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Results and perspectives from the NA62 experiment at CERN

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Summary. — The NA62 experiment at the CERN SPS collected a large sample of charged kaon decays with a highly efficient trigger for decays into electrons in 2007. The kaon beam represents a source of tagged neutral pion decays in vacuum. A preliminary result of a new measurement of the electromagnetic transition form factor slope of the neutral pion in the time-like momentum region from 1.05 million fully reconstructed π^0 Dalitz decays is presented in the first part of this report. In the second part, prospects and current status of a new measurement of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ at the NA62 experiment are summarised. The experiment took data in physics runs in 2014 and 2015 reaching the designed beam intensity.

1. – Measurement of π^0 electromagnetic transition form factor slope

1`1. *Introduction*. – The NA62 experiment at the CERN SPS collected a large sample of charged kaon ($K^\pm$) decays in flight in 2007, corresponding to about 2×10^{10} $K^\pm$ decays in the fiducial decay volume. The main goal of the experiment was to test lepton flavour universality by measuring the ratio $R_K = \Gamma(K^\pm \to e^\pm \nu)/\Gamma(K^\pm \to \mu^\pm \nu)$ [1, 2]. The experiment with its high intensity kaon beam can be also viewed as a π^0 factory. Neutral pions are produced in four of the six main $K^\pm$ decay modes. The $K^\pm \to \pi^\pm \pi^0$ ($K_{2\pi}$) decay channel was studied in the presented analysis as the main π^0 source.

The neutral pion is the lightest meson and plays a very important role in the study of low-energy properties of the strong nuclear force. The branching ratio of the dominant decay into two photons is $\mathcal{B}(\pi^0 \to 2\gamma) = (98.823 \pm 0.034)\%$; the second most important decay channel is the *Dalitz decay* (π_D^0) [3]: ($\pi^0 \to e^+ e^- \gamma$) with $\mathcal{B}(\pi_D^0) = (1.174 \pm 0.035)\%$ [4]. Kinematic variables x and y, commonly used to describe Dalitz decay kinematics, are defined in terms of particle four-momenta:

$$(1) \qquad x = \left(\frac{M_{e^+ e^-}}{m_{\pi^0}} \right)^2 = \frac{(p_{e^+} + p_{e^-})^2}{m_{\pi^0}^2}, \qquad y = \frac{2 \, p_{\pi^0} \cdot (p_{e^+} - p_{e^-})}{m_{\pi^0}^2 (1 - x)}.$$

The limits on the variables are given by

$$(2) \qquad r^2 \leq x \leq 1, \quad -\beta \leq y \leq \beta, \quad \text{where} \quad r = \frac{2m_e}{m_{\pi^0}} \quad \text{and} \quad \beta = \sqrt{1 - \frac{r^2}{x}}.$$

The normalised π_D^0 differential decay width reads

$$(3) \qquad \frac{1}{\Gamma(\pi_{2\gamma}^0)} \frac{\mathrm{d}^2 \Gamma(\pi_D^0)}{\mathrm{d}x \mathrm{d}y} = \frac{\alpha}{4\pi} \frac{(1-x)^3}{x} \left(1 + y^2 + \frac{r^2}{x} \right) |\mathcal{F}(x)|^2 (1 + \delta(x, y)) \,,$$

where $\mathcal{F}$(x) stands for the π^0 electromagnetic transition form factor (TFF), and $\delta(x, y)$ represents radiative corrections to the π_D^0 decay. The form factor $\mathcal{F}(x)$ is expected to

vary slowly in the allowed kinematic region and is parametrised by a linear expression

$$\mathcal{F}(x) = 1 + ax, \tag{4}$$

where a is the so-called TFF *slope* parameter. The decay width in eq. (3) integrated over y reads

$$\frac{1}{\Gamma(\pi^0_{2\gamma})} \frac{d\Gamma(\pi^0_D)}{dx} = \frac{2\alpha}{3\pi} \frac{(1-x)^3}{x} \left(1 + \frac{r^2}{2x}\right) \sqrt{1 - \frac{r^2}{x}} \ (1 + \delta(x)) \ (1 + a\,x)^2 \,. \tag{5}$$

The first theoretical investigation of the π^0 TFF came from Gell-Mann and Zachariasen in 1961 [5]. They estimated that $\mathcal{F}(x)$ is dominated by two resonances, ρ and ω mesons, resulting in a positive TFF slope value: $a \approx m^2_{\pi^0}(m^{-2}_\rho + m^{-2}_\omega))/2 \approx 0.03$. This approach to the TFF modelling is called *vector meson dominance* (VMD). The π^0 TFF enters predictions for other important observable quantities, like the rate of the rare $\pi^0 \to e^+ e^-$ decay, and the anomalous magnetic moment of the muon $a_\mu = (g - 2)_\mu$ in the space-like momentum transfer region. This has naturally attracted attention of many theorists and motivated studies of the form factor. The expectations for the TFF slope value are generally in agreement with the VMD model, for example the extended VMD model [6] ($a = 0.0309 \pm 0.0010$), the two-flavour chiral perturbation theory framework [7] ($a = 0.029 \pm 0.005$), the two hadron saturation model [8] ($a = 0.0292 \pm 0.0004$), the slope extraction from space-like data using Padé approximants [9] ($a = 0.0324 \pm 0.0020$), and a dispersive analysis of the TFF [10] ($a = 0.0307 \pm 0.0006$).

Radiative corrections to the π^0 Dalitz total decay rate were first studied by Joseph [11]. The corrections to the differential decay rate which are essential for the π^0 TFF measurement were first studied by Lautrup and Smith [12] using the soft-photon approximation. This analysis was later extended by Mikaelian and Smith in [13]. The issue has been recently revisited by Husek and others in [14]. In the presented analysis the radiative corrections are implemented at the level of the π^0_D MC event generator, including the generation of a radiative photon from the internal bremsstrahlung contribution to the radiative corrections.

1˙2. *NA62 experiment in 2007*. – The beam line and setup of the NA48/2 experiment were used for the NA62 data taking in 2007, with different beam parameters. Unseparated secondary charged hadronic beams with central momentum of $74 \, \text{GeV}/c$ and momentum spread of $\pm 1.4 \, \text{GeV}/c$ were derived from the primary $400 \, \text{GeV}/c$ protons extracted from the SPS and impinging on a beryllium target. The beam composition was dominated by pions with a kaon fraction of about 6%. The beam kaons decayed in a fiducial decay volume contained in a $114 \, \text{m}$ long cylindrical vacuum tank. The momenta of charged decay products were measured in a magnetic spectrometer, housed in a tank filled with helium placed after the decay volume. The spectrometer comprised four drift chambers (DCHs) and a dipole magnet. A plastic scintillator hodoscope (HOD) producing fast trigger signals and providing precise time measurements of charged particles was placed after the spectrometer. Further downstream was a liquid krypton electromagnetic calorimeter (LKr), an almost homogeneous ionization chamber with an active volume of $7 \, \text{m}^3$ of liquid krypton, $27 \, X_0$ deep, segmented transversally into 13248 projective $\sim 2 \times 2 \, \text{cm}^2$ cells and with no longitudinal segmentation. An iron/scintillator hadronic calorimeter and muon detectors were located further downstream. The beam intensity was reduced in comparison with NA48/2 by a factor of ~ 10 to enable the

operation of a minimum-bias trigger configuration with high efficiency, and to minimise the accidental background. A detailed description of the detector can be found in [15].

1'3. *Event selection and data sample*. – The event selection for the $K_{2\pi}$ decays followed by the prompt $\pi^0 \to e^+e^-\gamma$ (denoted as $K_{2\pi D}$ below) comprises the following conditions:

– Exactly one three-track vertex is required to be reconstructed in the fiducial decay region. No extra tracks are allowed to be present in the event. Track impact points in the DCH must be in the fiducial acceptance of the DCHs. The track impact points in the first drift chamber must be separated by at least $2\,$cm. Reconstructed track momenta are required to be in the range from 2 to $74\,$GeV/c.

– A single LKr energy deposition cluster is considered as a photon candidate. The cluster has to be well isolated from the track impact points in the LKr and compatible in time with the tracks.

– The total reconstructed momentum of the three tracks and the photon candidate has to be in the range from 70 to $78\,$GeV/c. The squared total reconstructed transverse momentum with respect to the nominal beam axis has to be below 5×10^{-4} (GeV/c)^2.

– The $K_{2\pi D}$ events are then identified in the following way. The track with the opposite charge with respect to the kaon ($K^\pm$) is considered to be an electron ($e^\mp$). There are two possible track identity hypotheses for the two remaining tracks with the same charge as the kaon ($\pi^\pm, e^\pm$). For each hypothesis the reconstructed invariant masses $M_{ee\gamma}$, $M_{2\pi}$ and the x, y variables (see eq. (1)) are computed. A hypothesis is considered as valid if $x, |y| < 1$, $M_{ee\gamma} \in (115, 145)\,$MeV/c^2 and $M_{2\pi} \in (465, 510)\,$MeV/c^2. Events with exactly one valid hypothesis are selected.

– The total energy deposit in the LKr of e^+, e^- and γ has to exceed $14\,$GeV. One of the e^+, e^- tracks is required to have momentum above $5.5\,$GeV/c and the LKr energy / momentum ratio $E/p > 0.8$. These cuts are needed in order to reproduce the online trigger conditions in MC simulated samples.

– Since the acceptance of events with $x \leq 0.01$ is not well reproduced in the simulation, the reconstructed x variable has to be above 0.01.

After all cuts, the selected sample amounts to 1.05×10^6 π_D^0 events. The acceptances, evaluated with MC simulations, are 1.81% for $K_{2\pi D}$ decays and 0.02% for $K^\pm \to \mu^\pm \pi_D^0 \nu$ ($K_{\mu 3D}$) decays. The spectra of the reconstructed $M_{ee\gamma}, M_{2\pi}$ invariant masses and the x variable are shown in fig. 1.

1'4. *Preliminary result of the π^0 TFF slope*. – The extraction of the π^0 TFF slope from the selected data sample is based on a comparison between the data distribution of the reconstructed x variable, and MC distributions corresponding to different TFF slope values used at the MC generator level. The fit result corresponds to the MC distribution with the best data/MC agreement. Both MC simulation samples ($K_{2\pi D}$ and $K_{\mu 3D}$) are included in the MC distribution, since they both contain genuine π^0 Dalitz decays. Selected events were divided into equipopulous bins and a χ^2 test was used for the data/MC histogram comparison. The fit result was then obtained by the χ^2 minimisation.
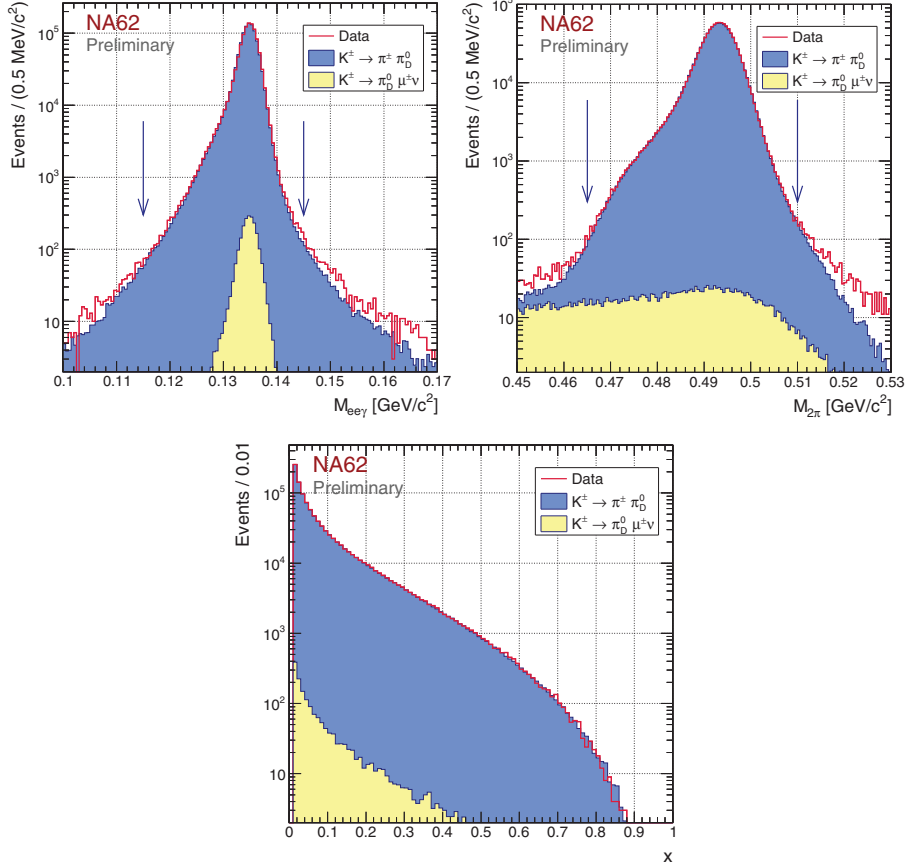
Fig. 1. – Top: invariant mass distributions of data and MC events. Bottom: distribution of the reconstructed x Dalitz variable.

The most important systematic uncertainties originate from an imprecise simulation of the beam momentum spectrum width, and from the result sensitivity to the spectrometer momentum scale calibration. The NA62 preliminary result for the π^0 TFF slope reads

(6) $$a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2} = (3.70 \pm 0.64) \times 10^{-2} \,,$$

with $\chi^2/n.d.f. = 52.5/49$, and a p-value of 0.34. The result improves the precision on the π^0 TFF in the time-like momentum region. An illustration of the result and a comparison with previous experiments [16-19] are shown in fig. 2.

2. – $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ measurement at the NA62 experiment

The rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ is both theoretically very clean and highly sensitive to short-distance physics. Therefore, it plays a key role among flavour changing neutral current processes both in the Standard Model (SM) [20] and its extensions [21]. The branching ratio of this process has been computed to a very high precision in the SM: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$ [20]. The dominant uncertainties originate from the CKM matrix parameters $|V_{ub}|$, $|V_{cb}|$ and γ.
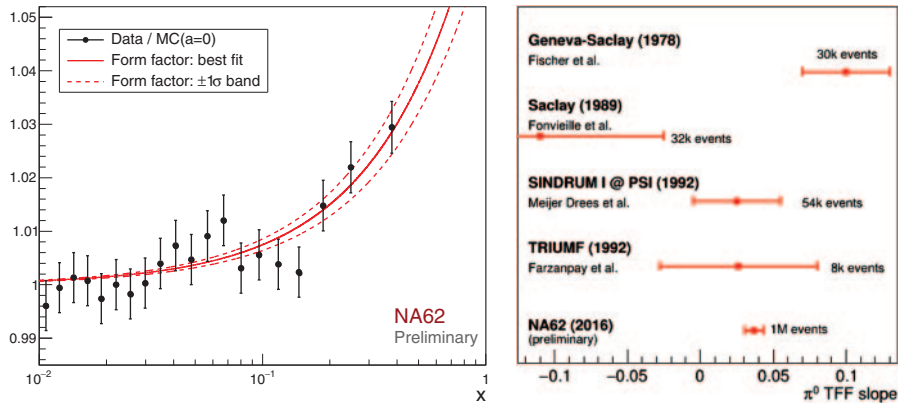
Fig. 2. – Left: fit result illustration showing the ratio of the reconstructed data and MC distributions, with the MC sample weighted to obtain $a = 0$. Data and MC events are divided into 20 equipopulous bins; the horizontal positions of markers correspond to the bin barycentres. Solid line represents the TFF function with the slope value equal to the fit central value. Dashed lines indicate the 1σ band. Right: comparison of the NA62 preliminary result with previous experiments measuring the π^0 TFF slope from the π_D^0 decay.

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay has been observed by the E787/E949 experiments at the Brookhaven National Laboratory. The measured branching ratio value is based on the observation of seven candidate events and reads $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [22]. High uncertainty of the experimental result motivates a new measurement of the branching ratio with an improved precision.

The NA62 experiment at CERN [23, 24] aims to measure the branching ratio of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay at the 10% precision level. The experiment is expected to collect about 50 signal events per year of data taking and to keep the total systematic uncertainty and backgrounds small. Assuming a 10% signal acceptance and the SM decay rate, the kaon flux should correspond to at least 10^{13} K^+ decays in the fiducial volume.

Unlike the experiments E787/E949 [22] which used separated K^+ beam with kaons stopped at a target, the NA62 experiment uses a high momentum ($\sim$75 GeV/c) unseparated kaon beam produced by 400 GeV/c momentum protons delivered from the Super Proton Synchrotron (SPS) accelerator impinging on a beryllium target. Consequently, a decay in flight technique is used to identify K^+ decay products.

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay contains two undetectable neutrinos in the final state, which means that the signal signature is one π^+ track in the final state matched to one K^+ track in the beam with no other particles detected. In the NA62 experiment, the most important background processes to $K^+ \to \pi^+ \nu\bar{\nu}$ events are the main K^+ decay modes (see table I). In order to achieve a signal/background ratio $\sim$ 10, a background rejection factor of the order of 10^{12} is required. Therefore, a precise measurement of the event kinematics, hermetic photon vetoes and particle identification are crucial for the success of the experiment.

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay kinematics can be fully described by the variable called missing mass squared, defined as $m^2_{miss} = (p_{K^+} - p_{\pi^+})^2$, where p_{K^+} and p_{π^+} are the four-momenta of the kaon and pion. The distribution of the m^2_{miss} variable allows a 92% separation of the signal and the main K^+ decay modes by defining two signal regions where a minimum background is expected. The signal regions are defined away from the

TABLE I. – *Main K^+ decay modes and suppression strategy in the NA62 experiment* [23].

Decay channel	Branching ratio (%)	Background rejection
$K^+ \to \mu^+ \nu_\mu$	63.560 ± 0.110	kinematics, μ ID
$K^+ \to \pi^+ \pi^0$	20.670 ± 0.080	kinematics, photon veto
$K^+ \to \pi^+ \pi^+ \pi^-$	5.583 ± 0.024	kinematics, charged particle veto
$K^+ \to \pi^0 e^+ \nu_e$	5.070 ± 0.040	E/p, photon veto
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3.352 ± 0.033	photon veto, μ ID
$K^+ \to \pi^+ \pi^0 \pi^0$	1.760 ± 0.023	kinematics, photon veto

$K^+ \to \pi^+ \pi^0$ peak and the $K^+ \to \pi^+ \pi^+ \pi^-$ threshold, see fig. 3.

The NA62 experiment uses high energy protons from the SPS ($400\,\mathrm{GeV/c}$) to produce a secondary hadron beam (6% kaons) of $75 \pm 0.8\,\mathrm{GeV/c}$ momentum and high intensity ($750\,\mathrm{MHz}$). The experimental set-up extends from the beryllium target to the beam dump over a distance of about $270\,\mathrm{m}$. A schematic view of the NA62 experiment layout is presented in fig. 4. The first $100\,\mathrm{m}$ are covered by beam elements and detectors measuring the incoming beam. The $65\,\mathrm{m}$ long decay region is contained in a vacuum (at $< 10^{-6}\,\mathrm{mbar}$) cylindrical tank. Properties of decay products coming from the decay region are measured in detectors placed over a $170\,\mathrm{m}$ long region ending shortly before the beam dump, see fig. 4.

The NA62 detector and beamline for the new measurement of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ have been commissioned and the experiment took data in 2014 and 2015 during its first physics runs. Analysis of the data recorded at different beam intensities, varying from one percent of the nominal intensity up to the nominal one, is ongoing.
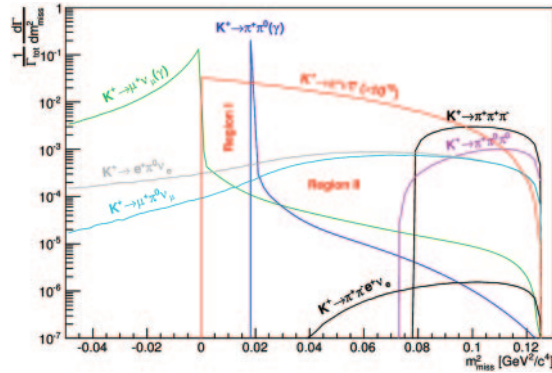

Fig. 3. – Distribution of m_{miss}^2 for signal and backgrounds from the main K^+ decay modes. Backgrounds are normalised according to their BR; the signal is multiplied by a factor of 10^{10}. Signal region I: between 0 and $\pi^+ \pi^0$ peak; Signal region II: between $\pi^+ \pi^0$ peak and $\pi^+ \pi^+ \pi^-$ threshold.
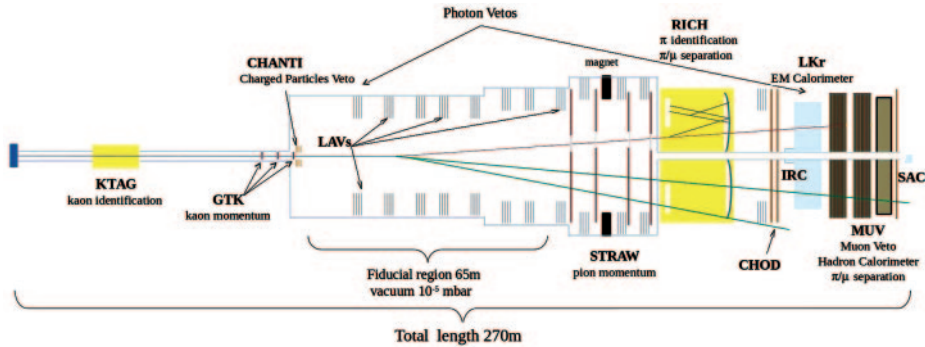
Fig. 4. – The NA62 detector layout.

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