Near Threshold K^+K^- Meson-Pair Production in Proton-Proton Collisions

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Abstract

The near threshold total cross section and angular distributions of K^+K^- pair production via the reaction $pp \longrightarrow ppK^+K^-$ have been studied at an excess energy of Q = 17 MeV using the COSY-11 facility at the cooler synchrotron COSY. The obtained cross section as well as an upper limit at an excess energy of Q = 3 MeV represent the first measurements on the K^+K^- production in the region of small excess energies where production via the channel $pp \longrightarrow pp\Phi \longrightarrow ppK^+K^-$ is energetically forbidden. The possible influence of a resonant production via intermediate scalar states $f_0(980)$ and $a_0(980)$ is discussed.

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1 Introduction

Recently, detailed measurements on the K^+ meson production in proton-proton collisions have been performed in the previously unexplored near threshold region of the reaction channels $pp \longrightarrow pK^+\Lambda$ and $pp \longrightarrow pK^+\Sigma^0$ [1–4]. On the other hand, there is a lack of data on the elementary K^- meson production in the proton-proton scattering, especially in the region of low excess energies. The reaction channel with the lowest threshold energy is given by the associated K^+K^- meson pair production via the reaction channel $pp \longrightarrow ppX$, X

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$= K^+K^-$. Therefore, measurements on the threshold production of negatively charged kaons (m($K^\pm$) = 493.677 MeV/c^2 [5]) have to be carried out in the mass range of m(X) $\sim$ 1 GeV/c^2. A study of this mass range is stimulated by the continuing discussion on the nature of the scalar resonances $f_0(980)$ and $a_0(980)$, which have been interpreted as conventional $q\bar{q}$ states [6], qq-$\bar{q}\bar{q}$ states [7] or as $K\bar{K}$ molecules [8, 9]. In the latter case the possibility of a $K\bar{K}$ molecule interpretation of the $f_0(980)$ particle crucially depends on the strength of the $K\bar{K}$ interaction, which can be probed in the near threshold production of kaon-antikaon pairs [10].

Exclusive K^- production data are also of special interest in the context of sub-threshold kaon production experiments in nucleus-nucleus interactions, which are expected to probe the antikaon properties at high baryon density. Recent inclusive sub-threshold measurements [11] resulted in comparable K^+ and K^- yields at the same energy per nucleon below the production thresholds for the elementary reactions $pp \rightarrow K^\pm X$. To explain this observation, different models [12] consider repulsive and attractive interactions of kaons and antikaons within the nuclear medium, respectively. In addition, the antikaon potential in dense nuclear matter is closely related to open questions in astrophysics [13,14]. However, for detailed calculations on the medium effects a precise knowledge of the elementary K^+ and K^- cross sections close to the production thresholds is needed.

We now present the first measurement of an absolute cross section on the close to threshold K^+K^- meson pair production via the reaction channel $pp \longrightarrow ppK^+K^-$ at an excess energy of Q = 17 MeV [15], i.e. below the Φ meson threshold. Angular distributions of final state particles and particle subsystems are included. In addition, one upper limit at an excess energy of Q = 3 MeV is reported (see also [16]).

The excitation function is generally expected to follow the four-body phase space volume modified by the proton-proton interaction. Final state interactions in the nucleon-kaon, nucleon-antikaon or kaon-antikaon subsystems as well as influences of the scalar resonances $f_0(980)$ and $a_0(980)$ on $K\bar{K}$ production might lead to deviations from this expectation.

2 Experiment

Measurements on the reaction $pp \rightarrow ppK^+K^-$ have been performed at the internal beam facility COSY-11 [17] at COSY-Jülich [18], using a hydrogen cluster target [19] in front of a C-shaped COSY-dipole magnet, acting as a magnetic spectrometer. Tracks of positively charged particles, detected in a set of two drift chambers (DC1 and DC2 in Fig. 1), are traced back through the magnetic field to the interaction point, leading to a momentum determination. The velocities of these particles are accessible by a time-of-flight path behind the drift chambers, consisting of two scintillation hodoscopes (start detectors S1 and S2) followed by a large scintillation wall (S3) at a distance of ~ 9.3 m, acting as a stop detector. The overall time-of-flight resolution for events with two identified protons has been determined to be $\sim$330 ps [20]. By measuring the momentum and the velocity, a particle identification of positively charged ejectiles via the reconstructed mass determination is possible and the four momentum vector can be completely determined.

The event selection for the reaction $pp \to ppK^+K^-$ was performed by accepting three-track events with two identified protons and one particle identified as a K^+ meson. With respect to the short lifetime and the opening angle of kaons in the laboratory system, an indirect time-of-flight measurement was used for the kaon identification. By calculating the start time of the event in the target via the precisely determined proton trajectories and velocities, the kaon hit in the start detectors is used as stop signal. The quality of this method is demonstrated in Fig. 2 with a clearly identified kaon peak.

The four-momentum determination of the positively charged ejectiles yields a full event reconstruction for the reaction type $pp \to ppK^+X$ and allows an identification of the undetected X-particle system using the missing mass method. The result of the measurements at an excess energy of Q = 17 MeV with respect to the K^+K^- threshold is shown in Fig. 3 (upper spectrum, thin line). As expected from Monte-Carlo simulations using the code GEANT-3 [21], including the phase-space event generator GENBOD, a sharp peak at the charged kaon mass with a missing mass resolution of FWHM ~ 2 MeV/c^2 is obvious, corresponding to an unambiguous detection of events from the ppK^+K^- reaction. The broad distribution in the region of lower missing masses can be explained by contributions from $pp \to pp\pi^+X$ events, misidentifying pions as K^+ mesons. Furthermore, the production of heavier hyperons, in particular $\Lambda(1405)$ and $\Sigma^0(1385)$, may contribute to this background. At the discussed beam energy these hyperons can be produced via the reactions $pp \to pK^+\Lambda(1405)/\Sigma^\circ(1385)$. Taking into account decay channels with one decay proton in the final state, these events can also show the requested signature of two protons and one K^+. However, due to the decay modes of these hyperons, here the system X of the reaction $pp \to ppK^+X$ consists of more than only one particle. Therefore, the missing mass distribution of the ppK^+ system originating from these reaction channels results in a broad distribution. In order to reproduce the observed broad missing mass distribution, both mentioned contributions have been considered. For this purpose, $pp \to pp\pi^+X$ events have been analyzed, assuming for the π^+ mesons the mass of charged kaons. Furthermore, using for simplicity only S-waves, phase space Monte-Carlo simulations on the hyperon production, applying the properties of the $\Sigma^0(1385)$ hyperon (mass m = 1383.7 MeV/c^2, width Γ = 36 MeV/c^2 [5]) and isotropic angular distributions have been carried out. The combination of both contributions can be seen in Fig. 3 (thick line). Obviously, these two effects, the misidentification of $pp\pi^+X$ events and the production of heavier hyperons,

are sufficient to reproduce the background distribution. It should be emphasized that the background contamination in the K^- peak area is in any case very small, leading finally to a total number of N = 61^{+0}_{-5} accumulated K^+K^- events.
For a further verification of the K^+K^- assignment, a silicon pad detector, mounted inside the COSY dipole magnet, has been used to determine the hit position of outgoing K^- mesons. Since the four-momentum vector of the K^- meson is accessible via the completely determined ppK^+ system, the hit position in the silicon pad detector can be predicted. Taking into account only events of the K^- peak of Fig. 3 (upper spectrum), the expected hit positions are compared with the measured ones, as seen in Fig. 4 (filled symbols). The upright dash-dotted lines indicate the region of the silicon pad detector, which can be hit by K^- mesons originating from the K^+K^- production at Q = 17 MeV excess energy. Based on Monte-Carlo simulations, the dashed lines specify the 3σ region for the deviation of the measured hit position from the calculated one ($\sim \pm$ 13.7 cm). Obviously, except for one event all events marked by filled symbols fulfill these requirements, giving additional and independent evidence for the exclusive K^- production. Contrary to this, events from the broad structure of Fig. 3 show no correlation between the measured and expected hit positions (open symbols). Due to geometrical acceptance only a few of these events have a hit in the pad detector at all.
Taking into account only ppK^+ events with an additional K^- candidate fulfilling the K^- hit correlation (Fig. 4), the primary missing mass distribution of ppK^+ events reduces to the lower spectrum of Fig. 3. This procedure leads, consistent with Monte-Carlo calculations to i) a drastic reduction of the broad structure and ii) to a 43% decrease of the counting rate for the K^- signal due to acceptance and decay losses. According to these results, the events represented by the K^- peaks can be identified as ppK^+K^- events with hardly any background contamination.

3 Results

In the following analysis we use the events of the K^- peak of the upper spectrum of Fig. 3.
In addition to the non-resonant production of K^+K^- events, we also consider the possibility, that the selected events originate from other reaction channels leading to the same final state particles. As discussed above, the production of heavy hyperons like the $\Lambda(1405)$ and the $\Sigma^\circ(1385)$ is of minor importance, since it appears only as a small background below a clear K^+K^- signal (see Fig. 3). Different to this it is more difficult to unravel the contribution of the scalar resonances $f_0(980)$ and/or $a_0(980)$ from which the higher energy part of these broad resonances might decay into K^+K^- pairs [5]. Due to the masses of the f_0- and a_0-resonances (m(f_0) = 980 MeV/c^2 $\pm$ 10 MeV/c^2 and m(a_0)

$= 984.8$ MeV/c^2 $\pm$ 1.4 MeV/c^2) and their large widths ($\Gamma(f_0)$ = 40 MeV/c^2 to 100 MeV/c^2 and $\Gamma(a_0)$ = 50 MeV/c^2 to 100 MeV/c^2) [5], kinematical distributions of both the resonant and the non-resonant channels are expected to be similar. The shape of the pp-missing mass distribution is sensitive to the assumed reaction channel and therefore offers the possibility to investigate contributions from resonant production. However, the available statistics of the extracted K^+K^- events at Q = 17 MeV is not sufficient to distinguish between four-body phase space and predictions on the resonant production. Since the structures of the $a_0(980)$ and $f_0(980)$ are rather similar with respect to their effect concerning the limited acceptance of COSY-11, we only consider the $f_0(980)$ in the further discussion.

The accessibility of the four-momentum vectors of all ejectiles from ppK^+K^- events allows to study angular distributions of the particles or particle systems. Monte-Carlo simulations on the free $pp \to ppK^+K^-$ reaction, considering also the pp FSI and the Coulomb interaction, have been performed to determine the acceptance of the detection system in order to obtain acceptance corrected kinematical distributions. The overall detection efficiencies for events from the non-resonant K^+K^- production, requiring the detection of both protons and the K^+ meson, were determined to be ϵ(3 MeV) $= 6.4 \cdot 10^{-2}\,{}^{+43\%}_{-28\%}$ and ϵ(17 MeV) $= 7.4 \cdot 10^{-3}\,{}^{+10\%}_{-13\%}$. These quantities take into account the kaon decay, detection and track reconstruction efficiencies as well as the influence of the error in the absolute excess energies, which are known with a precision of ΔQ = 1 MeV, caused by the uncertainty in the determination of the absolute COSY beam momentum ($\Delta p/p = 10^{-3}$). In Fig. 5 angular distributions in the center of mass system relative to the beam direction are shown for the extracted ppK^+K^- events for both outgoing protons (a), the K^+K^- system (b), the K^+ mesons (c) and the K^- mesons (d). Within the statistical errors the measured distributions of the protons and the kaons show no significant deviation from an isotropic emission.

The luminosity was determined by comparing the differential counting rates of elastically scattered protons with data obtained by the EDDA collaboration [22]. The integrated luminosities were extracted to be $\int L\,dt$ = 841 nb^{-1} $\pm$ 1% (stat.) $\pm$ 5% (syst.) at Q = 3 MeV and $\int L\,dt$ = 4.50 pb^{-1} $\pm$ 1% (stat.) $\pm$ 5% (syst.) at Q = 17 MeV, corresponding to a mean luminosity of $L = 2 \cdot 10^{30}$ cm^{-2} s^{-1}.

In Fig. 6 the present result at Q = 17 MeV (filled symbol) and a data point from the DISTO collaboration [23], neglecting the contribution from Φ, are plotted as function of the excess energy. These data represent the available world data for the K^+K^- production via the reaction channel $pp \to ppK^+K^-$ in the near threshold region (threshold: p_{beam} = 3.30175 GeV/c).

The total cross section at an excess energy of Q = 17 ± 1 MeV has been determined to be $\sigma = (1.80 \pm 0.27^{+0.28}_{-0.35})$ nb, including statistical and systematical errors, respectively [15]. The overall systematical error arises from uncertainties in the determination of the detection efficiency (8%), the luminosity

(5%), the COSY beam momentum ($^{+10}_{-6}$%) as well as different models for the proton-proton FSI [24–29] (2%). From each of the four angular distributions in Fig. 5 the total cross section was deduced and resulted in an additional error contribution of $^{+5\%}_{-16\%}$ where the influence of the few background counts in the K^- peak is included. The upper limit at Q = 3 MeV has been determined to be $\sigma < 0.16$ nb on the basis of a confidence level of 95% [15]. Additionally, Fig. 6 shows parametrizations on the K^+K^- cross sections assuming different production processes. The solid line, representing a fit to the data points on the basis of a four-body S-wave phase space expectations including the proton-proton final state interaction (FSI), describes the data points adequately within the error bars. Therefore, the total cross section data points are consistent with a description based on the free ppK^+K^- production with no distinct effects of higher partial waves or strong K^+K^- final state interactions. Although not suggested by our previously discussed results, one can calculate the cross section for the $pp \to ppf_0(980) \to ppK^+K^-$ channel, leading to a value of $\sigma(pp \to ppf_0 \to ppK^+K^-) = 1.84 \pm 0.29\,^{+0.25}_{-0.33}$ nb. Correspondingly, the dashed lines present three-body phase space calculations for the ppK^+K^- final state via the excitation of the broad f_0 resonance including the pp FSI and normalized to this $\sigma(pp \to ppf_0 \to ppK^+K^-)$. Here we assumed the $f_0(980)$ to be a Breit-Wigner distribution with a mass of m = 980 MeV/c^2. The effect of the large uncertainty about the width of the $f_0(980)$ resonance ($\Gamma = 40$ MeV/c^2 to 100 MeV/c^2 [5]) is indicated by the dashed area. Nevertheless, within the error bars also this description is consistent with the measured data. Consequently, the two data points are in agreement with both the assumption of a non-resonant as well as a resonant production via the f_0, always neglecting effects of higher partial waves.

4 Summary

At the COSY-11 facility the near threshold K^+K^- production in the reaction channel $pp \to ppK^+K^-$ has been studied at an excess energy of Q = 17 MeV. Approximately sixty K^+K^- events have been extracted, leading to a total cross section of $\sigma = 1.80$ nb. As a remarkable result we obtain, at same excess energies, a K^- cross section differing from the K^+ cross section by approximately two orders of magnitude.

The emission angle distributions of the ejectiles in the center of mass system show no significant deviation from expectations based on pure four body phase space simulations. The excitation function of available close to threshold data on this reaction channel can be described both by calculations based on the four-body phase space including effects of the pp FSI and the Coulomb interaction as well as by calculations based on three-body phase space considerations via the broad f_0 resonance including the pp FSI.

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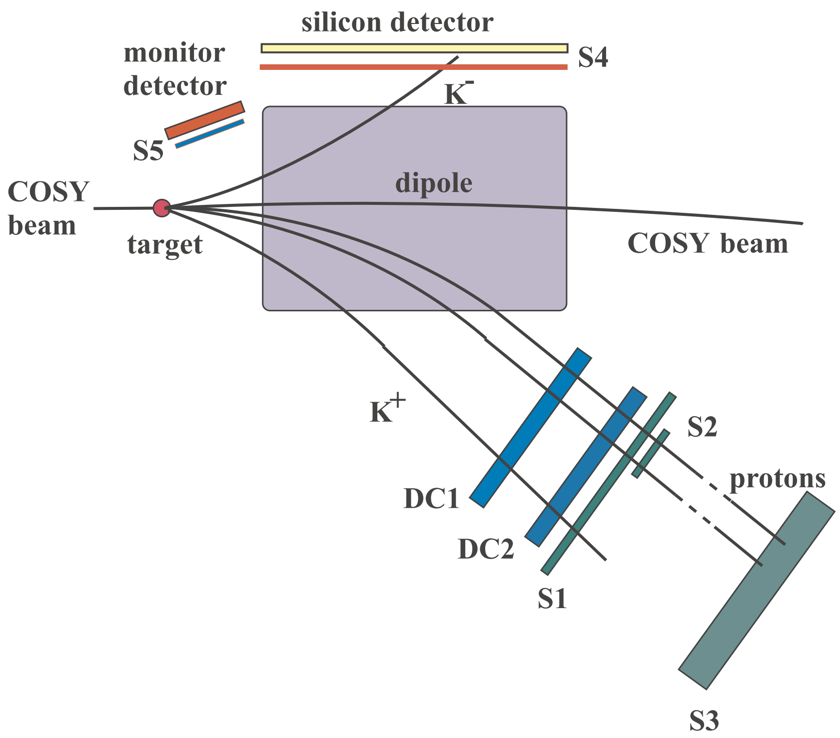

Figure 1: Sketch of the internal beam installation COSY-11 at COSY.

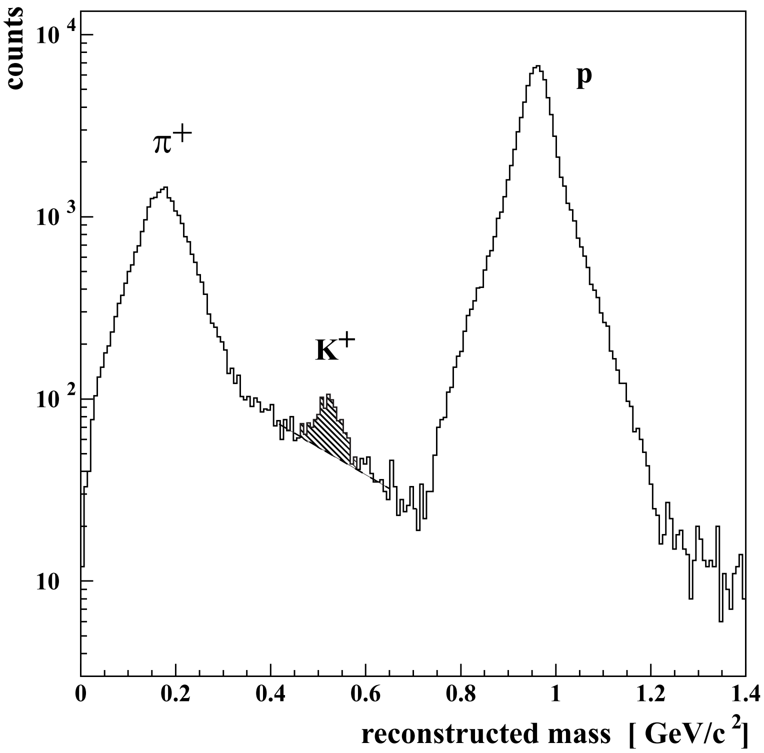

Figure 2: Particle identification via the determination of the reconstructed mass for events with three reconstructed tracks. Shown are the reconstructed masses of all three detected ejectiles.

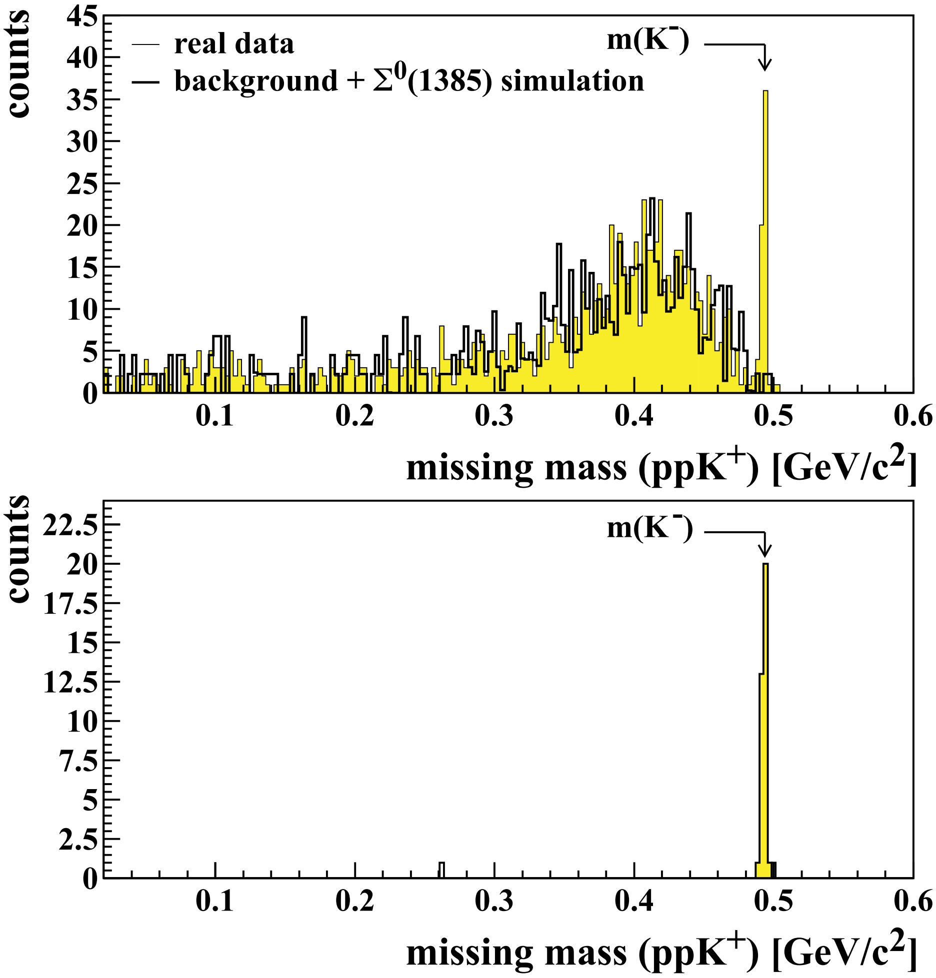

Figure 3: Missing mass distributions of the ppK^+ system at an excess energy of 17 MeV above threshold. The picture on the top presents events with two identified protons and one K^+ meson (thin solid line). The spectrum indicated by a thick solid line is a reproduction of the background distribution and is explained in the text. The lower spectrum represents events with an additional hit of the K^- mesons in the silicon pad detector, fulfilling the K^- hit correlation of Fig. 4.

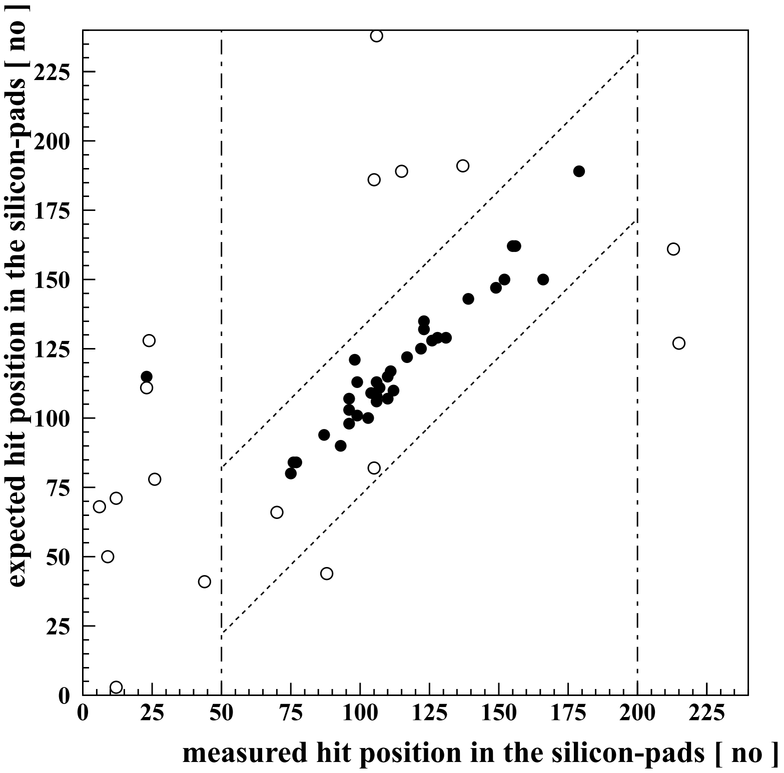

Figure 4: Comparison of detected hit positions of K^- mesons in the silicon pad detector with the calculated coordinates. Filled symbols correspond to events from the K^--peak whereas open symbols represent events from the continuous background of Fig. 3 (upper figure). The dashed and dash-dotted lines indicate cut conditions derived from Monte-Carlo simulations.

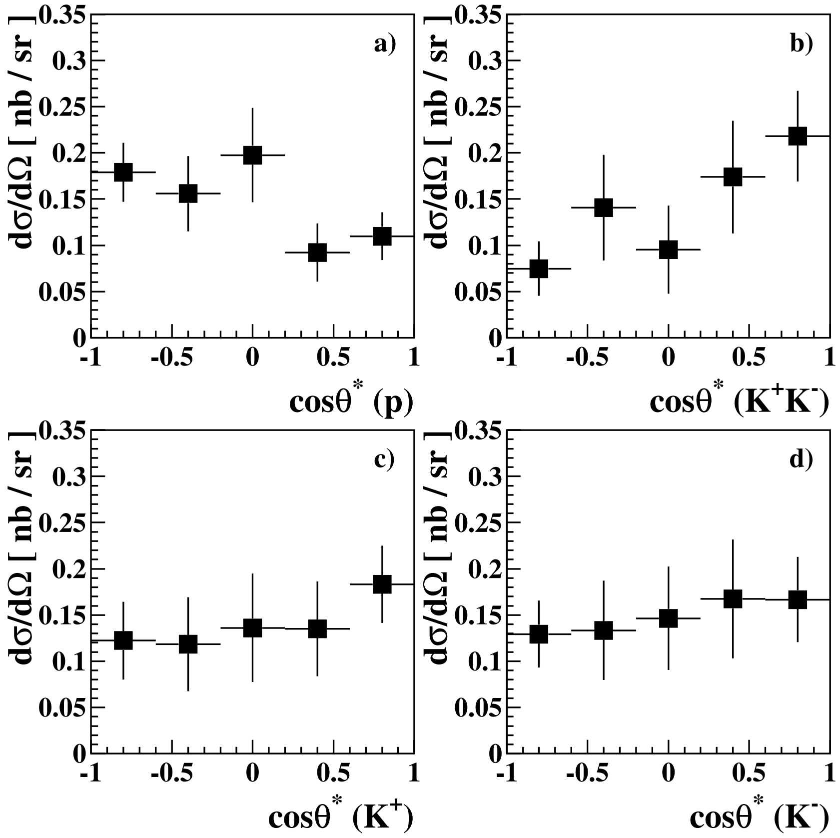

Figure 5: Angular distributions in the CMS relative to the beam direction of the extracted ppK^+K^- events for both outgoing protons (a), the K^+K^- system (b), the K^+ mesons (c) and the K^- mesons (d).

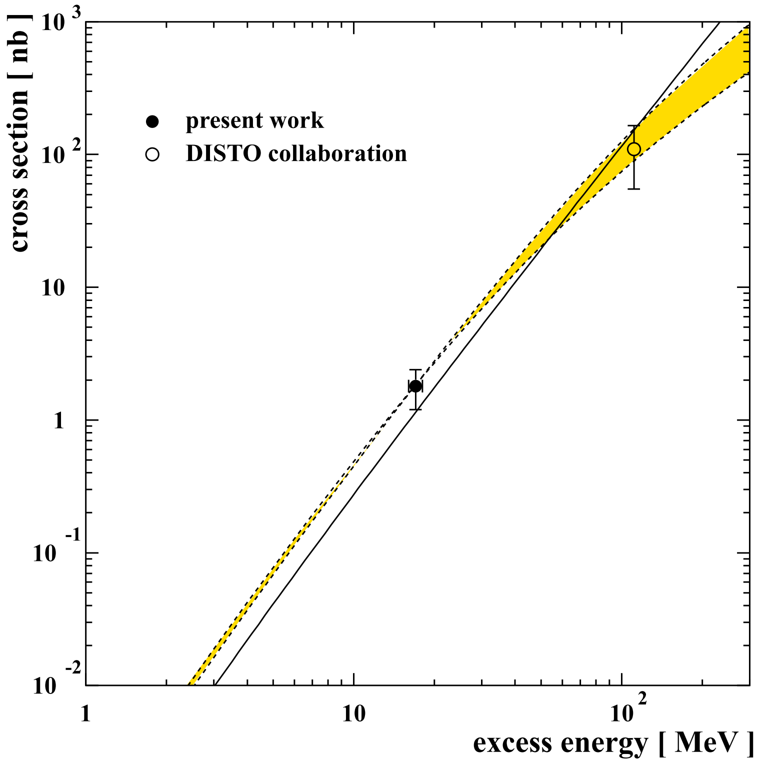

Figure 6: Total cross sections for the free K^+K^- pair production in proton-proton collisions. The lines are described in the text.