Pion Production Cross-section Measurements in p+C Collisions at the CERN SPS for Understanding Extensive Air Showers

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An important approach to studying high-energy cosmic rays is the investigation of the properties of extensive air showers; however, the lateral distribution of particles in simulations of such showers strongly depends on the applied model of low-energy hadronic interactions. It has been shown that many constraints to be applied to these models can be obtained by studying identified-particle spectra from accelerator collisions, in the energy range of the CERN Super Proton Synchrotron. Here we present measurements of the pion production cross-section obtained by the NA61/SHINE experiment at the SPS, in proton-carbon collisions at the beam energy of 31 GeV from the year 2007. Further analyses of identified-particle yields in SHINE, in particular with a pion beam, are in preparation.

I. INTRODUCTION

The most common way employed nowadays to study high-energy cosmic rays is to examine the properties of extensive air showers (EAS) they induce in the atmosphere, using several different observables and detection techniques. The latter include measurements of shower size and composition at ground level using surface arrays of scintillation or Cherenkov-light detectors, observation of energy losses of shower particles as they traverse the atmosphere using fluorescence detectors, detection of radio emission from the shower using appropriate antennae, and others. Examples of experiments measuring EAS include the surface arrays KASCADE and KASCADE-Grande as well as the hybrid surface-and-fluorescence Pierre Auger Observatory [1–3].

Unfortunately, determination of properties of the initial particle from such observables strongly depends on models, especially those of hadronic interactions occurring during shower development. Many such models exist yet they frequently fail to consistently and accurately reproduce experimental data, for instance underestimating the yield of shower muons at ground level or showing non-smooth transition from low- to high-energy hadronic interactions [4–7].

In light of the above, additional data is required in order to appropriately tune models of hadronic interactions in EAS. Such data can be provided by accelerator experiments observing collisions of hadrons such as protons or pions with light ions such as carbon nuclei. In particular, it has been demonstrated that the energy range of the Super Proton Synchrotron (SPS) at CERN makes it highly suitable for reproducing final hadronic interactions[8] in showers of energies studied by KASCADE, KASCADE-Grande and the Pierre Auger Observatory [5].

This article presents the first results by the NA61/SHINE experiment at the SPS obtained for the purpose of measuring the particle yield in the long-baseline neutrino experiment T2K and tuning EAS models — pion spectra from p+C collisions at 31 GeV.

II. THE NA61/SHINE EXPERIMENT

NA61/SHINE is an experiment at the CERN SPS using the upgraded NA49 hadron spectrometer to accomplish a number of physics goals. In addition to providing reference data for cosmic-ray experiments it shall also provide model-tuning information for the neutrino experiment T2K, produce for the first time in the SPS energy range large-statistics proton-proton data sets for high-p_T studies and, last but not least, perform a comprehensive energy and system-size scan in search for the QCD critical point. Its large acceptance (around 50 % for $p_T \leq 2.5$ GeV/c), high momentum resolution ($\sigma(p)/p^2 \approx 10^{-4}\ (GeV/c)^{-1}$) and tracking efficiency (over 95 %), and excellent particle-identification capabilities ($\sigma(\frac{\mathrm{d}E}{\mathrm{d}x})/\frac{\mathrm{d}E}{\mathrm{d}x} \approx 4\ \%, \sigma(t_{ToF}) \approx 100\ ps$) make it an excellent tool for investigating hadron spectra. Moreover, its kinematic range covers well that of KASCADE, KASCADE-Grande and the Pierre Auger Observatory (see Figure 1).

The following are the main features of the NA61 detector as shown in Figure 2 [10, 11]:

- tracking plus momentum, charge and $\mathrm{d}E/\mathrm{d}x$ measurement with five Time-Projection Chambers;
- three Time-of-Flight walls for additional identification information;
- high-precision downstream Projectile Spectator Detector;
- a number of beam and triggering detectors.

For the purpose of cosmic-ray studies, SHINE acquired in the years 2007 and 2009 5.4 million p+C events at 31 GeV, 3.6 million π^-+C events at 158 GeV and 4.7 million π^-+C events at 350 GeV. The analysis of these data sets is currently in progress. The results presented here have been produced from the 0.6 million p+C-at-31 GeV events registered during the 2007 pilot run.

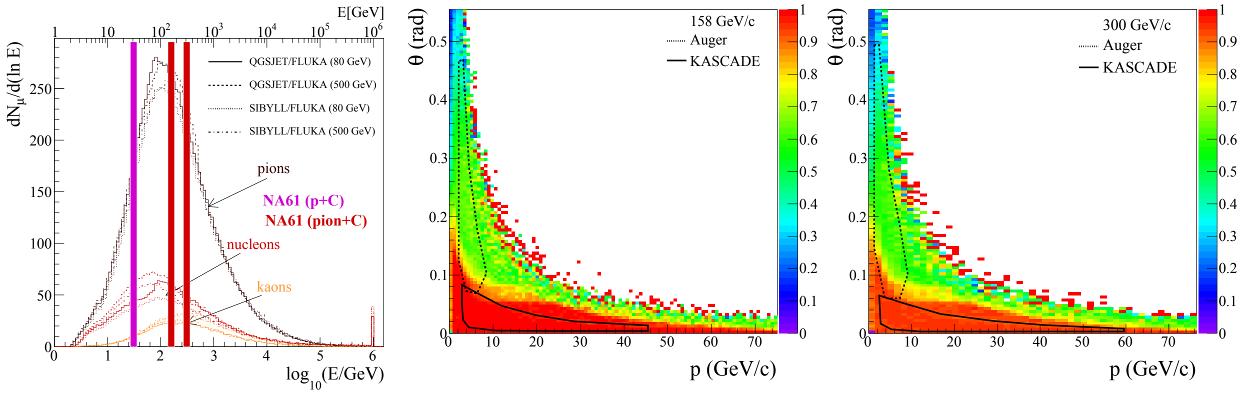

FIG. 1. **Left**: Energy distributions, simulated using several models, of the “grandfather” particles in extensive air showers with $E_0 = 10^{15}$ eV, with vertical lines indicating the beam energy in relevant NA61/SHINE runs. **Middle and right**: coverage of NA61 in pion–carbon collisions at 158 (middle) and 300 (right) GeV *vs* that of KASCADE and Auger, with contours indicating the 66-percent level for each [9].

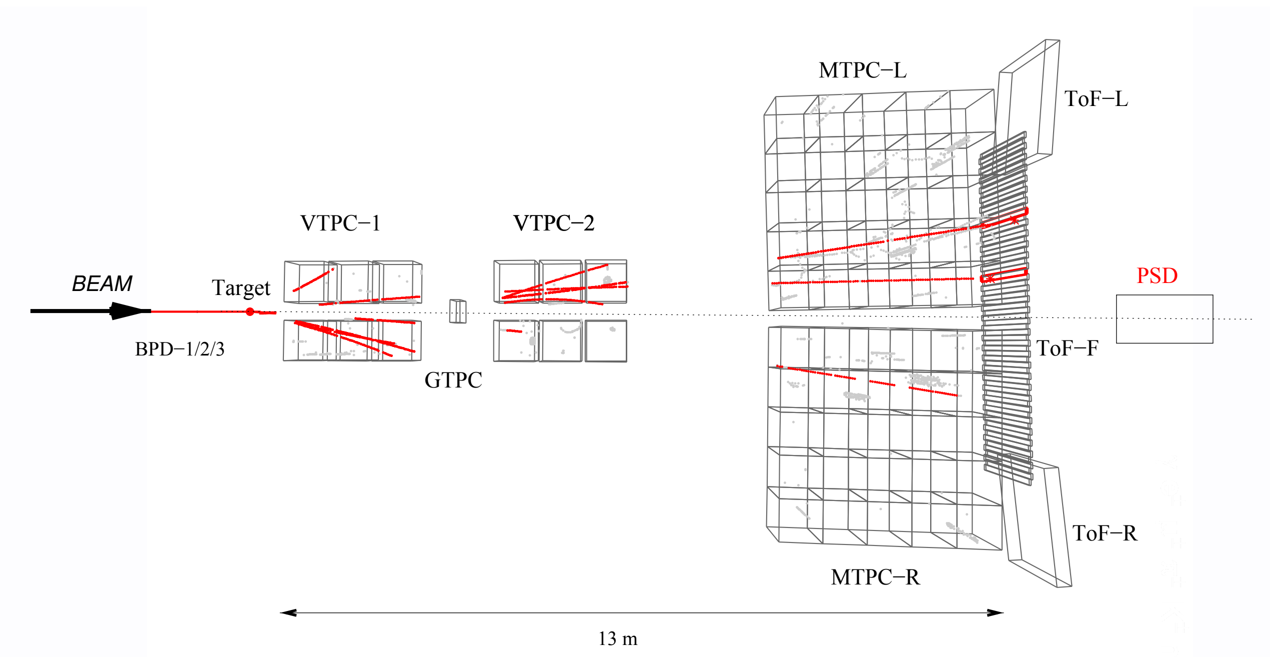

FIG. 2. A view of an NA61/SHINE p+C collision, superimposed on the layout of the apparatus.

III. THE METHOD

The pion spectra presented here have been obtained using three independent analysis techniques:

- The h^- method, in which all negative hadrons produced in a collision are assumed to be pions and the contribution of other species is corrected for using simulations. Pros: simple, high statistics. Cons: stronger model dependence, doesn't work for positive pions;
- dE/dx identification of $\pi^\pm$. Pros: explicit identification, still high statistics thanks to NA61 design. Cons: only works in the momentum regions where Bethe-Bloch bands do not overlap;
- dE/dx-plus-ToF identification of $\pi^\pm$. Pros: explicit identification over a wide momentum range. Cons: limited acceptance.

For all three approaches, particles passing all the cuts are divided into (p, θ) bins, where p is the total momentum and θ is the polar angle, to account for changing detection and identification properties.

Last but not least SHINE has estimated the systematic uncertainty of results obtained from all three analyses. At present this has been found to be less than on equal to 20 %; we are now working on reducing the systematic uncertainty further.

IV. RESULTS

Figures 3 and 4 show the production cross-section ($\sigma_{prod} = \sigma_{inel} - \sigma_{qel}$, where σ_{inel} and σ_{qel} are inelastic and quasi-elastic cross-section, respectively) of negative and positive pions in different θ bins, compared to air-shower simulations based on the CORSIKA package, using three different interaction models: GHEISHA, FLUKA and UrQMD [12–15]. Please see the summary for a discussion of these results.

V. SUMMARY AND OUTLOOK

NA61/SHINE has produced its first results relevant to tuning models of hadron production in extensive air showers: preliminary $\pi^{\pm}$ spectra from $p{+}C$ collisions at 31 GeV. The spectra were obtained using three different methods, with very good agreement observed between them. Systematic uncertainties are at the moment no greater than 20 %, with work ongoing to reduce them further. Last but not least, preliminary comparisons with simulations show good agreement with FLUKA for polar angles below 180 mrad and with UrQMD above that threshold.

We are now working on finalising and publishing these results, as well getting ready to analyse the large-statistics $p{+}C$ and $\pi{+}C$ runs from 2009.

ACKNOWLEDGMENTS

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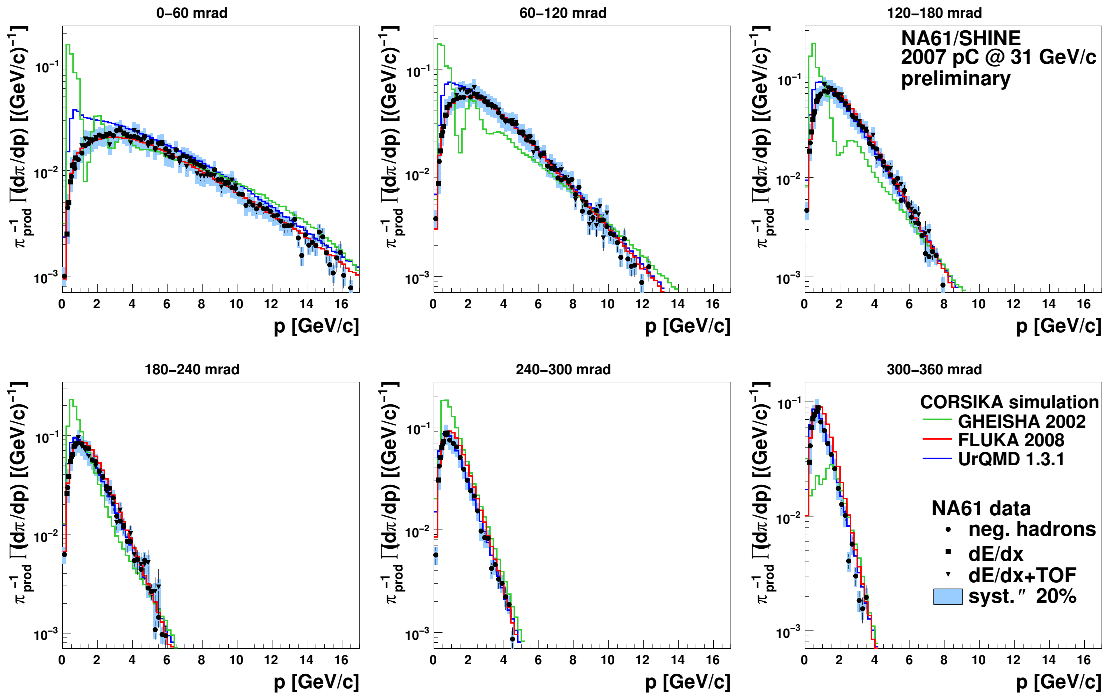

FIG. 3. Momentum dependence of π^- production cross-section in p+C collisions at 31 GeV/c. Circles: h^- analysis; squares: pions identified using dE/dx; triangles: pions identified using combined dE/dx and ToF information. Vertical bars and boxes indicate statistical and systematic uncertainties, respectively. Lines indicate model calculations.

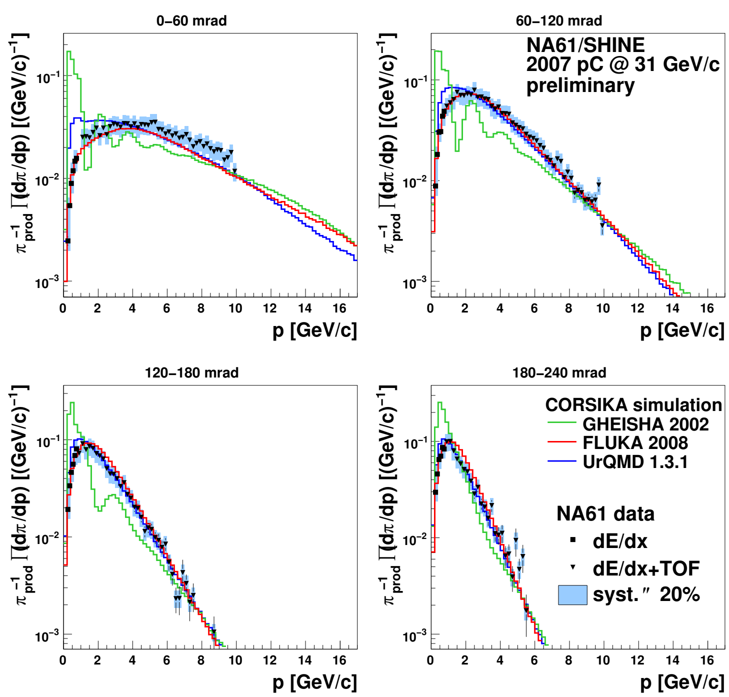

FIG. 4. Momentum dependence of π^+ production cross-section in p+C collisions at 31 GeV/c. Squares: pions identified using dE/dx; triangles: pions identified using combined dE/dx and ToF information. Vertical bars and boxes indicate statistical and systematic uncertainties, respectively. Lines indicate model calculations.