EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

August 16, 2024

Memorandum requesting use of the allocated test beam for data-taking on π^{+}+ C and π^{-}+ C interactions at 158 GeV/c

The NA61/SHINE Collaboration
https://shine.web.cern.ch/

In October 2024 NA61/SHINE has two weeks of the hadron beam time allocated for tests and calibration. This memorandum requests permission to use seven days in this period for measurements of π^{+}+ C and π^{-}+ C interactions at 158 GeV/c instead of testing the liquid hydrogen target.

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1 Introduction

Two weeks of the hadron beam are allocated to NA61/SHINE to calibrate the Projectile Spectator Detector (PSD) and test the new liquid hydrogen target in October 2024 (weeks 42 and 43). Recently, it turned out that the construction of the new hydrogen target has been delayed, making it impossible to conduct the test this year. Therefore, we request permission to use the allocated beam time to measure charged pion interactions with carbon at 158 GeV/*c*. The new data will help understand the recent unexpected NA61/SHINE observation - the large violation of isospin (flavour) symmetry in the kaonic sector of multi-particle production.

The document is organized as follows. Section 2 presents the physics motivation. Planned measurements are described in Sec. 3. The physics performance is discussed in Sec. 4.

2 Physics motivation

2.1 Strong interactions

In 2023, NA61/SHINE reported results on the unexpectedly large violation of isospin (flavour) symmetry in the kaonic sector of multi-particle production [1]. For colliding "charge-symmetric"[1] nuclei with an equal number of protons and neutrons, isospin symmetry implies equal probabilities for the production of hadrons from the same isospin multiplet and with opposite I_z: $(\pi^+ \leftrightarrow \pi^-)$, $(p \leftrightarrow n)$, $(K^+ \leftrightarrow K^0)$, $(\overline{K}^0 \leftrightarrow K^-)$, etc. This implies

$$\langle K_S^0 \rangle = \frac{\langle K^0 \rangle + \langle \overline{K}^0 \rangle}{2} = \frac{\langle K^+ \rangle + \langle K^- \rangle}{2} \quad . \tag{1}$$

The rapidity distributions of charged and neutral kaons produced central Ar+Sc collisions at 75*A* GeV/*c* beam momentum ($\sqrt{s_{NN}} = 11.9$ GeV) are compared in Fig. 1 (*top*). An excess of charged $(K^+ + K^-)/2$ over neutral kaon (K_S^0) production, reaching $(18.4 \pm 6.1)\%$ at mid-rapidity is seen. Data from other experiments in the collision energy range $5 < \sqrt{s_{NN}} < 200$ GeV support this result despite their larger uncertainties. This is apparent in Fig. 1 (*bottom*); see Ref. [1] for more details. The observed charged-over-neutral kaon excess cannot be explained by known effects quantified by the UrQMD and Hadron Resonance Gas (HRG) models, also shown in Fig. 1 (*bottom*). Thus, the result obtained by NA61/SHINE appears as an unexpectedly large effect of violation of isospin symmetry.[2]

Potentially related results are presented in Fig. 2 for π^-+ C reactions at 158 GeV/*c* beam momentum. The measured excess of charged over neutral kaon production reaches about 20%. As the figure shows, none of the microscopic models can reproduce this result. Also, it cannot be explained by arguments based on simple quark-counting [4]. While, in principle, the observed effect is as large and unexpected as shown before for Ar+Sc collisions, its interpretation remains less evident. The pionic projectile π^- has a non-zero third component

[1] For historical reasons, the inversion of the third component of the isospin I_z is called the "charge transformation". Charge-symmetric particles or nuclei have $I_z \equiv 0$ and are invariant under the charge transformation.

[2] The Ar+Sc system is not exactly charge-symmetric. The moderate excess of neutrons in both nuclei is predicted to decrease charged kaon compared to neutral kaon production, contrary to what is seen in the data [2].

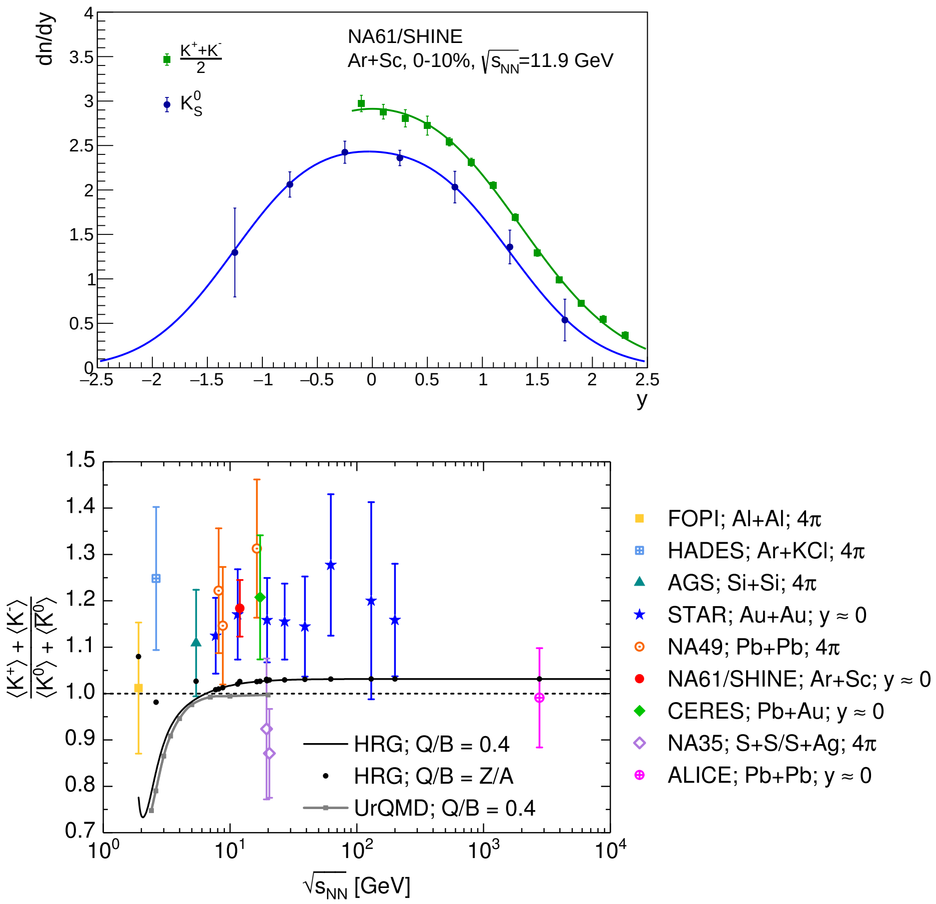

Figure 1: *Top:* Comparison of rapidity spectrum of neutral (K^0_S) with the average spectrum of charged (K^+ and K^-) mesons in Ar+Sc collisions. *Bottom:* The charged-to-neutral kaon ratio is shown as a function of collision energy. The black line shows the HRG predictions for $Q/B = 0.4$. The blue dots indicate the HRG predictions for Q/B values corresponding to the ones in the experiments. For different nuclei, Q/B corresponds to the electric charge over the baryon number of the whole system. The grey squares show UrQMD predictions. The plots are taken from Refs. [1–3].

of isospin ($I_z = -1$) and does not form a charge-symmetric ensemble. This precludes the formulation of any claim of the observed excess as an explicit violation of isospin symmetry. Therefore, we propose new measurements of kaon production in π^++ C and π^-+ C collisions under the same experimental conditions at the same beam momentum of 158 GeV/c. This will allow us to obtain kaon yields for a fully charge-symmetric ensemble of charged pion–carbon reactions defined as:

$$\pi^{\pm} + \mathrm{C} \;=\; \frac{(\pi^+ + \mathrm{C}) \;+\; (\pi^- + \mathrm{C})}{2} \;. \tag{2}$$

Then, exact charge symmetry implies an exact validity of Eq. (1). Consequently, the results on π^++ C and π^-+ C interactions will allow us to test whether the violation of charge symmetry observed in heavy-ion collisions is specific to heavy-ion reactions or is a general property of strong interactions.

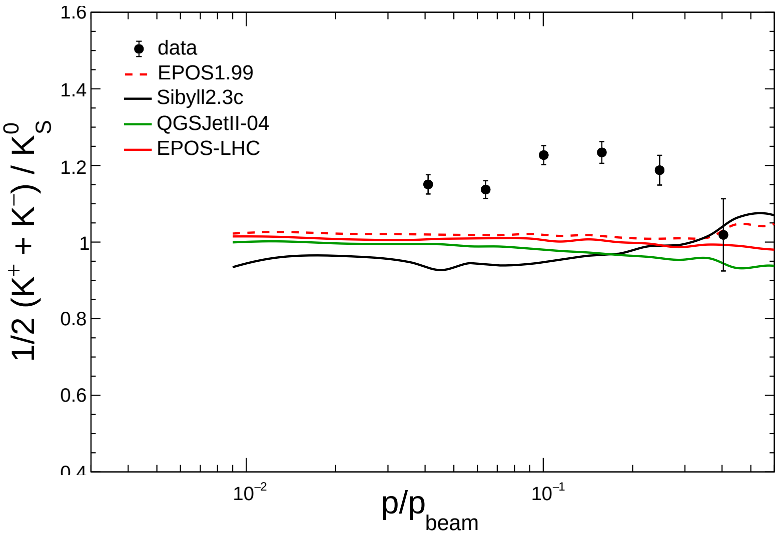

Figure 2: Yield ratio of charged to neutral K mesons in $\pi^- + \mathrm{C}$ reactions at 158 GeV/c, drawn as a function of scaled lab momentum p/p_{beam}. Statistical uncertainties are drawn, while systematic uncertainties are typically 5–10%. From Ref. [5].

The request is the fastest and most efficient way to achieve the above physics goals. Pion-nucleus reactions remain unique here, given that obtaining a charge-symmetric ensemble of collisions is not available for proton-proton collisions due to difficulties in measuring neutron-induced reactions. The new results obtained in this program are expected to be complementary to studies of collisions of light charge-symmetric nuclei planned by NA61/SHINE [6] and to puzzling findings on neutral to charged kaon yield fluctuations [7] recently reported by the ALICE experiment.

2.2 Cosmic-ray physics

The proposed data taking will also result in new precision data for the understanding of cosmic-ray-induced air showers. In particular, the expected ten-fold increase in statistics with respect to the data taken in 2009, the measurement of both pion projectile charges and the better coverage of the forward region with the Forward Time Projection Chamber (FTPC) will lead to a significant improvement of the spectra presented in Refs. [5,8]. Moreover, due to the large expected event statistics, it may be possible to study the production of π^0 and η mesons from the invariant mass distribution of two electron-positron pairs originating from converted photons in the carbon target. Based on the analysis of the data taken in 2009, we expect about 1.5×10^4 π^0 decays for which both photons converted in the target. A possible enhancement of the conversion rate using a dedicated lead converter placed between the target and vertex detector is under study.

3 Planned measurements

3.1 Experimental setup

A schematic layout of the NA61/SHINE detector is shown in Fig. 3. The main tracking devices are four large-volume Time Projection Chambers (TPC) and the Vertex Detector (VD). Two of TPCs, called Vertex TPCs (VTPC-1, VTPC-2), are located downstream of the target inside superconducting magnets. The MTPC detectors are placed symmetrically to the beamline downstream of the magnets. A GAP TPC and a set of three FTPCs improve the acceptance for 382 high-momentum forward-going tracks. In addition, one wall of pixel Time-of-Flight (ToF-L) is installed downstream from MTPC-L.

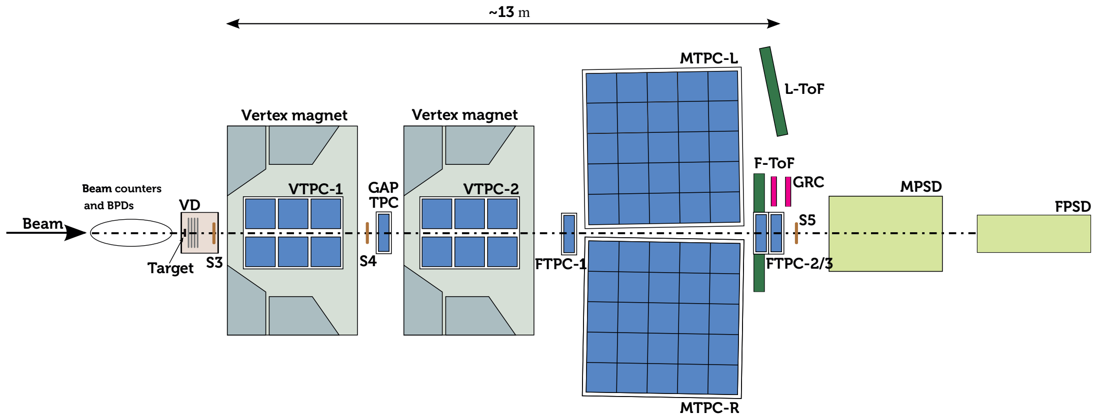

Figure 3: Schematic view of the NA61/SHINE experimental setup, which will be used for the proposed measurements (a detailed description of the detector can be found in Ref. [9]).

3.2 Beam request

Based on the presented physics case, we request:

(i) π^+ **beam**:

- Duration: 3 days
- Beam Momenta: 158 GeV/c

(ii) π^- **beam**:

- Duration: 3 days
- Beam Momenta: 158 GeV/c

The mean number of recorded $\pi^{\pm}$+ C collisions after off-line quality cuts (mostly off-time beam rejection) and reduction due to contamination of off-target interactions will be about 15 M events/day. During 6 days of data taking, approximately 45 M π^{+}+ C and 45 M π^{-}+ C events will be recorded.

Since part of the π^{-}+ C data was collected in 2009, although with a small sample size, we propose to start measurements with the π^{+} beam and then continue with the π^{-} beam. This will maximize the chance of having measurements for both reactions, even in the case of unforeseen problems with the beams or detector.

To efficiently utilize the allocated beam time (weeks 42 and 43), we propose the beam time schedule as depicted in Fig. 4. In the initial period, the calibration of the PSD detector will begin, and the whole detector will be prepared for the $\pi^{\pm}$+ C measurements. Next, we propose a 7-day period for the $\pi^{\pm}$+ C measurements, with three days for π^{+} and three days for π^{-}, with one day allocated for beam changing. After this period, the PSD detector calibration will continue, and the detector will be prepared for measurements using the lead beam.

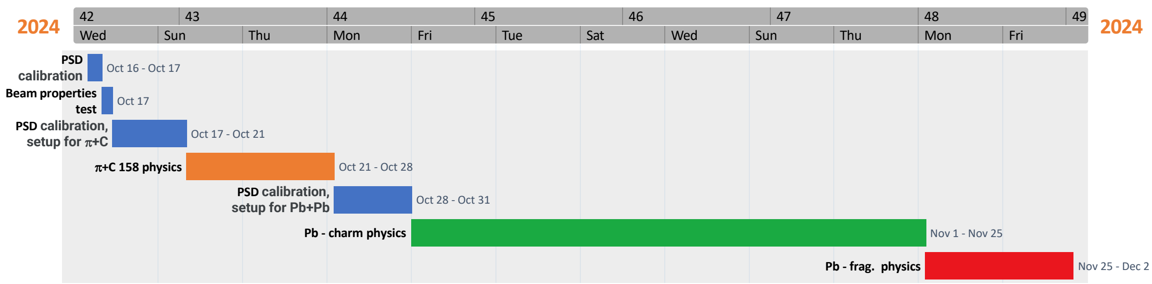

Figure 4: Proposed measurement schedule for PSD calibration and $\pi^{\pm}$+ C reactions in the weeks 42 and 43 of the 2024 beam period.

4 Physics performance

New high-statistics data on π^{+} and π^{-} interactions with carbon at 158 GeV/c will provide unique results on kaon yields in the charge-symmetric ensemble of pion-carbon reactions. To our knowledge, this possibility has never been exploited in high-energy collisions. The data will answer whether the observed charge-symmetry violation in heavy-ion collisions is unique to nucleus-nucleus collisions or is a general property of strong interactions. They will open a new field of dedicated studies of isospin symmetry-breaking in multi-particle production processes.

Importantly, the upgraded NA61/SHINE detector, with a 20 times faster readout, will collect high-statistics data quickly and reduce systematic uncertainties to a level required to reach the physics goal. Based on the NA61/SHINE results on π^-+ C interactions at 158 GeV/c [5], we conclude that systematic uncertainties will fully dominate the total uncertainties. The latter will be smaller than 4% and 2% for kaon momenta around 10 GeV/c, where the bulk kaon yield is located. Thus, the uncertainty of the charged-to-neutral kaon ratio, R_K, will be smaller than 5%. This will allow us to distinguish between the two possibilities:

(A) the charge-symmetry is obeyed in $\pi^\pm$+ C interactions: $R_K(\pi^-+\text{C})\approx 1.2$ and $R_K(\pi^++\text{C}) \approx 0.8$,

(B) the charge-symmetry is violated in $\pi^\pm$+ C interactions: $R_K(\pi^-+\text{C}) \approx 1.2$ and $R_K(\pi^++\text{C}) \approx 1.2$,

which differ by about 40% in the prediction for $R_K(\pi^++\text{C})$.

The systematic uncertainties will be reduced in comparison with the measurement of π^-+ C interactions in 2009 [5], because of the new time-of-flight detectors important for the identification of charged kaons and the new vertex detector important for the identification of neutral kaons.

References

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