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# Production of charged pions off nuclei with 3 · · 30 GeV incident protons and pions\*

K. Gallmeister<sup>†</sup> and U. Mosel

*Institut für Theoretische Physik, Universität Giessen, Germany*

We compare calculations for the production of charged pions by pion or proton beams off nuclei calculated within our coupled channel transport model (GiBUU) with recent data of the HARP collaboration for beam energies from 3 up to 13 GeV. Predictions for the 30 GeV data for pions and kaons from the NA61/SHINE experiment are included.

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## I. INTRODUCTION

Recently the HARP experiment has published data for  $\pi^\pm$  production by protons or pion beams in the momentum range 3 · · 13 GeV impinging on different nuclear targets [1, 2, 3]. Here the main goal is to contribute to the understanding of the neutrino fluxes of accelerator neutrino experiments such as K2K, MiniBooNE and SciBooNE or for a precise calculation of the atmospheric neutrino fluxes. Some of the experimental data were also compared to several different generator models used in GEANT4 and MARS simulation packages [2]. The overall agreement was reasonable, while for some models discrepancies up to factors of three were seen. Unfortunately, none of these models is applicable for all energies considered in the experiment: somewhere at 5 · · 10 GeV a distinction between low energies and high energies has to be done, limiting the range of validity of these models.

In this paper we employ the GiBUU model for an analysis of these data. This model has been developed as a transport model for energies from some MeV up to tens of GeV [4]. Here we can study all kind of elementary collisions induced by baryons, mesons (see e.g. [5]), (real and virtual) photons (see e.g. [6, 7]) and neutrinos (see e.g. [8, 9] and further references therein) on all kind of nuclei within a unique framework.

The model relies on a separation of processes for the reaction mechanisms on nuclei. First the beam particle interacts with a nucleon inside the nucleus. At the given energies (3 · · 12 GeV beam momenta), these  $pN$  or  $\pi^\pm N$  interaction are simulated within a hard pQCD interaction framework, since the available collision energies are above the resonance regions ( $\sqrt{s}_{\pi N, pN} = 2.8 \cdot \cdot 4.9$  GeV). Contrary to most other hadronic interaction models, which are using a string excitation picture via Pomeron exchange (e.g. FRITIOF or some own implementations), we are using PYTHIA (v. 6.4) also at these low energies. We have ascertained that PYTHIA describes the hadron production cross sections in general quite well even at relatively low invariant masses; the detailed comparison with the HARP data can serve as a further test of the general accuracy of the method.

The elementary interaction with the nucleon is assumed to be the same as that with a free nucleon. All the standard nuclear effects like Fermi motion, Pauli blocking and nuclear shadowing are properly taken into account. In a second step, all produced (pre-)hadrons are propagated through the nuclear medium according to the semi-classical Boltzmann-Uehling-Uhlenbeck transport equation. The concept of pre-hadrons (i.e. produced hadrons interact with some reduced cross section during their hadronization time) was introduced in order to realize color transparency and formation time effects [10, 11]. All interactions, primary or secondary, are therefore treated within the same prescription and we thus present a full consistent coupled channel transport approach.

In this paper we show comparisons of our calculations to data obtained with the forward spectrometer as well as with the large-angle spectrometer of the HARP experiment. The calculations are done without any fine tuning to the data covered here with the default parameters as used in the GiBUU framework for all possible processes.

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<sup>†</sup>Electronic address: Kai.Gallmeister@theo.physik.uni-giessen.de

## II. RESULTS

We begin our comparison with data obtained with the forward spectrometer for a Carbon target [1]. In fig. 1 we show the double differential production cross section of charged pions for the 12 GeV proton beam. Here the covered momentum range of the detected pions reaches up to 8 GeV. For more backward angles ( $\gtrsim 120$  mrad) the agreement is perfect. For the very forward angles (up to 120 mrad) we observe a too flat behavior of the calculated spectra compared to data. The calculations overshoot the data for large momenta significantly, especially for the  $\pi^-$  channel.

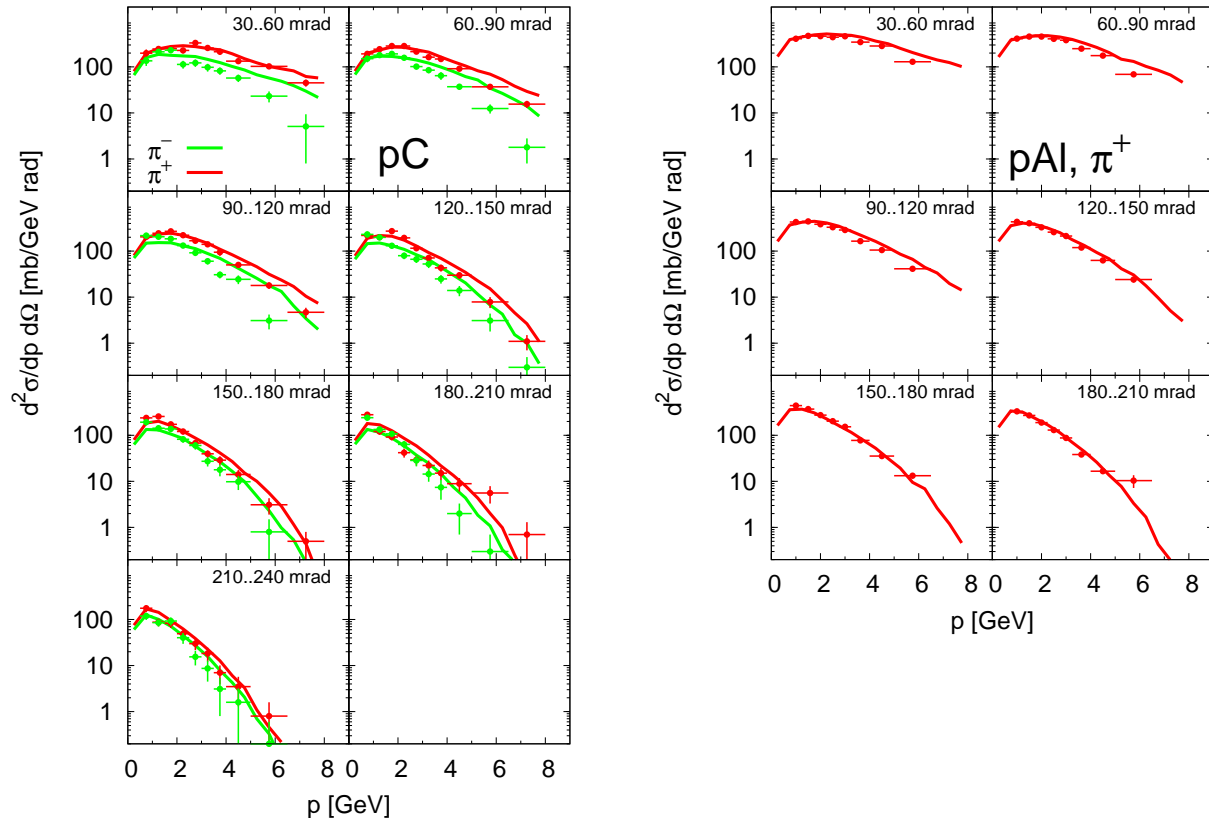


FIG. 1: Cross section  $d^2\sigma/dpd\Omega$  for  $p + C \rightarrow \pi^\pm + X$  with 12 GeV beam momentum (left) and  $p + Al \rightarrow \pi^+ + X$  with 12.9 GeV beam momentum (right). Experimental data are from [1, 3] (HARP small angle analysis).

This seems to be a general shortcoming of all the hadronic interaction models GHEISHA, UrQMD and DPMJET-III shown in [1]. However, in contrast to the model predictions of these models, our calculations reproduce the decrease of the cross section for very small momenta (e.g. for  $p \lesssim 2$  GeV for angles smaller than 90 mrad).

In fig. 1 (right panel) we also show a comparison of our model calculations with experimental data [3] with a 12.9 GeV beam on an Al target for positive charged pions. Here the agreement is very good for all momenta and angles.

For further comparisons we note that the laboratory angles of the HARP experiment can be translated into a cm pseudo rapidity  $\eta^*$ . With the given angular bins the pseudo rapidity covers the range  $\eta^* = 0.5 \cdots 2.1$ . The three smallest angles correspond to the range  $\eta^* > 1.2$ .

In order to clarify the question whether the problems observed for the very forward angles for  $^{12}C$  are due to problems in the treatment of the FSI or already present in the hard first interaction, we compare in fig. 2 our model with experimental data for elementary reactions [13]. Here the relevant kinematical variables are the transverse momentum  $p_T$  and the cm rapidity  $y^*$ . It is obvious that the actual model implementation agrees very well with these data, even though there are small discrepancies visible around  $y^* \sim 1.5$ .

It is worthwhile to mention, that this holds only for the newest versions of PYTHIA (v6.4). Older versions (e.g. v6.2) prefer low transverse momentum and high rapidity. At the energies covered here, we are in a transition region, where the high energy processes embedded in the PYTHIA model may reach their limits. However, PYTHIA also contains some low energy processes. Contrary to a Pomeron exchange model, as e.g. implemented in FRITIOF or UrQMD, low

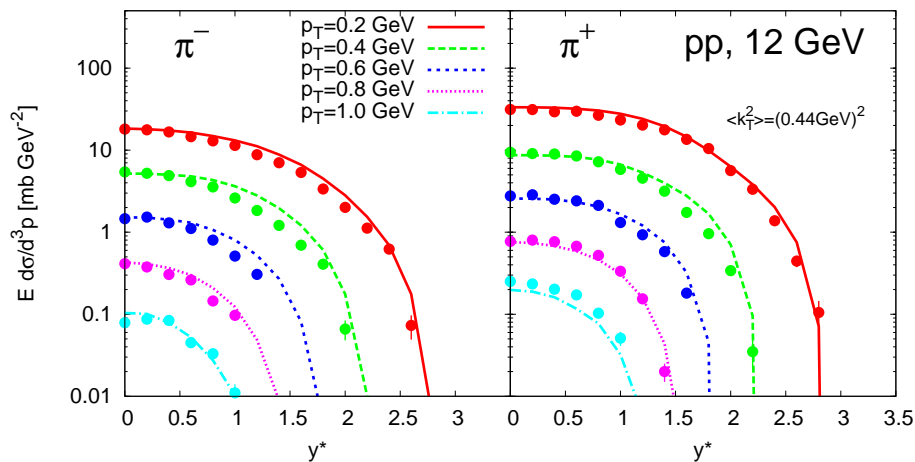


FIG. 2: Invariant cross section  $E d\sigma/d^3p$  for  $pp \rightarrow \pi^\pm X$  with 12 GeV beam momentum. Experimental data are from [13]. Due to symmetry only  $y^* > 0$  is shown.

energy interactions are treated as string flips in PYTHIA. Thus only the JETSET-Part of PYTHIA is responsible for these processes and, therefore, the influence and number of (internal) model parameters is limited.

In fig. 3 we show the comparison with data with  $\pi^+$  and  $\pi^-$  beams. Here the agreement is excellent for all available

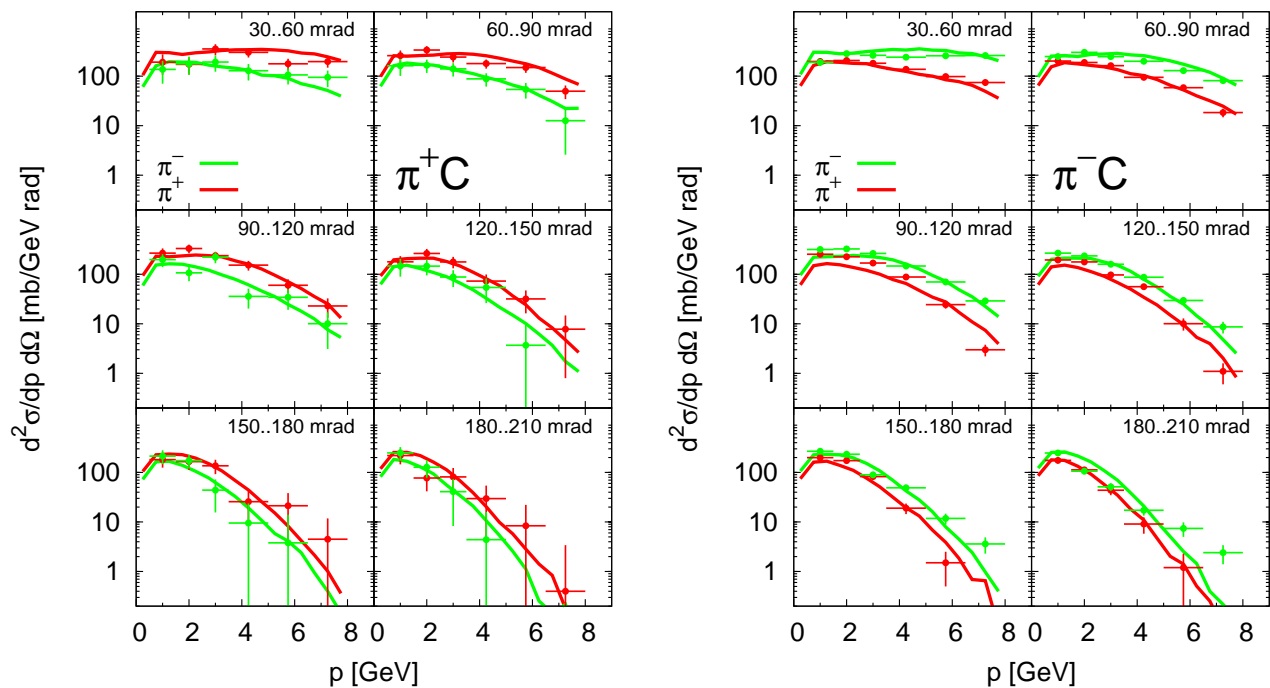


FIG. 3: Cross section  $d^2\sigma/dp d\Omega$  for  $\pi^\pm + C \rightarrow \pi^\pm + X$  with 12 GeV beam momentum. Experimental data are from [1] (HARP small angle analysis).

angles and all momenta. Not only the charge-conserving channels, but also the double charge exchange channels are perfectly reproduced. This limits the uncertainties connected with the final state interactions in the proton induced reactions discussed before.

We continue our comparison with data with the large angle spectrometer [2]. In order to keep this paper reasonably short we restrict ourselves to comparisons for a few selected energies only. A gallery of more comparisons is available at [12].

In fig. 4 we compare calculations with the data for the proton beam at 3 GeV. In the large angle analysis all the

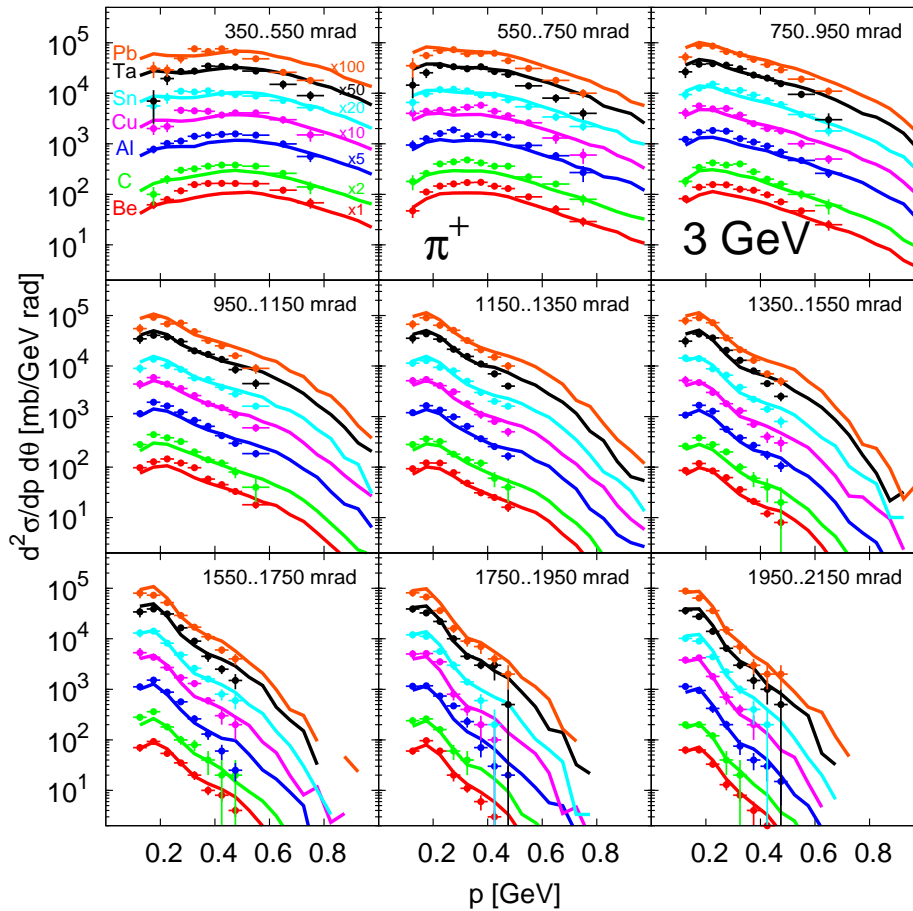


FIG. 4: Cross section  $d^2\sigma/dp d\theta$  for  $p + A \rightarrow \pi^+ + X$  with 3 GeV beam momentum. Experimental data are from [2] (HARP large angle analysis), curves and data scaled as indicated.

momenta of the detected pions are below 1 GeV. One sees a very good overall agreement for perpendicular or even backward directions for all nuclei. Small discrepancies occur mainly for angles below 750 mrad at very low momenta  $\lesssim 0.2$  GeV where the calculations are higher than the experimental data. Correspondingly, the slope for momenta larger than 0.4 GeV is too flat in our calculations. For light nuclei the slope is in agreement with data, while the overall yield is somewhat too small. We note that these observations also hold for the negatively charged pions not shown here.

In order to illustrate the energy dependence of our results, we compare in fig. 5 the calculations for positive pion production with the 12 GeV proton beam. The overall behavior of the calculations changes smoothly from 3 GeV to 12 GeV, a comparison for 5 and 8 GeV can be found in [12].

For the higher energies the data do not show the strong dip observed for small angles and small momenta. Therefore, our calculations are in better agreement also for the smaller momenta with the data than for the small energies, although the overall yield for the small angles is still somewhat too low.

For all energies one observes for the perpendicular directions ( $\simeq 1550$  mrad) a 'bumpy' structure around  $p \approx 0.5$  GeV. We note, that while this structure is not very pronounced in the experimental data for  $\pi^+$ , the experimental data for the  $\pi^-$  channel (not shown here) do exhibit this feature. Calculations for a nucleon target indicate a smooth behavior. For the nuclear target at momenta around 0.2 GeV rescattering and the  $\Delta$  resonance dominate. This small momentum regime is populated by originally higher-energy pions that have been slowed down due to rescattering; only due to these final state interactions the overall yield is reproduced. Without FSI the yield for momenta around 0.2 GeV is underestimated by at least one order of magnitude.

We note, that one can again translate these data into data as function of the cm pseudo rapidity and transverse momentum. The discrepancies for large angles then show up as discrepancies at rapidities  $\eta^* < -1.8$ . This is the feature already seen in the comparisons to the small angle analysis, but now for the very backward rapidities. The transverse momentum region in the data for these extreme rapidities is comparable.

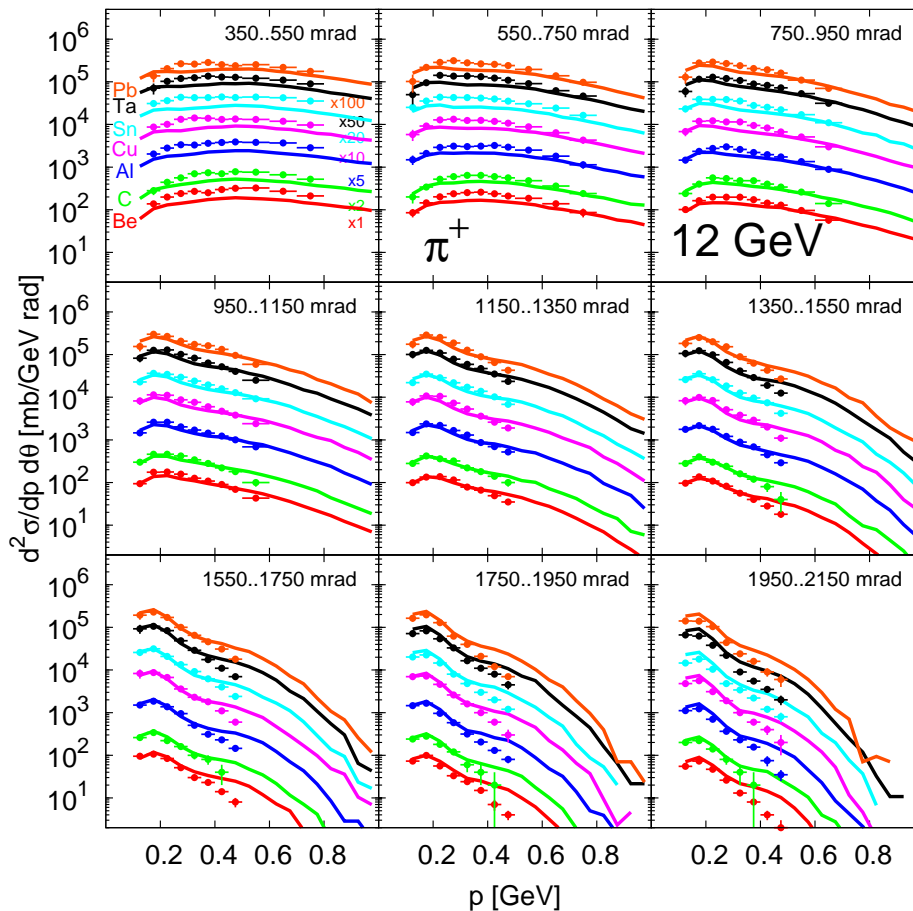


FIG. 5: Cross section  $d^2\sigma/dpd\theta$  for  $p + A \rightarrow \pi^+ + X$  with 12GeV beam momentum. Experimental data are from [2] (HARP large angle analysis), curves and data are scaled as indicated. The targets are indicated in the top-left frame.

While the experimental spectra of positive and negative charged pions show substantial differences, the spectra resulting from our calculations do exhibit the same features for both charge states. In order to quantify the differences between the two isospin states, we show in fig. 6 the ratio of the yields of  $\pi^-$  over the yield of  $\pi^+$ . We have chosen the two smallest and the two largest nuclei. The discrepancies between data and calculations are quite significant, although the overall tendencies are reproduced. As in experiment we observe an excess of  $\pi^-$  over  $\pi^+$  for large nuclei at low momenta. It was suggested by the experiment E910 [14] that this is due to production of  $\Lambda^0$ . However, this is not supported by our calculations where the charge asymmetry calculation for the pions originates in decays of  $\Delta$ 's at rest; these latter particles have long collision histories. In every collision the excess of neutrons over protons favors the creation of negatively charged pions over their positively charged partners. We have checked, that in a (fictitious) symmetric nucleus of the size of Pb the ratio of negative over positive charged pions is indeed the same as in Be. We have also checked, that our results are not affected by switching on or off baryonic potentials or Coulomb corrections.

At the same time the HARP experiment is used to reduce uncertainties on the flux calculations of the K2K experiment, the NA61/SHINE experiment is aimed to measure the pion and kaon yields for the T2K experiment [15, 16]. Here the beam energy is 30 GeV, while also upgrades to 40 GeV and 50 GeV are foreseen. Responsible for the neutrino flux will be pions and kaons with momenta  $1 \cdots 10$  GeV and angles  $\theta \lesssim 300$  mrad.

In order to ease the comparison with the previous parts, we will use the same binning for the calculations at these higher energies as those for HARP with the forward spectrometer. In fig. 7 we show our resulting spectra of charged pions and kaons for a proton beam on a Carbon target. We note that a comparison of the calculated pion yields with 24 GeV on a proton target with experimental data [13] is as good as for 12 GeV beam momentum [12]. Therefore the uncertainties of the calculations are again mainly due to the final state interactions. As soon as experimental binning is available, we are able to produce the spectra directly comparable with the upcoming data.

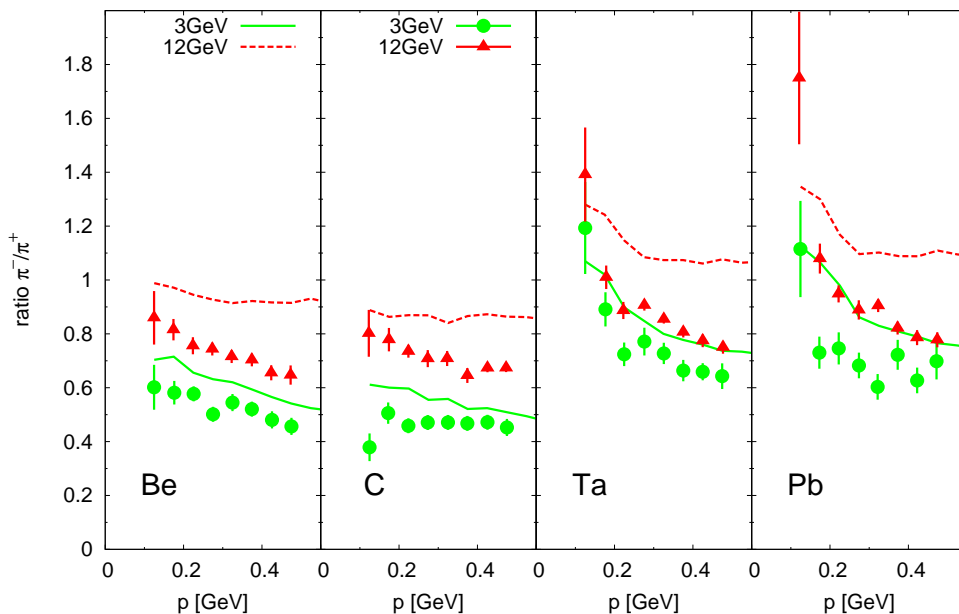


FIG. 6: Ratio of cross section for  $\pi^-$  over  $\pi^+$  for  $p+Be$ ,  $p+C$ ,  $p+Ta$  and  $p+Pb$  interactions at 3 and 12 GeV as function of the momenta of the pions, integrated over the angles 350mrad to 1550mrad. Data are from [2].

### III. CONCLUSIONS

We have presented a comparison of calculations within the GiBUU transport framework with recent data on inclusive pion production on different nuclear targets with pion or proton beams in the region of 3 up to 12 GeV beam momentum. Contrary to other theoretical frameworks we are, while using the GiBUU coupled channel transport model, able to cover the full energy range of the HARP experiment.

The best description is achieved for the data with pion beams. The agreement obtained for proton beams is very good over the whole energy-range, except for very forward and very backward directions. These deficiencies seem to be due to FSI as a comparison with corresponding data for elementary  $p + p$  collisions shows. This underlines the need to understand results on elementary collisions before drawing conclusion on data taken on nuclei as targets.

While the experimental data are especially useful as input to neutrino flux calculations, we also have here a very powerful set of data for checking final state interactions within our transport code, not only as needed for the neutrino production processes, but also for describing the interactions of neutrinos with nuclei in one and the same theory and code.

We have also presented first theoretical results for the 30 GeV proton run in the NA61/SHINE experiment which aims for a precise determination of the neutrino flux in the T2K experiment. Since soon the data from this experiment will cover a wide range of beam energies, it will be interesting to extract from the beam energy dependence conclusions on formation time aspects and color transparency [17].

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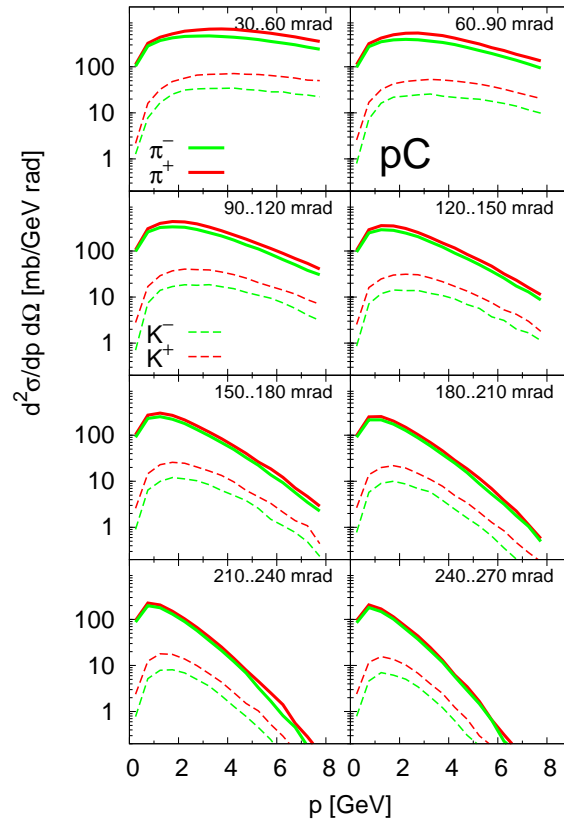


FIG. 7: Cross section  $d^2\sigma/dpd\Omega$  for  $p + C \rightarrow \pi^\pm + X$  and  $p + C \rightarrow K^\pm + X$  with 30 GeV beam momentum as for the NA61/SHINE experiment. Thick lines show the yields of charged pions, while thin dashed curves indicate the yields of charged kaon states.

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