c in the range $0.4 < x_F < 0.5$. Dots with error bars denote the data and the fitted resonance templates are shown as filled histograms. The vertical lines indicate the range of the fit.

the background is the so called charge mixing, which uses the $(\pi^+\pi^+ + \pi^-\pi^-)$ mass spectra as an estimate of the background.

The fitting procedure uses templates of the $\pi^+\pi^-$ mass distribution for each resonance. These templates are constructed by passing simulated π+C interactions, generated with the EPOS1.99 [20] hadronic interaction model using CRMC [21] (v1.5.3), through the full NA61 detector Monte Carlo chain. All the cuts that are applied to the data are also applied to the templates. This method of using templates allows for the fitting of both resonances with dominant three body decays, such as the ω, and resonances with non-$\pi^+\pi^-$ decays, such as the K^{*0}. The data is split into bins of Feynman-x, x_F.

The fit to the $\pi^+\pi^-$ mass spectrum is performed between masses of 0.4 GeV/c and 1.5 GeV/c using the expression

$$F(m) = \sum_i \beta_i T_i(m),$$

where β_i is the relative contribution for each template, T_i, used. An example of one of these fits can be seen in Fig. 4, The templates in the fit are the background found from charge mixing and the following resonances: ρ^0, K^{*0}, ω, f_2, f_0 (980), a_2, η and K^0_S.

The fitting method is validated by applying the same procedure to the simulated data set which was used to construct the templates for the fit. For the majority of x_F bins there is good agreement between the fit and the true value, with some discrepancies for larger x_F bins of up to 20%. This bias is corrected for in the final analysis. The data is also corrected for losses due to the acceptance of the detector, as well as any bias due to the cuts used and any reconstruction efficiencies. Apart from the acceptance, these corrections are typically less than 20%.

The average multiplicity of ρ^0 mesons is presented in Fig. 5. Also shown are predictions by EPOS1.99 [20], DPMJET3.06 [22], SIBYLL2.1 [23], QGSJETII-04 [24] and EPOSLHC [25]. It

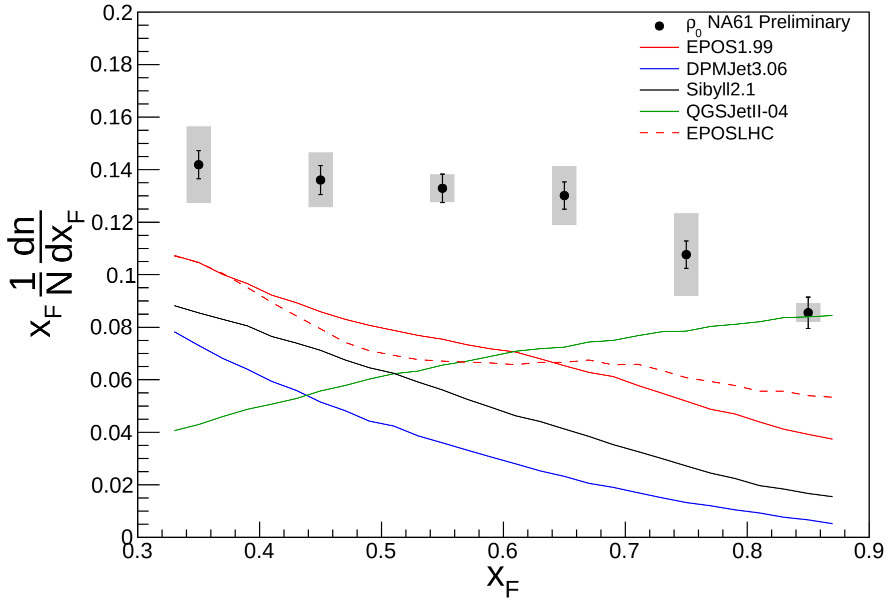

Figure 5: Average multiplicity of the ρ^0 meson in π+C at $p_{\text{beam}} = 158\,\text{GeV}/c$ as a function of Feynman-x. The bars show the statistical errors; the bands indicate systematic errors. The lines depict predictions of hadronic interaction models: red - EPOS1.99, blue - DPMJET3.06, black - SIBYLL2.1, green - QGSJETII-04, dashed red - EPOSLHC.

can be seen that there is an underestimation of the ρ^0 for almost all hadronic interaction models, with the exception of QGSJETII-04 for $x_F > 0.8$. It is interesting to note that while QGSJETII-04 and EPOSLHC were tuned to NA22 π^++p data [26], there is an underestimation in π^-+C.

Systematic errors are estimated by comparing correction factors for different hadronic interaction models (EPOS and DPMJET), comparing the correction for the bias using different background estimates and varying the cuts applied to the data. The systematic is dominated by the background estimates, up to 14%, where as the other errors are less than 4%. Other sources of uncertainty, such as using templates from a different model, are found to be much smaller.

5. Conclusions and Outlook

In this article, we summarized results from pion-carbon interactions measured with the multi-purpose experiment NA61/SHINE at the CERN SPS, which are of importance for the modeling of cosmic ray air showers.

The comparisons to hadronic interaction models shown in this article suggest that these models require further tuning to reproduce the charged pion spectra and ρ^0 production.

It is planned to further refine both analyses presented here, including the measurement of inclusive spectra of charged kaons and protons as well as the study of the multiplicities of other resonances in addition to the ρ^0.

Acknowledgment: This work was supported by the Hungarian Scientific Research Fund (grants OTKA 68506 and 71989), the Janos Bolyai Research Scholarship of the Hungarian Academy of Sciences, the Polish Ministry of Science and Higher Education (grants 667/N-CERN/2010/0, NN 202 48 4339 and NN 202 23 1837), the Polish National Center for Science (grant 2011/03/N/ST2/03691), the Polish National Center for Science (grant 2013/11/N/ST2 /03879) the Foundation for Polish Science – MPD program, co-financed by the European Union within the European Regional Development Fund, the Federal Agency of Education of the Ministry of Education and Science of the Russian Federation (grant RNP 2.2.2.2.1547), the Russian Academy of Science and the Russian Foundation for Basic Research (grants 08-02-00018 and 09-02-00664), the Ministry of Education, Culture, Sports, Science and Technology, Japan, Grant-in-Aid for Scientific Research (grants 18071005, 19034011, 19740162, 20740160 and 20039012), the German Research Foundation (grant GA 1480/2-1 and GA 1480/2-1), Ministry of Education and Science of the Republic of Serbia (grant OI171002), Swiss Nationalfonds Foundation (grant 200020- 117913/1) and ETH Research Grant TH-01 07-3.

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