Energy dependence of the analysing power $A_y(\Theta_q^*)$ for the $\vec{p}p \to pp\eta$ reaction

COSY–11 Collaboration

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Abstract
It is proposed to study the production mechanism of the η meson in near threshold proton-proton collisions via the measurement of the energy dependence of the analysing power $A_y(\Theta_q^*)$ for the $\vec{p}p \to pp\eta$ reaction in the excess energy range between threshold and 40 MeV.

The determination of that dependence would allow to establish the exchange processes which lead to the excitation of the S_{11} nucleon isobar in the proton-proton reaction, whose subsequent decay results in the creation of the η meson. The angular dependence of A_y in the excess energy range of the s–wave dominance will also permit to derive a magnitude of the small admixtures of the higher partial waves via the determination of the interference terms, which are inaccessible from the distributions of the spin averaged observables. The more precisely these contributions are known the more accurate are inferences concerning the production dynamics of the η meson and the η-proton interaction.

Guided by the predictions based on the dominance of the ρ meson exchange model – favoured slightly by our previous measurement performed at the the excess energy of Q = 40 MeV [1, 2] – we would like to measure the angular dependence of the η meson analysing power $A_y(\Theta_q^*)$ at Q = 2 MeV, 10 MeV, and 25 MeV, complementary to the investigations carried out at higher energies by the TOF collaboration [3]. The realisation of the proposed investigation requires 7 weeks of beam time in total, which we would like to divide into two runs with **3 weeks** in the coming period.

1 Introduction

It is rather well established that close to threshold the energy dependence of the total cross section is due to the interaction among the outgoing particles and that the entire production dynamics manifests itself only in a single constant which determines the magnitude of the total cross section [4]. Therefore, in spite of the precise measurements of the total cross section for the creation of η meson in proton-proton [5, 6, 7] as well as proton-neutron [8] collisions there is still a lot of ambiguities in the description of the mechanism underlying the production process. It is generally anticipated [9, 10, 11] that the η meson is produced predominantly via the excitation of the S_{11} baryonic resonance $N^*(1535)$, whose creation is induced through the exchange of the virtual π, η, ρ, σ and ω mesons, however at present it is still not established what the relative contributions originating from a particular meson are. Measurements of the total cross section in different isospin channels put some more limitations to the models, yet still the η meson production in the $pp \to pp\eta$ and $pn \to pn\eta$ reactions can be equally well described by eg. assuming the ρ meson exchange dominance [10] or by taking contributions from the pseudoscalar and vector meson exchanges [11]. Therefore, for a full understanding of the production dynamics the determination of polarisation observables is mandatory. The precise measurement of the beam analysing power could already exclude one of the above mentioned possibilities. The first measurement of that quantity has been recently performed [1](see points in figure 1 (right)), but for a conclusive inference a better accuracy of the data is required.

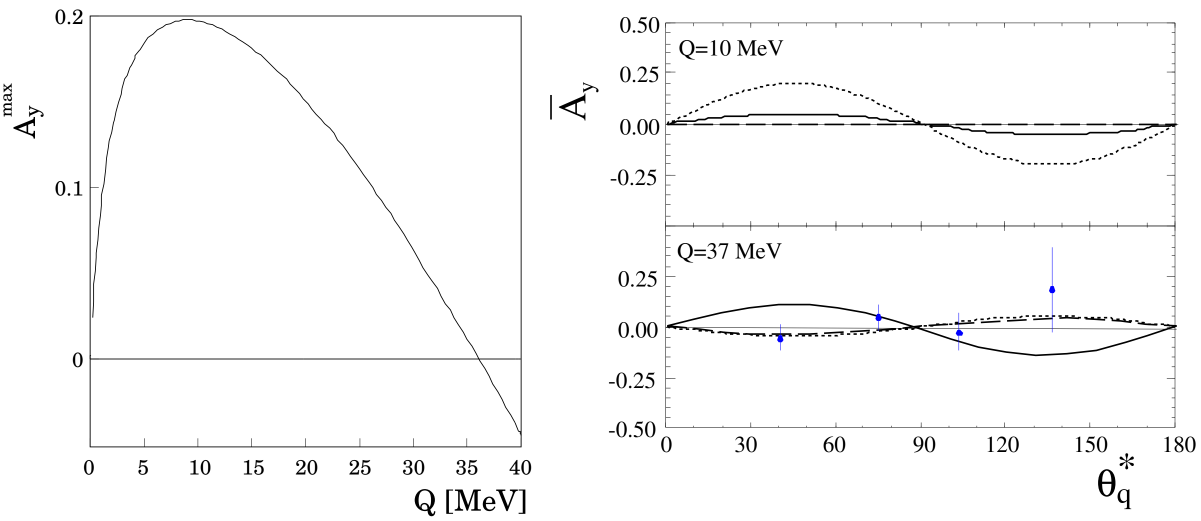

Figure 1: (**left**) Predictions for the A_y^{max} as function of the excess energy for the reaction $\vec{p}p \to pp\eta$ obtained assuming the vector meson exchange only [10].
(**right**) Theoretical predictions for the angular dependence of the analysing power for the reaction $\vec{p}p \to pp\eta$ at $Q = 10$ and 37 MeV [11] compared to the data taken at $Q = 40$ MeV [1]. The solid line presents the result of the full model calculations taking into account resonance as well as mesonic and nucleonic currents [11]. The dashed line shows the predictions of that model yet only when the exchanges of vector mesons have been accounted for. The dotted line stands for the predictions of the one-boson-exchange model of reference [10] with the dominant contribution from the ρ-meson exchange.

The dependence of the analysing power on the polar emission angle of the η meson in the center-of-mass system Θ_q^* can be expressed as [10]:

$$A_y = 2A_y^{max} sin(\Theta_q^*) cos(\Theta_q^*). \tag{1}$$

Figure 1(right) indicates that the value of the A_y^{max} coefficient varies strongly with the excess energy Q for each of the presented models. In case of the ρ meson dominance this dependence is shown explicit in figure 1(left). From figure 1(right) it is also evident that the variations of A_y^{max} depends significantly on the production dynamics. This feature gives the possibility to judge about the validity of the different hypotheses by the experimental determination of the excess energy dependence of the A_y^{max}.

Motivated by the theoretical predictions for the ρ-meson dominance model of reference [10] we would like to establish the angular dependence of the analysing power for the $\vec{p}p \to pp\eta$ reaction at excess energies Q = 2 MeV, 10 MeV, 25 MeV, and 36 MeV(measured already). At Q = 10 MeV the coefficient A_y^{max} acquires — according to the anticipated model — the highest value, whereas at 36 MeV it should be close to zero, and at Q = 2 MeV and 25 MeV it is expected to be approximately half of the maximum. At present there are no strong arguments against any of the mentioned models. Our choice is dictated only by the fact that the data gathered during the first ever run of η production with polarised beam at COSY, and at COSY-11 in particular, indicate that both vector meson exchange dominance models of references [10] and [11] are in the range of one standard deviation from each of the measured point, whereas the full model with nucleonic, mesonic, and resonance currents taking into account pseudoscalar and vector mesons exchanges deviates slightly, but not significantly, from the experimental points (see figure 1(right)). Out of those a bit more favoured hypotheses we have chosen the one for which we possess an explicit prediction in the full excess energy range between Q = 0 MeV and 40 MeV.

The data on the angular distributions of the analysing power would also enable to determine the relative magnitudes — or at least to set upper limits — for the contribution from the higher than s-wave partial waves to the production dynamics. This can be done with a accuracy by far better than this resulting from the measurements of the distributions of the spin averaged cross sections. This is because the polarisation observables are sensitive to the interference terms between various partial amplitudes, which may become measurable even if one of the interfering terms alone appears to be insignificant in case of the spin averaged cross sections. The analysis would be based on the formalism developed for the measurement of the π^0 meson production with a polarised proton beam and target [12], which we have already used for the analysis of our first measurement with a polarised proton beam [1, 2]. This procedure permits for the derivation of all available information contained in the distributions of the cross sections and the analysing power. Information about the partial wave decomposition is of crucial importance for the interpretation of the production dynamics but also for the study of the mutual interaction of the produced η-proton-proton system. The dynamics of that system became recently a subject of theoretical investigations in view of the possible existence of quasi-bound or resonant states [13] [1]. The knowledge of the proton-η interaction cannot be, however, derived univocally from the differential cross section distributions alone, without the knowledge of the contribution of various partial waves. The examples are the measured invariant mass distributions of the two-particle subsystems of the $pp \to pp\eta$ reaction [14, 15], which await a strict theoretical explanation.

2 Measurements at COSY–11

After the successfull measurement of the energy dependence of the unpolarized total cross section [6] and the population distributions of the phase-space for the $pp \to pp\eta$ reaction [7, 15] the COSY-11 collaboration has studied the analysing power A_y of the $\vec{p}p \to pp\eta$ reaction at excess energies Q = 40 MeV [1] and Q = 36 MeV, in January 2001 and September 2002, respectively. The first measurement has proven the ability of the COSY-11 facility to study the polarisation observables, however, the small degree of polarisation (only $\sim$ 48%) and low statistics allowed only for qualitative conclusions concerning the production mechanism which have been already published [1]. The second measurement at Q = 36 MeV has been performed with a significantly larger proton beam polarisation which on the average amounted to approximately 75 % and also with by about a factor of 1.5 larger luminosity integrated over the measurement period. These two together, give over twice better accuracy of the measurement, in the sense, that the errors corresponding to those in figure 1 are expected to be two times smaller.

In the previous measurements with unpolarised [6, 15] as well as with vertically polarised [1, 2] proton beam we have proven the ability of the COSY-11 detection system to register and identify the $pp \to pp\eta$ reactions with a mass accuracy of about 1 MeV/c^2 as can be deduced from the examples of the missing mass spectra presented in figure 2. In order to measure spin dependent observables of the studied reaction additionally to the four-momentum vector

[1] see reference [4] for a review.

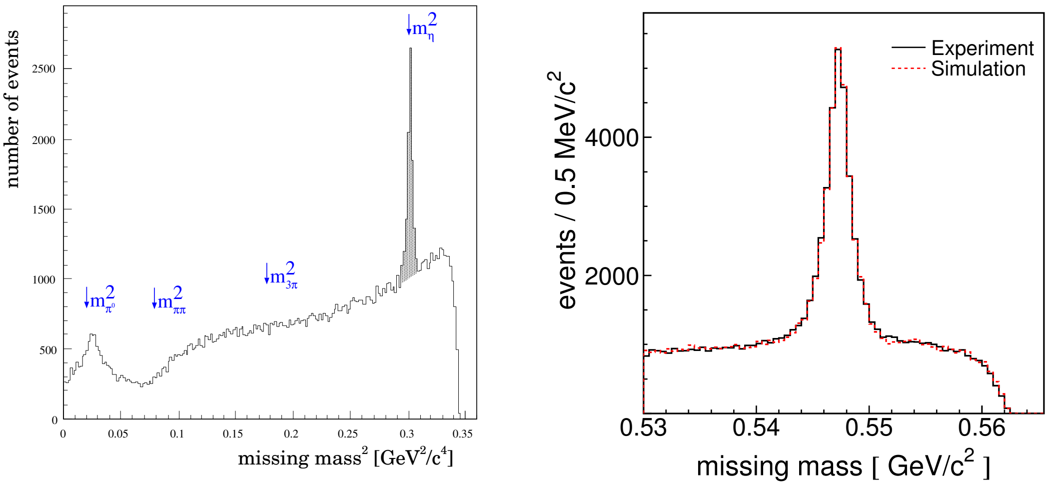

Figure 2: Missing mass for events with two protons in the exit channel obtained at Q = 40 MeV [1] **(left)** and Q = 15.5 MeV [7] **(right)**. In the left figure the literature values of the particles mases [20] are indicated by arrows.

measurements of the outgoing particles it is necessary to monitor the polarisation and the luminosity. This can be realised by the simultaneous measurement of the elastically scattered protons, for which the angular distribution of the analysing power is well known [21]. To facilitate monitoring of luminosity and polarisation simultaneously, we use two independent detection subsystems which measure the elastically scattered protons in the horizontal and vertical planes. The former plane being perpendicular to the COSY dipol magnetic field and the latter containing the vector of polarisation. Due to the parity conservation there is no asymmetry in the plane containing the vector of polarisation, and hence in that plane the number of registered events is not sensitive to the spin projection of the proton beam. This allows to monitor the luminosity with the subdetectors installed in the vertical plane, and to monitor the polarisation with the detectors in the horizontal plane.

During the last run the averaged beam polarisation has been measured simultaneously in three independent ways. During the measurements we used the COSY internal polarimeter [16], the EDDA experimental setup [17], as well as our own monitoring system (further referred to as COSY-11 polarimeter). The EDDA facility was run in parallel in order to calibrate and to check the performance of the COSY and COSY-11 polarimeters, respectively. The COSY-11 monitoring system is depicted in figure 3.

A coincidence between the lower-vertical and upper-horizontal orientated or the lower-horizontal and upper-vertical orientated scintillators as shown in figure 3 (upper left panel) serves as a trigger for the vertical luminosity system. The event population observed in the MWPC is shown in figure 3 (upper right panel). One can clearly realise the elliptical shape of the distribution which corresponds to the circular form of the thick scintillator installed in front of the dipole coil. Events that are scattered outside the ellipse originate from particle production reactions, where the ejectiles do not fullfil a two body kinematics.

The system for detecting the elastically scattered protons in the horizontal plane is presented in figure 3 (lower left panel). The two body kinematics requires a unique correlation between the positions in the S1 and Si detectors, which is expected to be approximately a straight line as can be seen in figure 3(lower right panel). Using this systems we can monitor luminosity and polarisation also on-line. Figure 4 (left) shows the results from the on-line analysis of the September 2002 beam time. On the right panel of that figure an example of the EDDA beam polarisation monitoring integrated over about 10 hours of beam time is presented as a function

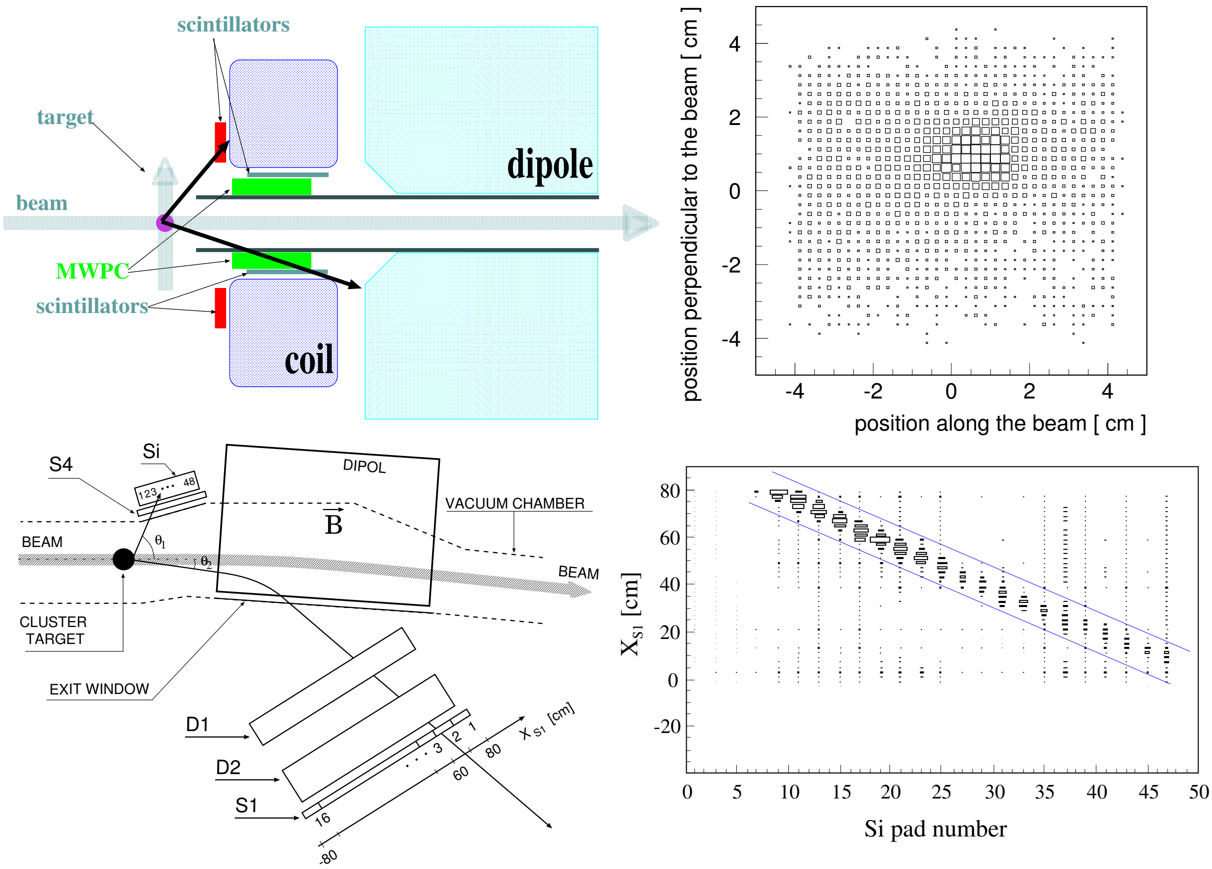

Figure 3: Schematic view of the COSY-11 detection setup. The detectors needed for the measurement of proton-proton elastic scattering in the vertical [18] and the horizontal [19] plane are shown in the upper left and lower left panels, respectively. D1 and D2 denote the drift chambers; S1 and S4 are the scintillator detectors; Si denotes the silicon monitor detectors and MWPC stands for the multiwire proportional chambers. Each system alone allows for the registration and identification of events with elastically scattered protons which is demonstrated by the correlation plots presented in the right panels (experimental plots [2, 18]). In both spectra a clear signal originating from the elastic events is seen on a rather uniformly scattered background.

of the time of the COSY cycle. Results consistent with the EDDA measurements were obtained using the COSY-11 polarimeter. The precise differential analysis is still in progress, however to an accuracy of a few per cent the estimations can be done even by eye referring to the trigger counting rate, an example is shown in figure 5.

The angular range in the center-of-mass frame covered by the luminosity/polarisation monitoring system is spread between 40° and 70°, where the analysing power for the $\vec{p}p \to pp$ elastic scattering varies from 0.377 to 0. [21] However, due to the strong angular dependence of the total cross section most of the registered $pp \to pp$ events (80%) are distributed between 40° and 60°, where the average A_y for proton-proton elastic scattering amounts to 0.29. Figure 5 presents a typical counting rate from the measurement taken in September where the thin solid line (showing a decrease of rate during the cycle) corresponds to the coincidence between S1 and S4 scintillator detectors. As it is well established by the off-line analysis this coincidence rate is by about 70% caused by the $pp \to pp$ events. Thus even from that counting rate difference we can roughly (within a few percent accuracy) estimate the polarisation $P = \frac{N_\uparrow - N_\downarrow}{A_y \cdot (N_\uparrow + N_\downarrow)}$, which is in that case $P = \frac{125-90}{0.29\cdot(125+90)\cdot 0.7} = 0.8$, where the factor 0.7 in denominator accounts for the fact that only 70% of the events originate from the $\vec{p}p \to pp$ reaction. Since the analysing power was averaged over a rather large angular range this value

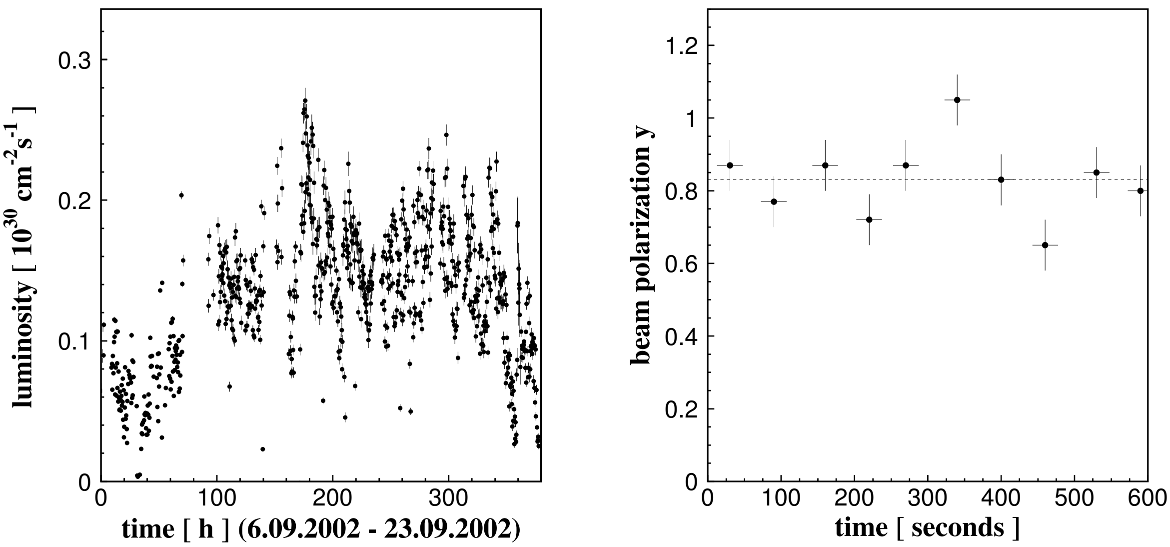

Figure 4: **left**) On-line determination of the luminosity during the measurement of the reaction $\vec{p}p \to pp\eta$ carried out in September 2002. A total integrated luminosity equals approximately to 180 nb^{-1}. (**right**) On-line estimation of the beam polarisation as measured using the EDDA polarimeter. The value of vertical beam polarisation is shown versus the time of the cycle.

can be treated only as a rough estimate, but it is in accordance with the results obtained by the EDDA detector.

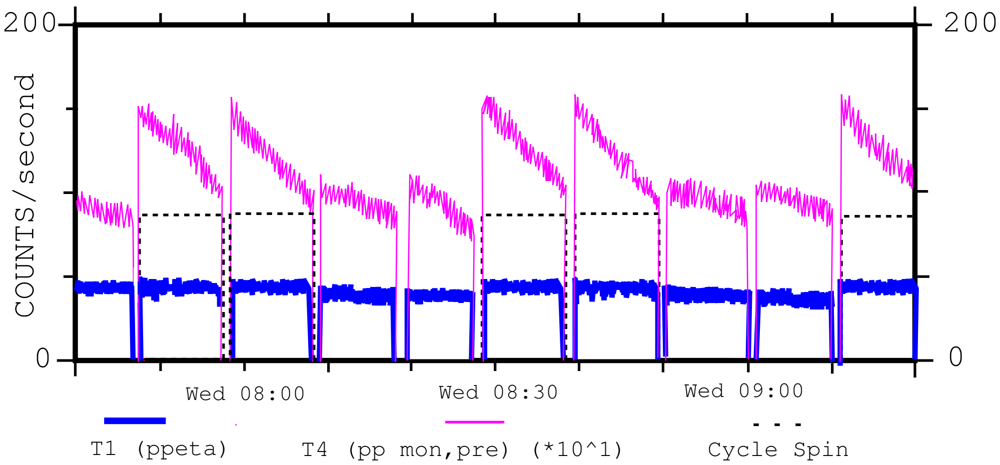

Figure 5: Trigger rate from the measurement performed in September 2002.

Alltogether the polarisation integrated over the whole measurement period estimated by means of the EDDA facility resulted in $P \approx 75\%$, which is about 1.5 times better than during the first measurement with polarized proton beam at COSY-11.

3 Estimation of the requested beam-time

In order to estimate the time needed to perform the measurements of $A_y(\Theta_q^*)$ and A_y^{max} at $Q = 2$ MeV, 10 MeV, and 25 MeV, we have assumed that an accuracy of 50% of determining the A_y value in each $\cos(\Theta_q^*)$ range is sufficient to decide between the two models presented in figure 1. This accuracy should result in an A_y^{max} determination with a precision of about

25%. Thus, in the case of $Q = 10$ MeV we should obtain A_y^{max} with a standard deviation of less than 0.05. This would lead to error bars more than two times smaller than those in figure 1. Having a closer look at figure 1 (right) one can come to the conclusion that this should be sufficient to judge between the two presented models. To estimate the time required to perform the measurements, we first have to formulate the relation between accuracy of ($\sigma(A_y)$) and the measurement duration. The latter one is uniquely related to the number of events to be measured in order to achieve the required precision. In the beginning we should ask: what is an error of the analysing power? According to the convention used in [1], the analysing power A_y is given by:

$$A_y(\xi) \;=\; \frac{L_{rel}\,N_{\uparrow} \,-\, N_{\downarrow}}{P_{\uparrow}\,N_{\downarrow} \,-\, L_{rel}\,P_{\downarrow}\,N_{\uparrow}}\,(\xi), \tag{2}$$

where the relative time-integrated luminosity L_{rel} is defined as: $L_{rel} \;=\; \frac{\int L_{\downarrow} dt_{\downarrow}}{\int L_{\uparrow} dt_{\uparrow}}$, and $N_{\uparrow}$ and $N_{\downarrow}$ are the yields with the beam polarisation up ($P_{\uparrow}$) and down ($P_{\downarrow}$), respectively[2].
ξ denotes the set of five kinematical variables that completely describe the exit channel.
To find out the main factors determining the error of the analysing power A_y we will perform a few approximation. First we assume the relative luminosity to be $L_{rel} = 1$ and $|P_{\uparrow}| = |P_{\downarrow}| = |P|$. This holds within a few per cent accuracy as observed in the previous measurements [1]. This simplifies the above equation to:

$$A_y \;\approx\; \frac{1}{P}\cdot\frac{N_{\uparrow} \,-\, N_{\downarrow}}{N_{\uparrow} \,+\, N_{\downarrow}}. \tag{3}$$

Now we can estimate the error of A_y:

$$\sigma^2(A_y) \;=\; \frac{1}{P^2}\,[(\frac{\partial\, A_y}{\partial\, N_{\uparrow}})^2\,\sigma^2(N_{\uparrow}) \,+\, (\frac{\partial\, A_y}{\partial\, N_{\downarrow}})^2\,\sigma^2(N_{\downarrow})], \tag{4}$$

where $\sigma(P)$ was neglected, since $\frac{\sigma(P)}{P}$ — the relative accuracy of determining the averaged value of P– is by far better [1] than the relative accuracy for $N_{\uparrow}$ or $N_{\downarrow}$. The standard deviations we estimated as:

$$\sigma^2(N_{\uparrow,\downarrow}) \;=\; N_{\uparrow,\downarrow}\,(1 \,+\, 2B_{\uparrow,\downarrow}), \tag{5}$$

where we introduced the parameter $B_{\uparrow,\downarrow}$ as a background-to-signal ratio in the missing mass peak. This ratio depends on the η meson emission angle (see figure 6), and therefore $B_{\uparrow,\downarrow}$ was estimated for each considered range of $\cos(\Theta_q^*)$ separately. After simple calculations of the partial differentials in equation 4 and making assumptions that $B_{\uparrow}(\Theta_q^*) \;\approx\; B_{\downarrow}(\Theta_q^*) \;\approx\; B(\Theta_q^*)$ and that $N_{\uparrow}(\Theta_q^*) \;\approx\; N_{\downarrow}(\Theta_q^*) \;\approx\; \frac{1}{2}\,N(\Theta_q^*)\cdot E_{ff}(\Theta_q^*)$, where $E_{ff}(\Theta_q^*)$ denotes the detection efficiency for the center-of-mass Θ_q^* angle, and $N(\Theta_q^*)$ is the number of η mesons produced during the whole measurement and emitted in the solid angle around a polar angle Θ_q^* [3], we obtain:

$$\sigma\,(A_y(\Theta_q^*)) \;=\; \frac{1}{P}\sqrt{\frac{1+2B(\Theta_q^*)}{N(\Theta_q^*)\;E_{ff}(\Theta_q^*)}}. \tag{6}$$

By introducing the precision of the measurement ε, defined as $\varepsilon \;=\; \frac{\sigma(A_y)}{A_y}$ and using equation 6 we obtain the following formula for the number of events needed to satisfy the requirement of a measurement with the precision ε:

$$N(\Theta_q^*) \;=\; \frac{1+2B(\Theta_q^*)}{P^2\cdot\varepsilon^2\cdot A_y^2(\Theta_q^*)\cdot E_{ff}(\Theta_q^*)}. \tag{7}$$

[2]For definition of ”up” and ”down” polarisation see for instance [1]

[3]Since the COSY-11 detection system is an ”one-arm” spectrometer we need to measure $N_{\uparrow}$ and $N_{\downarrow}$ separately. Therefore in the above definition N is divided by a factor of 2.

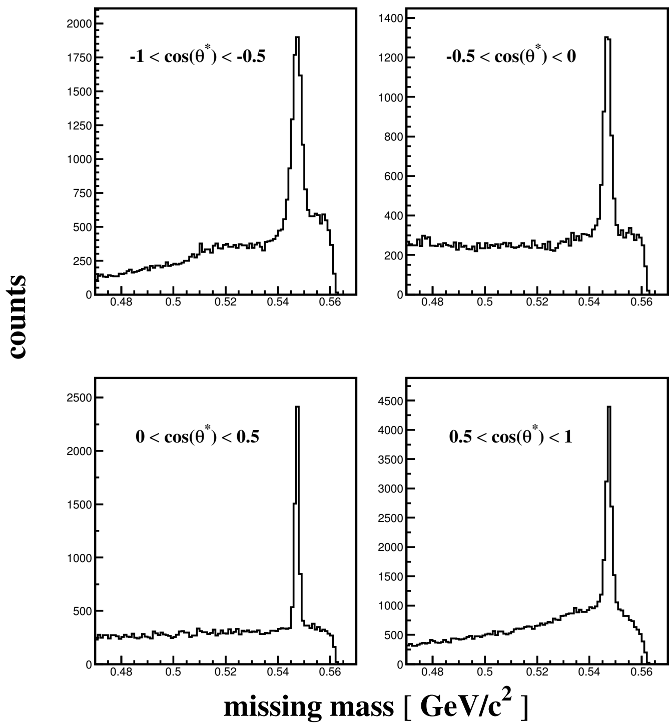

Figure 6: Missing mass distribution for four equal intervals of the cosine of the polar emission angle of the η meson in the center-of-mass system, as measured using the COSY-11 facility at an excess energy Q = 15.5 MeV [7, 15].

In our estimation of beam time length we have assumed that the average luminosity will be equal to: $L = 2.5 \cdot 10^{29} \frac{1}{cm^2 s}$. This value of the luminosity multiplied by the total cross section gives the total number of η mesons produced in the target per second (column *counting rate* in table 3 presents the total number of η mesons produced in the target within one day of measurement). The average polarisation was assumed to be $P = 0.8$, which is the estimation of the polarisation that was available during the second week of the last run (see fig. 4 (right)). The values of $B(\Theta_q^*)$ and $E_{ff}(\Theta_q^*)$ are given in tables 1 and 2. Background-to-signal ratios have been measured at $Q = 15.5$ MeV for different angles (fig. 6). The values of $B(\Theta_q^*)$ for $Q = 2$ MeV and $Q = 40$ MeV(compare figure 2(left)) are also known from the other experiments at COSY-11 [1, 6]. Values of $B(\Theta_q^*)$, given in table 1, are simply an interpolation made on the basis of these measurements. The efficiency values $E_{ff}(\Theta_q^*)$ from table 2 were determined from Monte-Carlo calculations for corresponding excess energies (see fig. 7).

Q [MeV]	$B((\Theta_q^*)_1)$	$B((\Theta_q^*)_2)$	$B((\Theta_q^*)_3)$	$B((\Theta_q^*)_4)$
2	0.031	0.025	0.014	0.029
10	0.612	0.504	0.288	0.576
25	1.190	0.980	0.560	1.120

Table 1: Background-to-signal ratio for the $\vec{p}p \to pp\eta$ reaction as a function of the Θ_q^* angle. ($-1 < \cos((\Theta_q^*)_1) < -0.5$; $-0.5 < \cos((\Theta_q^*)_2) < 0$; $0 < \cos((\Theta_q^*)_3) < 0.5$; $0.5 < \cos((\Theta_q^*)_4) < 1$)

The numbers of events required for a measurement with a precision of $\varepsilon = 0.5$ and corresponding beam times duration, calculated according to the equation 7, are listed in table 3.

Q [MeV]	eff($(\Theta_q^*)_1$)	eff($(\Theta_q^*)_2$)	eff($(\Theta_q^*)_3$)	eff($(\Theta_q^*)_4$)
2	0.172	0.108	0.108	0.172
10	0.020	0.012	0.012	0.028
25	0.005	0.004	0.004	0.010

Table 2: Efficiency of the COSY-11 detection system for the $\vec{p}p \to pp\eta$ reaction as a function of the angle Θ_q^*.

Q [MeV]	σ_{tot} [μb]	N_{tot}–number of events required	counting rate $[\frac{events}{day}]$	**days to run**	number of detected ppη events
2	0.27	38000	5900	**6**	5300
10	1.50	216000	32400	**7**	3900
25	3.50	2640000	75600	**35**	15200

Table 3: Beam time estimation. σ_{tot} is the total cross section for η meson production; N_{tot} is the number of η mesons to be produced in order to achieve the accuracy of $\varepsilon = 0.5$; counting rate denotes the number of η mesons produced in the target within one day (assuming the luminosity $L = 2.5 \cdot 10^{29} \frac{1}{cm^2 s}$), and in the last column the number of detected $\vec{p}p \to pp\eta$ events is given.

Note, that given precision requires different duration of measurement for various Θ_q^* ranges. The numbers given in table are just the average.

Summarising, the COSY-11 collaboration would like to ask for:

1) One week of beam time
at a momentum of the polarized proton beam of
$\vec{p}_{beam} = 1.987$ **GeV/c**
equivalent to an excess energy of Q = 2 MeV;

2) One week of beam time
at a momentum of the polarized proton beam of
$\vec{p}_{beam} = 2.010$ **GeV/c**
equivalent to an excess energy of Q = 10 MeV

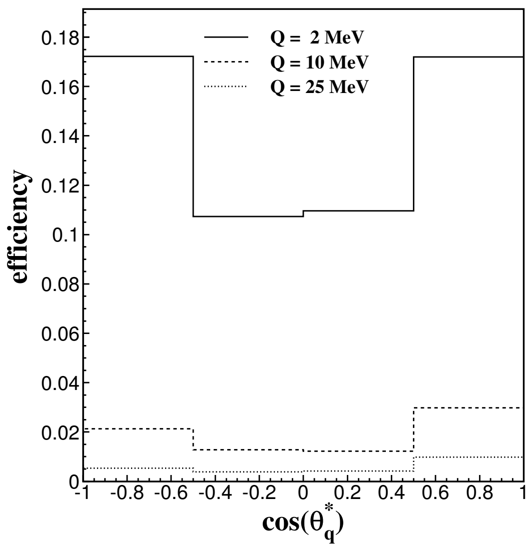

Figure 7: Experimental efficiency for registering and identifying the $pp \to pp\eta$ reaction at Q = 2 MeV (solid line), Q = 10 MeV (dashed line), and Q = 25 MeV (dotted) presented as a function of the polar angle of the η meson emission in the centre-of-mass system.

and

3) Five weeks of beam time
at a momentum of the polarized proton beam of
$\vec{p}_{beam} = 2.053$ **GeV/c**
equivalent to an excess energy of Q = 25 MeV.

Total length of the beam time: 7 weeks.

For the beam time period under discussion (I/2003), we would like to ask for **3 weeks** of beam time to cover the first two data points at Q = 2 MeV and Q = 10 MeV and to start the data production at Q = 25 MeV.

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