NA48/2 Results and NA62 Perspectives

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Abstract. Recent results on rare and radiative $K^{\pm}$ decays from the NA48/2 experiment are reported. Among many rare decay modes, the analysis of $K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$ (K_{e4}) decays allows a quasi model-independent approach to the study of low energy $\pi\pi$ scattering. With more than 1 million K_{e4} decays the form factors and their energy dependence are measured with an improved precision. In the channel $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ more than 1 million decays were reconstructed, leading to the first measurement of the interference between direct photon emission and inner bremsstrahlung contributions as well as new limits on CP violation. For $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$, a precise measurement of the branching fraction was performed, based on more than 1000 events. In addition the perspectives of NA62 to measure the branching ratio of the very rare kaon decay $K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$ at the CERN SPS are described.

Keywords: Kaon decays, $\pi\pi$ scattering, K_{e4} form factors, $K_{2\pi(\gamma)}$ branching ratio, CP violation, $K_{\pi\gamma\gamma}$ branching ratio, rare decays.
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INTRODUCTION

Radiative kaon decays offer a unique possibility to study Chiral Perturbation Theory (ChPT) in detail. In particular, direct photon emission as in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decays or in decays vanishing at first order as $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ are of theoretical interest. In the past years, $K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$ (K_{e4}) were traditionally the cleanest laboratory to study $\pi\pi$ scattering close to threshold and extract the values of the S-wave scattering lengths, precisely predicted by ChPT.

In the years 2003 and 2004 the NA48/2 experiment has collected data from charged kaon decays. Two simultaneous K^{+} and K^{-} beams were produced by 400 GeV/c primary protons delivered by the CERN SPS. The NA48/2 beamline was designed to select kaons with a momentum range of (60 ± 3) GeV/c. The data were recorded with both a highly efficient 3-track-trigger for decays of charged kaons into three charged particles, and a 1-track-trigger, which required a minimum invariant mass of the neutral decay particles to exclude the abundant $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ and $K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$ decays. In total, several billions of reconstructed decays were recorded.

The main components of the NA48/2 detector were a magnetic spectrometer, composed by four drift chambers and a dipole magnet deflecting the charged particles in the horizontal plane, providing a resolution on the momentum measurement of 1.4% for 20 GeV/c charged tracks, and a liquid- krypton electromagnetic calorimeter (LKr) with an energy resolution of about 1% for 20 GeV photons and electrons. The NA48 detector is described in detail elsewhere [1].

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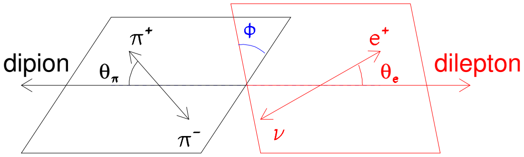

FIGURE 1. Topology of the charged K_{e4} decay showing the angle definitions in the dipion (dilepton) rest frame and between the two rest frames.

K_{e4} DECAY ANALYSIS

The $K^\pm \to \pi^+\pi^- e^\pm \nu$ (K_{e4}) kinematics are fully described using the 5 Cabibbo-Maksymowicz variables [2]: the dilepton invariant mass $S_e(M_{e\nu}^2)$, the dipion invariant mass $S_\pi(M_{\pi\pi}^2)$ and the three angles θ_π, θ_e and ϕ, as defined in Fig.1. The two axial (F,G) and one vectorial (H) form factors contributing to the transition amplitude can be written in terms of a partial wave expansion [3]:

$$F = F_s e^{i\delta_s} + F_p e^{i\delta_p} + \cdots, \quad G = G_p e^{i\delta_p} + \cdots, \quad H = H_p e^{i\delta_p}$$

Limiting the expansion to S- and P-waves, the form factors can be further expanded in powers of $q^2 = (M_{\pi\pi}^2/4m_\pi^2) - 1$:

$$F_s = f_s + f_s' q^2 + f_s'' q^4, \quad F_p = f_p, \quad G_p = g_p + g_p' q^2, \quad H_p = h_p,$$

and only the phase shift $\delta(q^2) = \delta_s - \delta_p$ can be measured.

K_{e4} decays candidates were selected by requiring events with three good reconstructed tracks in the spectrometer. The main background came from $K_{3\pi}$ decays where one pion was misidentified as an electron or decays into electron and neutrino. The background was measured from data by selecting "wrong" sign events $K^\pm \to \pi^\pm\pi^\pm e^\mp \nu$. The total background was at the level of 0.5 %.

To extract the form factors and the phase shift, the selected events are distributed in 15000 iso-populated boxes in the 5-dimensional space of the Cabibbo-Maksymowicz variables. In each of the 10 bins along $M_{\pi\pi}$, a four-parameter fit is performed to extract the form factors and phase shift values allowing to analyze their energy dependence in a quasi model-independent way. All form factors are measured relative to f_s determined from the branching ratio value, not reported here. The numerical results are:

$$\begin{aligned}
f_s'/f_s &= 0.152 \pm 0.007_{\text{stat}} \pm 0.005_{\text{syst}} \\
f_s''/f_s &= -0.073 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}} \\
f_p/f_s &= -0.048 \pm 0.003_{\text{stat}} \pm 0.004_{\text{syst}} \\
g_p/f_s &= 0.868 \pm 0.010_{\text{stat}} \pm 0.010_{\text{syst}} \\
g_p'/f_s &= 0.089 \pm 0.017_{\text{stat}} \pm 0.013_{\text{syst}} \\
h_p/f_s &= -0.398 \pm 0.015_{\text{stat}} \pm 0.008_{\text{syst}}
\end{aligned}$$

Using Roy equation [4], and their numerical solutions [5], it is possible to relate the phase shift δ to the S-wave scattering lengths in the isospin $I = 0$ and $I = 2$ states, a_0 and

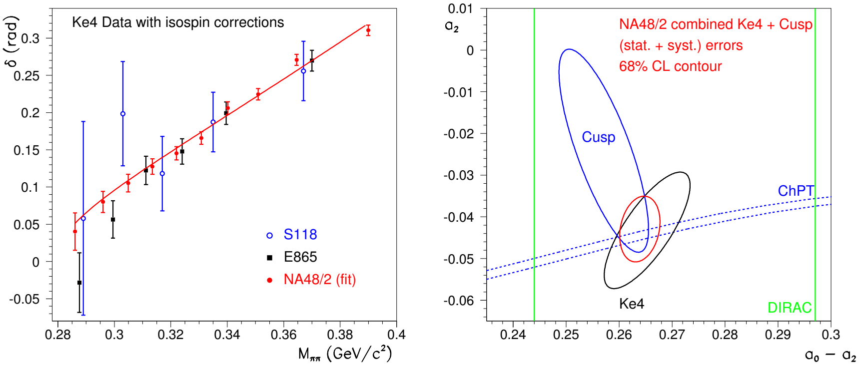

FIGURE 2. Left: Phase shift δ measurements with isospin mass effects included for all available K_{e4}results. The line corresponds to the 2-parameter fit of the NA48/2 data alone. Right: NA48/2 K_{e4} (black) and cusp (blue) results in the $(a_0 - a_2, a_2)$ plane.

a_2. Isopsin symmetry breaking corrections [8], neglected so far in previous K_{e4} analyses [6, 7], are applied to the now precisely measured phase values and result in a coherent shift of 10 to 15 mrad. The energy dependence of the phase shift is shown in Fig.2 (left). The best fit values for the scattering lengths (in units of $1/m_{\pi^+}$) are:

$$\begin{aligned} a_0 &= 0.2220 \pm 0.0128_{\text{stat}} \pm 0.0050_{\text{syst}} \pm 0.0037_{\text{theo}} \\ a_2 &= -0.0432 \pm 0.0086_{\text{stat}} \pm 0.0034_{\text{syst}} \pm 0.0028_{\text{theo}} \end{aligned}$$

with a 97% correlation coefficient. Using the relation among a_0 and a_2, predicted by ChPT [9], the value from the 1-parameter fit is:

$$a_0 = 0.2206 \pm 0.0049_{\text{stat}} \pm 0.0018_{\text{syst}} \pm 0.0064_{\text{theo}}$$

This result can be combined with the NA48/2 measurement of pion scattering lengths from the $\pi^0\pi^0$ invariant mass distribution in the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay [10]. The two analyses have different systematics and theoretical inputs, and also different correlations in the (a_0, a_2) plane. The combined result for the scattering lengths is:

$$a_0 = 0.2210 \pm 0.0047_{\text{stat}} \pm 0.0040_{\text{syst}},\ a_2 = -0.0429 \pm 0.0044_{\text{stat}} \pm 0.0028_{\text{syst}}$$
$$a_0 - a_2 = 0.2639 \pm 0.0020_{\text{stat}} \pm 0.0015_{\text{syst}}$$

In Fig.2 (right) the two results and their combination in the $(a_0 - a_2, a_2)$ plane are shown.

$K_{2\pi\gamma}$ DECAY ANALYSIS

The total amplitude of the $K^\pm \to \pi^\pm\pi^0\gamma$ decay is the sum of two terms: inner bremsstrahlung (IB), with the photon being emitted from the outgoing charged pion, and direct emission (DE), where the photon is emitted from the weak vertex. The IB

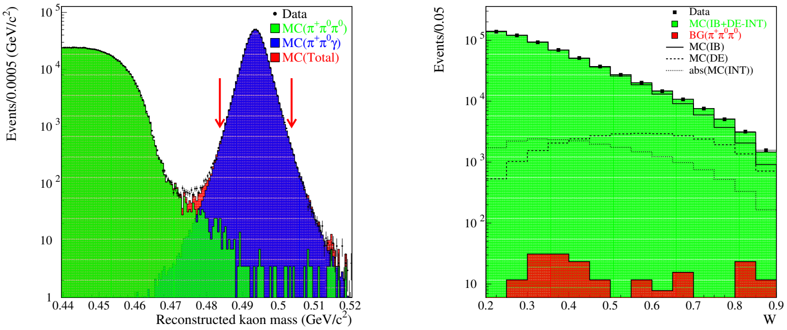

FIGURE 3. Left: Reconstructed mass of the Kaon with selection cut marked. Right: Contribution of the different component of the decay rate, their sum and the data distribution.

component can be predicted from QED corrections to $K^\pm \to \pi^\pm\pi^0$ in a straight-forward way [11, 12]. For the DE term, several studies within the framework of Chiral Perturbation Theory (ChPT) exist [13, 14, 15, 16, 17]. At $O(p^4)$ ChPT, direct photon emission can occur through both electric (X_E) and magnetic (X_M) dipole transitions. The magnetic part is the sum of a reducible amplitude, that can be calculated using the Wess-Zumino-Witten (WZW) functional [18, 19], and a direct amplitude, which size is expected to be small. For the electric transition no definite prediction exists.

The properties of the $K^\pm \to \pi^\pm\pi^0\gamma$ decays can be described in terms of the variables T^*_π and W, with T^*_π the kinetic energy of the charged pion in the kaon rest frame and W a Lorentz invariant given by $W^2 = (p_\pi \cdot p_\gamma)(p_K \cdot p_\gamma)/(m_K^2 m_\pi^2)$. The differential decay rate is given by:

$$\frac{\partial\Gamma^\pm}{\partial W} = \frac{\partial\Gamma^\pm_{\rm IB}}{\partial W}\left[1+2\cos\left(\pm\phi+\delta_1^1-\delta_0^2\right)m_\pi^2 m_K^2|X_E|W^2+m_\pi^4 m_K^4\left(|X_E|^2+|X_M|^2\right)W^4\right]$$

In addition to the IB and DE contributions, the decay rate contains also the interference (INT) between IB and DE, which, apart of the strong $\pi\pi$ re-scattering phases δ_1^1 and δ_0^2, depends only on $|X_E|$ and a possible CP violating phase ϕ. By measuring the INT term it is possible to disentangle the electric and magnetic amplitudes and to investigate possible CP violation in the $K_{2\pi\gamma}$ decay. Previous measurements have been performed by several experiments. The combined DE branching fraction, based on the world total of about 30000 $K^\pm \to \pi^\pm\pi^0\gamma$ events, is $\mathrm{Br(DE)} = (4.3 \pm 0.7) \times 10^{-6}$ [20], with the assumption of no interference term, consistent with the only previous measurement of $\mathrm{Frac(INT)} \equiv \mathrm{Br(INT)}/\mathrm{Br(IB)} = (-0.4 \pm 1.6)\%$ by the E787 experiment [21]. All previous measurements were performed in the restricted kinematic region $55 < T^*_\pi < 90$ MeV.

NA48/2 is the first experiment which can use both K^+ and K^- events. In addition, a strong suppression of $K^\pm \to \pi^\pm\pi^0\pi^0$ events, based on the excellent performance of the LKr calorimeter, was implemented. This allowed to extend the kinematic region to $0 < T^*_\pi < 80$ MeV, with a slightly stronger upper cut due to the online trigger

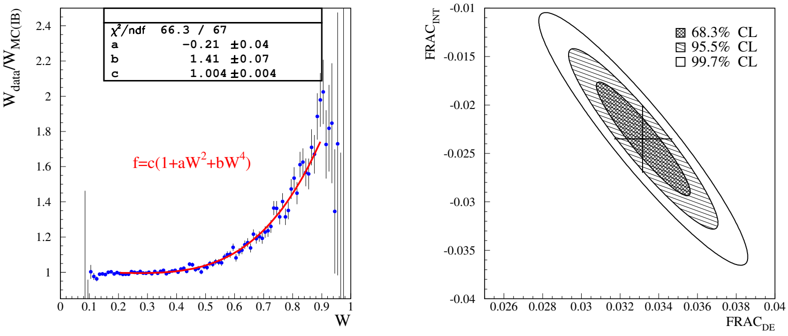

FIGURE 4. Left: Polynominal fit to the ratio of data over IB Monte Carlo. Right: Contour plot for the DE and INT terms. The black cross shows the σ statistical uncertainties of the projections.

rejection of $K^{\pm} \to \pi^{\pm}\pi^{0}$ events. The remaining background, coming mainly from $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$, was estimated with Monte Carlo simulated events to be less than 1% of the DE contribution. The probability of misidentifying the odd photon was estimated to be less than 10^{-3}.

In total, about 1 million of $K_{2\pi\gamma}$ events were reconstructed by NA48/2 (Fig. 3 (left)). The extraction of the IB, DE, and INT contributions was done with an extended maximum-likelihood fit of the Monte Carlo W distributions of the single components to the data distribution. For the fit, the gamma energy was required to be above 5 GeV to be insensitive of inefficiencies of the L1 trigger for small cluster energies. In addition, the kinematic range was restricted to $0.2 < W < 0.9$, leaving about 600 000 events for the fit. The final result given by the performed fit, including also systematic uncertainties, is

$$\mathrm{Frac(DE)}_{0<\mathrm{T}^*_\pi<80\ \mathrm{MeV}} = (3.32 \pm 0.15_{\mathrm{stat}} \pm 0.14_{\mathrm{syst}}) \times 10^{-2}$$
$$\mathrm{Frac(INT)}_{0<\mathrm{T}^*_\pi<80\ \mathrm{MeV}} = (-2.35 \pm 0.35_{\mathrm{stat}} \pm 0.39_{\mathrm{syst}}) \times 10^{-2}$$

with a correlation coefficient of -0.93 between both values. As a cross-check, a simple polynomial fit to the data W distribution, divided by the Monte Carlo IB distribution was performed (Fig. 4 (left)). Although this method does not fully correctly take into account the acceptances, the result was in perfect agreement with the maximum-likelihood method. Fig.4 (right) shows the confidence regions for the statistical uncertainties. From this, the electric and magnetic amplitudes X_E and X_M can be extracted to

$$X_E = (-24 \pm 4_{\mathrm{stat}} \pm 4_{\mathrm{syst}})\ \mathrm{GeV}^{-4}$$
$$X_M = (254 \pm 6_{\mathrm{stat}} \pm 6_{\mathrm{syst}})\ \mathrm{GeV}^{-4}$$

with the magnetic amplitude very close to the WZW prediction of about 270 GeV^{-4} [16, 22, 23]. For comparison with previous experiments, a fit with the INT term set to 0 was performed. The result, extrapolated to the kinematic range $55 < T^*_\pi < 90$ MeV, was

$$\mathrm{Br(DE)}^{\mathrm{INT=0}}_{55<\mathrm{T}^*_\pi<90\ \mathrm{MeV}} = (2.32 \pm 0.05_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}}) \times 10^{-6},$$

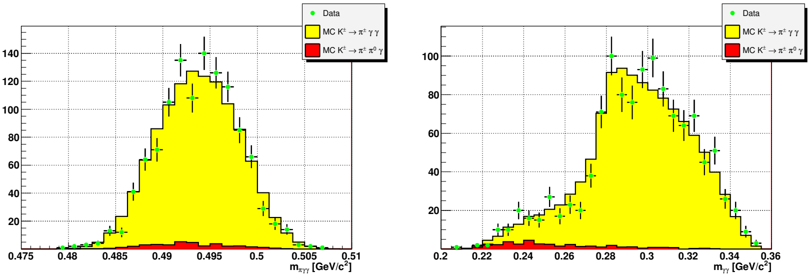

FIGURE 5. Selected $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ candidates. Left: Invariant $\pi^{\pm}\gamma\gamma$ mass. Right: Invariant $\gamma\gamma$ mass.

in clear disagreement with the previous measurements. The χ^2 of this fit was 51.0/12 (compared to 14.3/11 when including the INT term as a free parameter), strongly indicating the need of the INT term for a proper description of the data.

Possible direct CP violation in the decay rate asymmetry of K^+ and K^- into this channel was also investigated. This CP violation would be due to a nonvanishing phase ϕ in the decay rate. A decay rate asymmetry can be expressed in an asymmetry of the total number of events, defined as $A_N = (N_+ - RN_-)/(N_+ + RN_-)$, with N_+ and N_- the numbers of K^+ and K^- decays, and R the ratio of K^+ to K^- in the beam, determined from $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$ decays[1]. Using the complete data set of more than a million decays, NA48/2 found $A_N = (0.0 \pm 1.0_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-3}$, corresponding to $|A_N| < 1.5 \times 10^{-3}$ at a confidence level of 90%. Extraction of the CP violating phase ϕ yielded $\sin\phi = -0.01 \pm 0.43$, equivalent to $|\sin\phi| < 0.56$ at 90% CL. Assuming the interference to be the origin of possible CP violation, a fit to the ratio of the W spectra of K^+ and K^-, given by the function $\frac{d\Gamma^{\pm}}{dW} = \frac{d\Gamma^{\pm}_{\text{IB}}}{dW}(1 + (a \pm e)W^2 + bW^4)$ was also performed. With the parameters a and b from the DE and INT fractions, a single parameter fit obtained $A_W = (-0.6 \pm 1.0) \times 10^{-3}$, in good agreement with the previous value of A_N .

$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ DECAY ANALYSIS

The $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay is of high interest in ChPT, since tree-level contributions at $O(p^2)$ vanish, thus giving high sensitivity to $O(p^4)$ and $O(p^6)$. The differential decay rate of $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ is given by

$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_{K^{\pm}}}{(8\pi)^3} \cdot \left[z^2 \cdot \left(|A+B|^2 + |C|^2\right) + \left(y^2 - \frac{1}{4}\lambda\left(1, z, r_\pi^2\right)\right)^2 \cdot \left(|B|^2 + |D|^2\right) \right]$$

with $y = (E^*_{\gamma 1} - E^*_{\gamma 2})/m_K$ and $z = m^2_{\gamma\gamma}/m^2_K$ [24]. The leading contribution at $O(p^4)$ is given by loop diagrams leading to a cusp in the invariant $\gamma\gamma$ mass at $2m_{\pi^{\pm}}$. The amplitude

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[1] This assumes negligible CP violation in $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$, which is consistent with the NA48/2 limit on CP violation in the $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$ Dalitz plot

A is known up to a parameter $\hat{c}$, which needs to be measured from experiment. Also at $O(p^4)$, pole and tadpole diagrams contribute to the C amplitude. At $O(p^6)$, unitarity corrections could increase the branching fraction by 30 - 40% [25]. A sample of about 40% of the complete data set of NA48/2 has been analyzed. Due to the similarity in topology to the $K^\pm \to \pi^\pm\pi^0$ decays, which were suppressed by the trigger, the signal trigger efficiency for this channel was only about 40%. In total, 1164 $K^\pm \to \pi^\pm\gamma\gamma$ candidates were reconstructed, which corresponds to 40 times the current world statistics for this channel. The background contribution, mainly from $K^\pm \to \pi^\pm\pi^0\gamma$ events, was determined from Monte Carlo simulation to 3.3%. The invariant $\pi^\pm\gamma\gamma$ and $\gamma\gamma$ mass distributions are shown in Fig. 5, the latter exhibiting the expected cusp at twice the pion mass. Obtaining the detector acceptance from a simulation using $O(p^6)$ ChPT with $\hat{c} = 2$, a preliminary, model-dependent branching fraction was obtained:

$$\mathrm{Br}(\mathrm{K}^\pm \to \pi^\pm\gamma\gamma)_{\hat{\mathrm{c}}=2,\mathrm{O(p^6)}} = (1.07 \pm 0.04_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}}) \times 10^{-6}$$

The systematic uncertainty is dominated by the trigger efficiency. A model-independent measurement and the extraction of the parameter $\hat{c}$ are in preparation.

NA62 PERSPECTIVES

The NA62 experiment at the CERN SPS aims at measuring $O(100)$ $K^\pm \to \pi^\pm\nu\bar{\nu}$ events in two years of data-taking. The theoretical cleanness of the Standard Model (SM) branching ratio prediction for this decay mode makes it very attractive both as a powerful test of the CKM paradigm and as a probe for new physics beyond the SM. Experimentally, the detection of this process is very difficult due to the smallness of the signal (in the SM the expected BR is at level of $\sim 8.5 \times 10^{-11}$) and the presence of a very sizable concurrent background, mainly from $K^\pm \to \pi^\pm\pi^0$ decays. The present measurement of this decay channel is based on 7 candidates collected by E949+E787 Brookhaven experiments [26] leading to a value of $\mathrm{BR} = (1.47 \pm 1.30) \times 10^{-10}$.

NA62 is a fixed target experiment in which a charged hadrons beam, containing $\sim 6\%$ of kaons, will be produced from 400 GeV/c protons from the SPS accelerator. The kaon decays in flight will be studied in a fiducial region $\sim$ 100 meters long, placed in vacuum in order to reduce secondary interactions. The decays products and the primary particles momentum will be measured with high resolution by straw chambers and a beam spectrometers, in order to achieve good signal reconstruction and kinematic rejection. An efficient veto system for photons and charged particles and a particale ID system for primary particles and decay products, will guarantee the identification of decay modes not kinematically constrained. In Fig.6 a schematic view of the experiment is shown. In order to collect the required number of events in a reasonable amount of time, a very intense hadron beam will be employed (3×10^{12} proton per SPS pulse will produce $\sim 5 \times 10^{12}$ K^+ per year). An efficient online selection of candidates represents a very important item for this experiment, because of the large reduction to be applied on data before tape recording. On the other hand a loss less data acquisition system is mandatory to avoid adding artificial detector inefficiencies, e.g. when vetoing background particles.

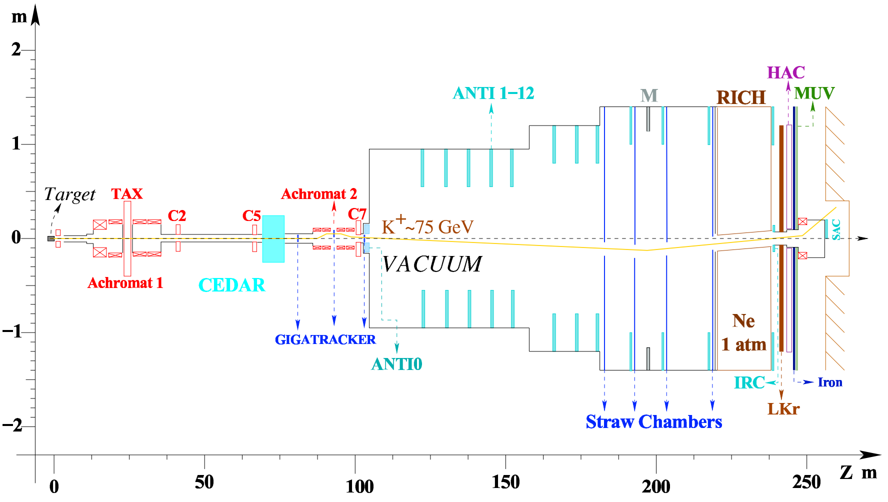

FIGURE 6. Layout of the NA62 experiment.

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