Eurasian Journal of Physics and Functional Materials

2022, 6(4), 275-284

Analysis procedures in deriving of the differential cross section of the reaction $pp \to \{pp\}_s\pi^0$ at energies 1.6–2.4 GeV

B.S. Baimurzinova[*,1,2,3], D.A. Tsirkov[2]

[1]Joint Institute for Nuclear Research, Dubna, Russia

[2]Institute of Nuclear Physics, Almaty, Kazakhstan

[3]L.N. Gumilyov Eurasian National University, Astana, Kazakhstan

E-mail: baimurzinova@jinr.ru

DOI: **10.32523/ejpfm.2022060403**
Received: 16.12.2022 - after revision

The reaction $pp \to \{pp\}_s\pi^0$, where $\{pp\}_s$ denotes a diproton, i.e. an unbound interacting proton pair in the $^1S_0$, state, was investigated in order to obtain a differential cross section $d\sigma/d\Omega$ at small angles in the energy range 1.6–2.4 GeV. This work is intended for the presentation of the main procedures in the processing of experimental data.

Keywords: strong interactions; diproton; inelastic pp interactions; reactions with the production of pions

Introduction

The study of short-range nucleon-nucleon interactions is a fundamental problem of nuclear physics. Useful information about the structure of nuclei at short distances can be obtained from hadron processes at large transferred momenta Q, however, the analysis of such processes is a rather difficult task for the theory due to the complex structure of the involved nucleus and the interactions of the initial and final states in the nuclear environment. Therefore, it is important to study elementary processes in systems with interacting nucleons. Such conditions make the theoretical interpretation of the NN interaction more transparent and understandable. A classic example of a such reaction is

$$p + p \to d + \pi^{+} \tag{1}$$

which has been widely studied, and rich statistics have been collected for it [1, 2]. Also, in [3], the possibility of obtaining new information using reactions of the form $N + d \to N + \{NN\}_s$ was shown for the first time. Later, this theoretical work served as the basis for a series of experiments at the COSY accelerator at the Research Center Jülich. The following reactions were studied [4-6]:

$$p + d \to \{pp\}_s + n, \tag{2}$$

$$p + p \to \{pp\}_s + \pi^0, \tag{3}$$

$$p + p \to \{pp\}_s + \gamma \tag{4}$$

where $\{pp\}_s$ is a proton pair in the $^1S_0$ state as opposed to the $^3S_1 - ^3D_1$ deuteron state. The dominance of the $^1S_0$ state is guaranteed by selecting protons with the low excitation energy of the pair $E_{pp} < 3$ MeV. Reactions (1) and (3) have very similar kinematics, but significantly differ dynamically. The diproton quantum numbers ($J_\pi = 0^+$, $I = 1$, $S = 0$, $L = 0$) differ from the corresponding deuteron quantum numbers ($J_\pi = 0^+$, $I = 0$, $S = 1$, $L = 0,2$). This fact indicates the usefulness of joint study of these reactions (1) and (3). In reaction (1), an intense peak is observed in the energy region corresponding to the sum of the masses $N\Delta(1232)$, $\sqrt{s} \approx 2.15$ GeV [7], which has been explained with a partial wave analysis by three dominant transitions: $^1D_2$, $^3F_3$ and $^3P_2$ [8]. When analyzing ANKE-COSY data, a similar peak in the reaction (3) was detected in approximately the same energy region. Using the results of [7, 8] and a partial wave analysis, it was explained by two interfering resonance transitions: $^3P_2$ and $^3P_0$ [9]. Moreover, in this analysis, the second $^3P_0$ resonance transition was observed for the first time. For reaction (1), in addition to the first peak, there is a second peak at energy $\sqrt{s} \approx 3$ GeV, the nature of which remains less clear. The previously published ANKE-COSY data [10] also indicate the possibility of the existence of a similar second peak in the reaction (3). The analysis of the differential cross section (3) performed in the proton beam energy range of 1.6–2.4 GeV will provide new data for further interpretation of the second peak. Physics results of this experiment are presented in [11].

Experimental setup and measurements

The measurements were carried out with an ANKE magnetic spectrometer [12] at the COSY-Jülich synchrotron (Figure 1). The main element of the ANKE magnetic system is a D2 spectrometric magnet. Positively charged secondary particles formed in the target leave the vacuum chamber D2 through an aluminum outlet window 0.5 mm thick and enter the forward detector, where there is a set of multi-wire chambers and a hodoscope consisting of two counter planes with vertically oriented scintillators. The scintillation hodoscope FD triggers the data acquistion

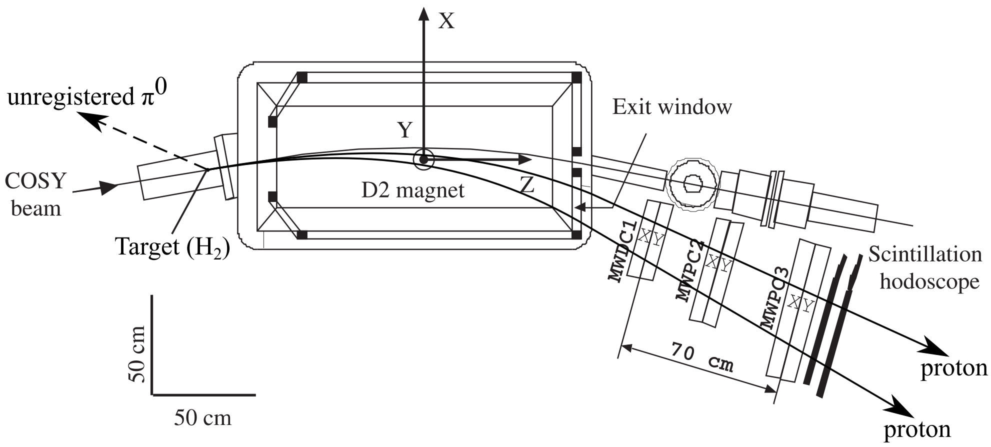

Figure 1. Forward detector of the ANKE spectrometer.

system and provides the measurement of energy losses. Data acquistion was provided by two types of triggers that were applied in parallel. The first (single-particle) trigger was initiated by any charged particle registered simultaneously by two planes of the hodoscope. The second (double-particle) trigger used a special electronic unit that suppressed most of the single-particle events, storing mainly events with two charged particles in the FD. The momentum resolution of the experimental setup was studied using Monte Carlo simulation based on the GEANT3 software package. Particle tracks were simulated taking into account multiple scattering on the setup materials. On their basis, the triggering of detector elements with the addition of random noise was generated based on the distributions obtained from experimental data. Then the obtained coordinates were analyzed using track reconstruction algorithms. The measurements were carried out at proton beam energies T_p = 1.6, 1.8, 2.0, 2.2, 2.4 GeV. The reaction $pp \to \{pp\}_s\pi^0$ events were selected from double-track events and their number was measured, the correction for effective acceptance was taken into account. Integral luminosity was used for normalization, which was estimated from the analysis of the elastic scattering reaction $pp \to pp$. This procedure made it possible to obtain a differential cross section of the reaction (3) at small angles of emission of the proton pair 0–23°.

Analysis

Identification of proton pairs

The main criterion in the identification of proton pairs is based on the time information obtained from the hodoscope. Flight times of the particles from the target to the detector ($\Delta\mathrm{TOF}_{\mathrm{meas}}$) can be measured. Using the measured momenta of the particles and making an assumption about their masses, it is possible to calculate the difference in the flight times $\Delta\mathrm{TOF}_{\mathrm{calc}}$. If the assumption made is correct, then $\Delta\mathrm{TOF}_{\mathrm{meas}}$ and $\Delta\mathrm{TOF}_{\mathrm{calc}}$ must match. This criterion can be applied to approximately 85% of all double-track events, where tracks hit different counters at least in one hodoscope wall. Figure 2 shows the particle identification spectra $\Delta\mathrm{TOF}_{\mathrm{meas}}$ vs. $\Delta\mathrm{TOF}_{\mathrm{calc}}$.

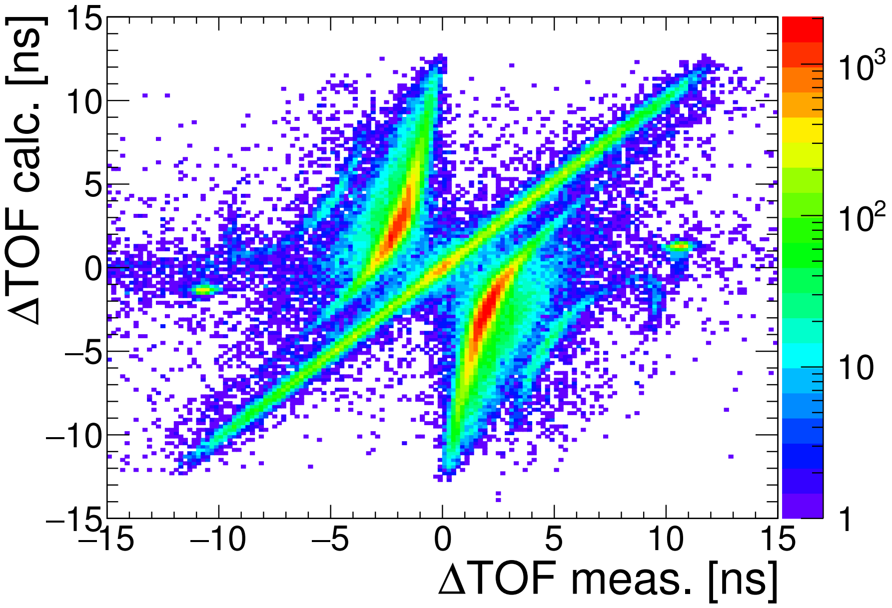

Figure 2. Identification of particles: measured vs. calculated time-of-flight differences at an energy $T_p = 1.6$ GeV.

After the events with two final protons were isolated, proton pairs with $E_{pp} < 3$ MeV in the final $^1S_0$ state were selected. Next, the kinematics for each event was reconstructed and the distributions of the square of the missing masses M_x^2 were constructed. Such a distribution in the $pp \to ppX$ process with proton pairs demonstrates a distinct peak near the pion mass at all beam energies (Figure 3). In order to estimate the number of one pion events, the peak was fitted by the sum of the Gaussians and the background from the multipion production. In addition to the statistical error, the systematic error was assessed by comparing the fit results with different background shapes. Events that are in the range of two sigma were selected for further analysis, and the kinematic fitting procedure was applied to them to improve the momentum-angular resolution.

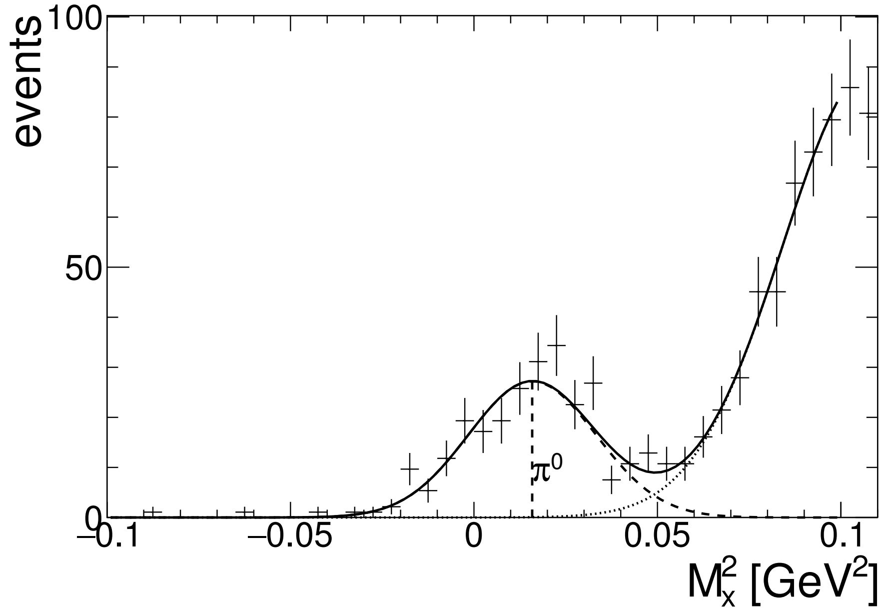

Figure 3. Distribution of the square of missing masses M_x^2 for the $pp \to \{pp\}_s\pi^0$ reaction at an energy $T_p = 1.6$ GeV.

Determination of luminosity

The luminosity was determined based on the analysis of the elastic pp scattering reaction. To determine the luminosity, first of all, the following steps had to be done: selection of single-track events, identification of registered particles and separation of reaction channels. Figure 4 shows the acceptance of the forward

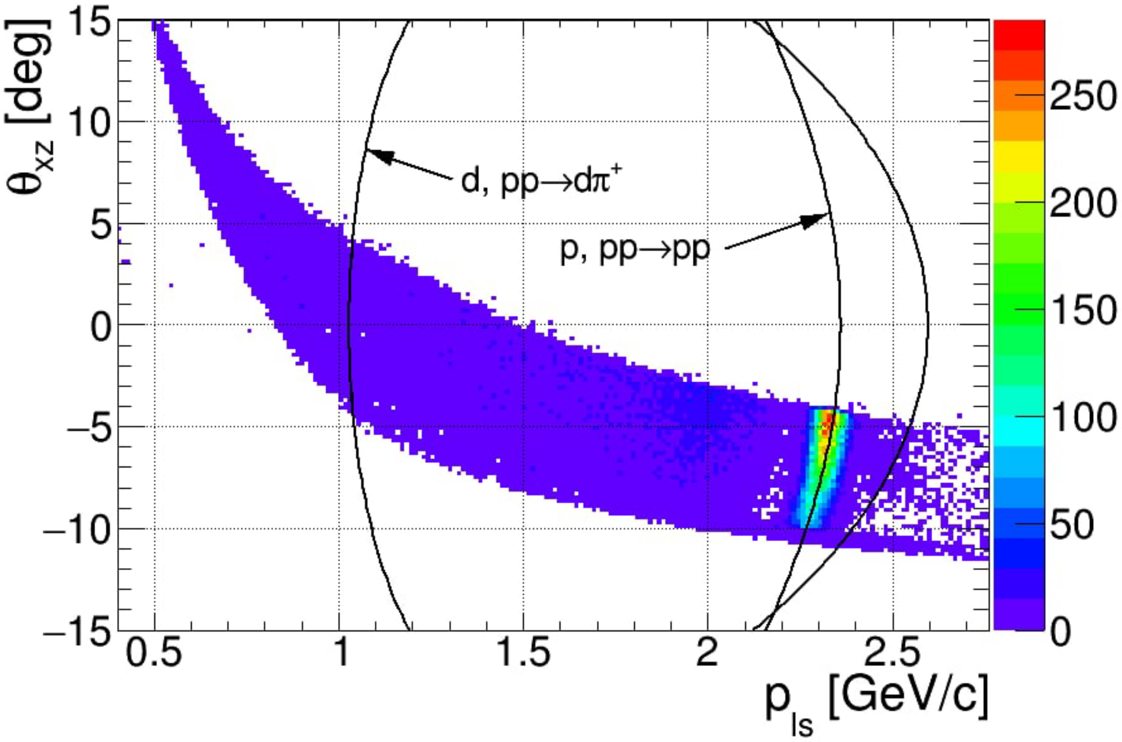

Figure 4. Momentum-angular acceptance of the forward detector ($T_p = 1.6$ GeV).

detector in terms of the momentum of the particle and the projection of the polar angle of its emission on the XZ plane. The lines show where the $pp \to pp$ and $pp \to d\pi^+$ reaction events should be located on the diagram. The analysis showed that the number of $pp \to d\pi^+$ reaction events is negligible compared to elastic scattering. This is quite understandable, because the reaction cross section $pp \to d\pi^+$ is very small compared to $pp \to pp$ in this energy range. The luminosity was estimated using the formula:

$$L = \frac{N}{A\Delta\sigma}, \tag{5}$$

where L is the luminosity, N is the number of registered events, A is the effective acceptance, $\Delta\sigma$ is the integral of the differential cross section in the corresponding angular interval. The angular range was divided into intervals where the number of events was estimated. For each interval, it is necessary to know the ratio of registed particles to all secondary particles to the number of registered ones, that is, the effective acceptance $A(\Delta\Omega)$. For the proton elastic scattering, the efficiency of particle detection by the detector is very high > 99%. Thus, it is possible to take the pure geometric acceptance of the setup instead of the effective acceptance $A(\Delta\Omega)$.

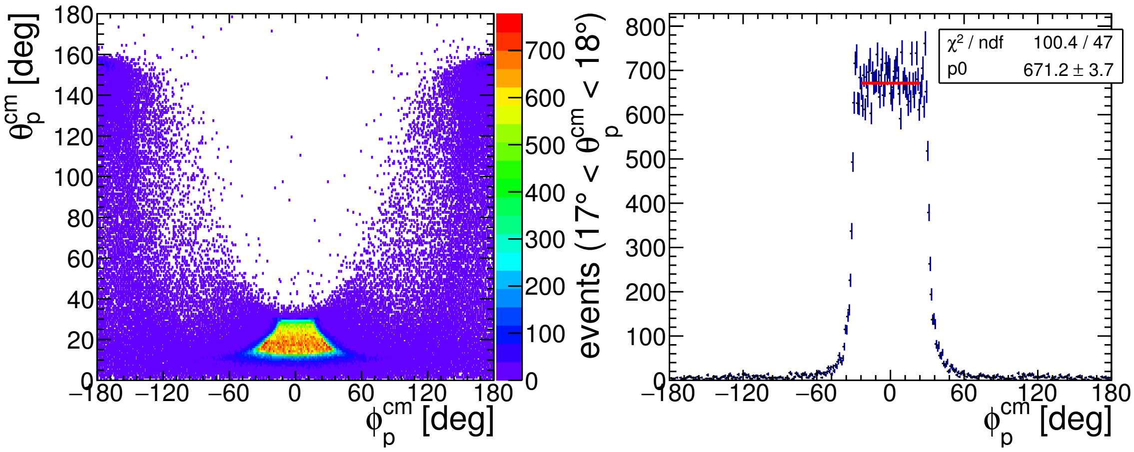

Figure 5. Distribution of events by ϕ depending on the angle in the c.m.s., $Tp = 1.6$ GeV.

The geometric acceptance was estimated according to the following procedure. Since the proton beam is not polarized, the particles fly isotropically at all azimuthal angles but are registered in the detector location area. In order to avoid the influence of edge effects, events were taken from the angular interval, where distribution of events can be approximated by a constant. In this case, the geometric acceptance is equal to the ratio of the selected angular interval to $360°$. The number of registered events is found by fitting the distribution of the square of the missing mass in a certain angular interval by the sum of the Gaussian and the linear background (Figure 6).

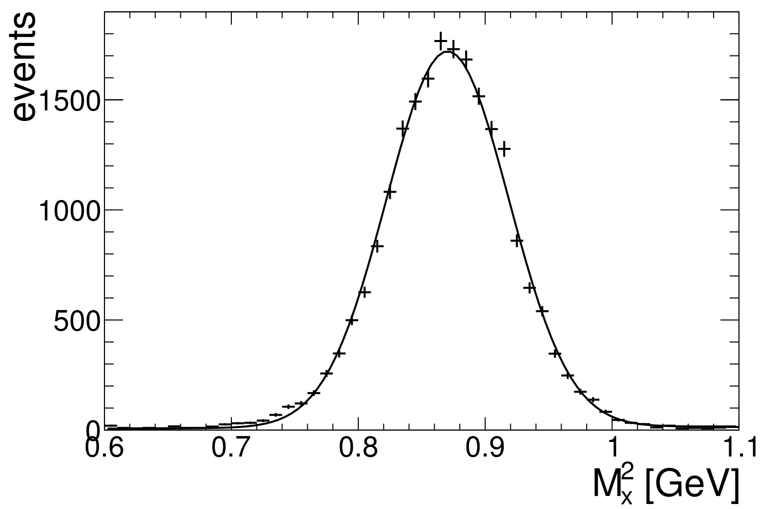

Figure 6. Distribution of missing mass squared for the $pp \to pp$ reaction, $T_p = 1.6$ GeV.

The necessary differential cross sections were taken from the database SAID [13], the solution SP07 for elastic pp scattering. The luminosities calculated in different angular intervals must match. Therefore, fitting the angular dependence with a constant gives the final values of luminosities, which are presented in Table 1 for five energies. As a result, the procedure described made it possible to determine luminosities with an error of 5%, that mostly comes from the uncertainties of the identification of the elastic pp scattering channel and the error of the SAID differential cross section. The values of luminosities found were applied at the further stages of data processing of the $pp \to \{pp\}_s\pi^0$ reaction.

Table 1.
Integral luminosities at various energies. T_p is the proton beam energy, L is the luminosity, σ_{stat} is the statistical error, σ_{sys} is the systematic error.

T_p [GeV]	$L \pm \sigma_{stat} \pm \sigma_{sys}$ $[nb^{-1}]$	χ^2/ndf
1.6	$37.9 \pm 0.3 \pm 1.9$	11.7/12
1.8	$35.2 \pm 0.3 \pm 4.6$	12.5/13
2.0	$36.07 \pm 0.3 \pm 4.7$	12.5/13
2.2	$1.6 \pm 0.01 \pm 0.2$	10.7/11
2.4	$15.7 \pm 0.15 \pm 2.06$	12.5/13

Effective acceptance

To find out the differential cross section $d\Omega/d\sigma$, one needs to know the effective acceptance $A(d\Omega)$ of double-track events. To determine this value, it is necessary to measure the efficiency of the detectors and simulate the flight of particles from the target to the detector and further track search, taking into account the material of detector, the residual magnetic field outside the D2 spectrometric magnet and the effectiveness of software track-finding algorithm. The simulation of the track search is carried out using the TFSimulator program, adapted for use in the analysis of the beam times under consideration. The GEANT3 package was used for tracking: particle trajectories were simulated and their intersections with the detector chambers were calculated, thus multiple scattering in the output window of the vacuum chamber and in the detector materials was taken into account. The tracks received from the GEANT3 package were fetched to the track search software module. The track search procedure applied to the detector signals simulated this way was identical to the one used for processing experimental data. Thus, the maximum similarity between the simulation and the experiment was achieved.

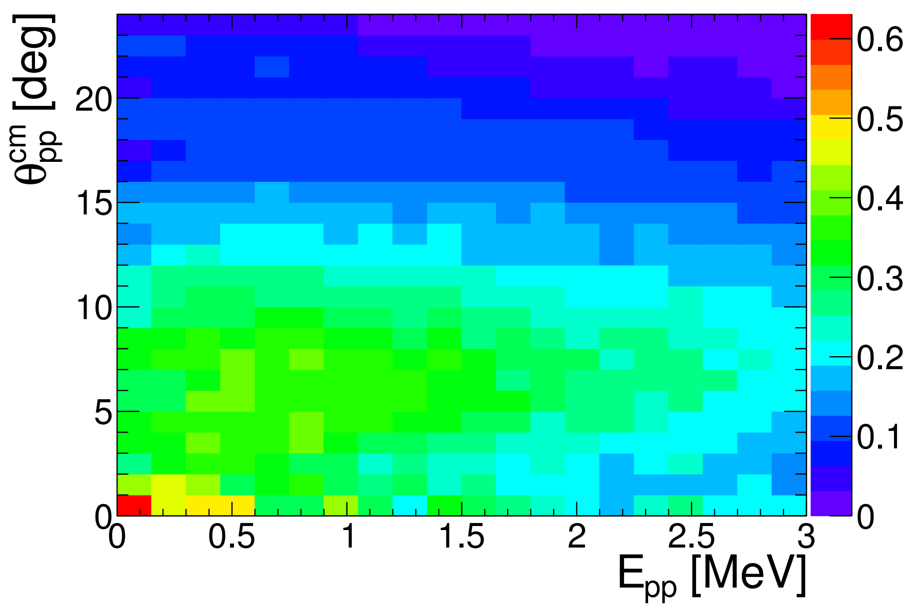

Figure 7. Effective acceptance of detector A with respect to the excitation energy of the proton pair E_{pp} and its angle in the c.m.s. θ_{pp}^{cm} for the reaction $pp \to \{pp\}_s\pi^0$.

For the reconstructed events, the corresponding number of generated events was recorded, so it was possible to determine the effective acceptance of the setup A. Its dependence on the excitation energy of the proton pair E_{pp} and its angle in the CMS $\theta_{pp}^{\mathrm{cm}}$ was calculated (see Figure 7).

Results

In order to obtain differential cross section, the registered reaction events $\{pp\}_s\pi^0$ were corrected for the effective acceptance A and normalized for the integral luminosity, so the cross section was calculated according to the formula

$$\frac{d\sigma}{d\Omega} = \frac{1}{L\Delta\Omega}\sum_i A_i^{-1} \tag{6}$$

where i is the event number, A_i is the effective acceptance for this event, L is the integral luminosity, and $\Delta\Omega$ is the interval of the solid angle for which the cross section is determined. To find the differential cross section angular dependence, the events were divided into four intervals by $\theta_{pp}^{\mathrm{cm}}$: 0°–6°, 6°–12°, 12°–18°, 18°–24° (except $T_p = 2.2$ GeV, where we used only two intervals 0°–12° and 12°–24° because of smaller statistics), and then the cross section was fitted by the function:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma(0)}{d\Omega}(1 + k\sin^2\theta_{pp}^{\mathrm{cm}}), \tag{7}$$

where the first parameter $d\sigma(0)/d\Omega$ is the value of the differential cross section at zero angle, the second parameter k is the slope parameter (see Figure 8 and Table 2). The values of the differential cross section at zero angle $d\sigma(0)/d\Omega$ were

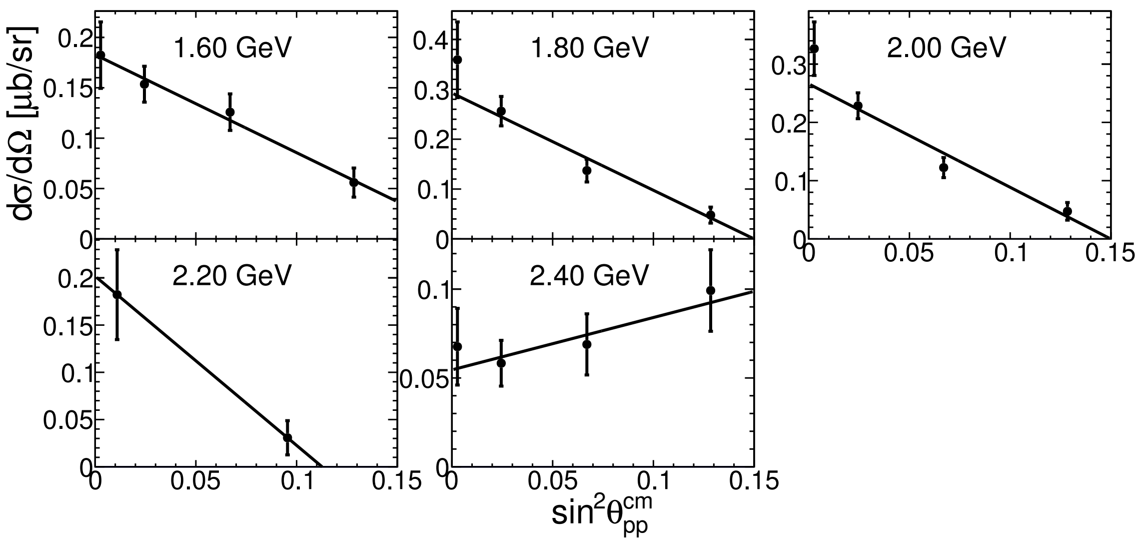

Figure 8. Angular dependence of the differential cross section of the reaction $pp \to \{pp\}_s\pi^0$ [11].

fitted by the Breit-Wigner function

$$\frac{d\sigma(0)}{d\Omega} = \frac{N}{(\sqrt{s} - E_0)^2 + \Gamma^2/4}. \tag{8}$$

in the T_p energy range 1.5 – 2.3 GeV. The energy dependence of the forward differential cross section $d\sigma(0)/d\Omega$ for the $pp \rightarrow \{pp\}_s\pi^0$ reaction shows a resonance peak at the energy $\sqrt{s} \approx 2.65$ GeV as can be seen from Figure 9.

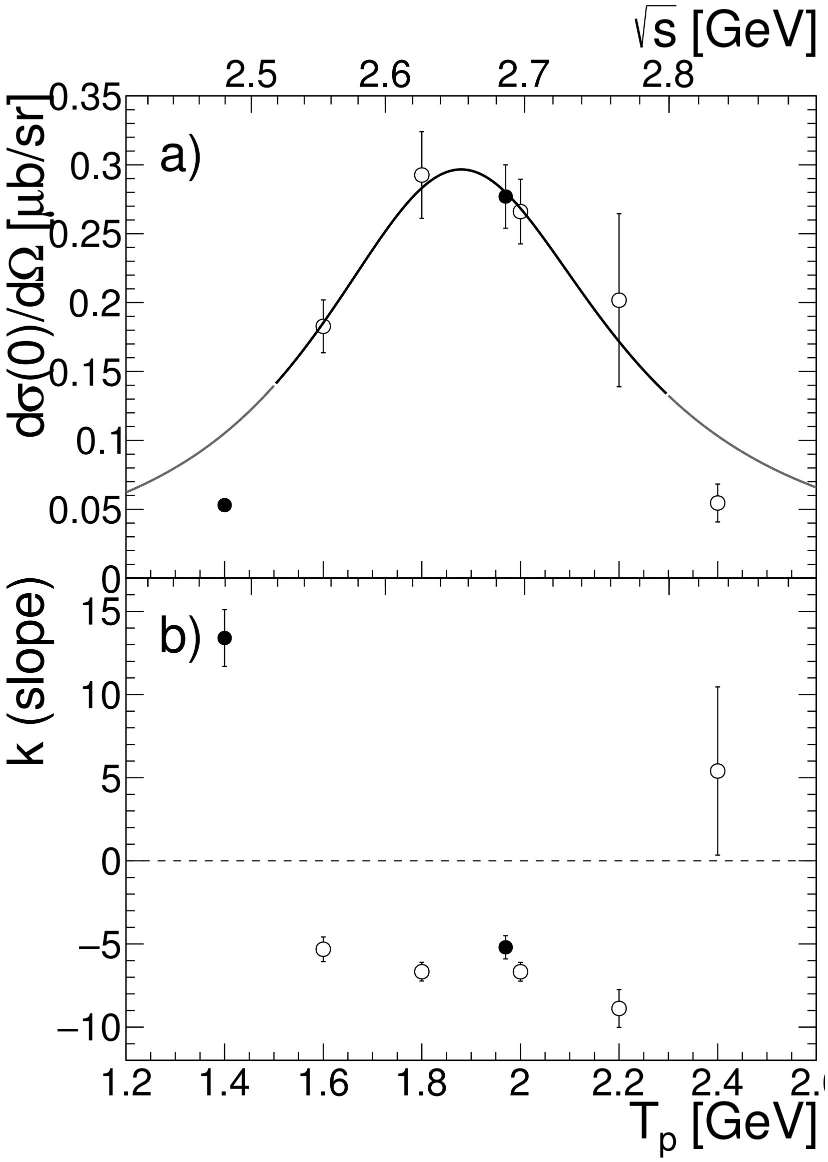

Figure 9. Energy dependence of (a) the differential cross section at the zero angle $d\sigma(0)/d\Omega$ and (b) the slope of the differential cross section k for the $pp \rightarrow \{pp\}_s\pi^0$ reaction. Full circles are ANKE values from [5], and open circles are the current ANKE data.

Table 2.
Final results for the differential cross section of the $pp \rightarrow \{pp\}_s\pi^0$ reaction. T_p is the proton beam energy, $d\sigma(0)/d\Omega$ is the forward differential cross section, k is the slope parameter.

T_p [GeV]	$d\sigma(0)/d\Omega$ [μb/sr]	k
1.6	0.183 ± 0.019	-5.3 ± 0.7
1.8	0.293 ± 0.031	-6.7 ± 0.6
2.0	0.266 ± 0.023	-6.7 ± 0.6
2.2	0.202 ± 0.063	-8.9 ± 1.1
2.4	0.055 ± 0.014	5 ± 5

Conclusion

Single-pion production in pp collisions was studied with the final protons detected at large transferred momenta and small forward angles. Decay of the excited intermediate state of the baryon pair leads to the production of a $^1S_0$ proton pair (diproton) and a single pion. This reaction was measured at ANKE-COSY in 2013 at five values of the energy of the incoming proton 1.6–2.4 GeV. We have analyzed the experimental data—as a result, the values of the differential cross section were determined. The observed energy dependence of the forward differential cross section $d\sigma(0)/d\Omega$ for the $pp \to \{pp\}_s\pi^0$ reaction exhibits a resonance-like structure at the energy $\sqrt{s} \approx 2.65$ GeV. Breit-Wigner parameters of the peak are: $M = 2.652 \pm 0.005$ GeV and $\Gamma = 0.26 \pm 0.02$ GeV.

Preliminary, we consider that this peak might be a result of interference between the $\Delta(1232)$ and $N(1440)$ resonance excited in the intermediate two-nucleon system [11]. The suggested interpretation requires a consistent theoretical study for its justification.

Acknowledgments

The authors wish to thank other members of the ANKE collaboration for their help and assistance in the running of the experiment and in the data analysis.

References

[1] J. Arvieux et al., Nucl. Phys. A **431** (1984) 613. [*CrossRef*]
[2] F.M. Kondatyuk et al., Yadern. Fiz. **33** (1981) 1208. (In Russian)
[3] O. Imambekov et al., Yadern. Fiz. **5** (1990) 1361. (In Russian)
[4] V. Komarov et al., Phys. Lett. B **553** (2003) 179. [*CrossRef*]
[5] S. Dymov et al., Phys. Lett. B **635** (2006) 270. [*CrossRef*]
[6] V. Komarov et al., Phys. Rev. Lett. **101** (2008) 102501. [*CrossRef*]
[7] H.L. Anderson et al., Phys. Rev. D **3** (1971) 1536. [*CrossRef*]
[8] R.A. Arndt et al., Phys. Rev. C **48** (1993) 1926. [*CrossRef*]
[9] V. Komarov et al., Phys. Rev. C **93** (2016) 065206. [*CrossRef*]
[10] V. Kurbatov et al., EPJ Web Conf. **204** (2019) 08008. [*CrossRef*]
[11] D. Tsirkov et al., arXiv:2207.13575 [*CrossRef*]
[12] S. Barsov et al., Nucl. Instrum. Methods Phys. Res. A **462** (2001) 364. [*CrossRef*]
[13] SAID interactive code, https://gwdac.phys.gwu.edu [*Web Link*]