

# Reaction $pp \rightarrow pp\pi\pi\pi$ as a background for hadronic decays of the $\eta'$ meson.

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**Abstract.** Isospin violating hadronic decays of the  $\eta$  and  $\eta'$  mesons into  $3\pi$  mesons are driven by a term in the QCD Lagrangian proportional to the mass difference of the  $d$  and  $u$  quarks. The source giving large yield of the mesons for such decay studies are  $pp$  interactions close to the respective kinematical thresholds. The most important physics background for  $\eta, \eta' \rightarrow \pi\pi\pi$  is coming from direct three pion production reactions. In case of the  $\eta$  meson the background for the decays is relatively low ( $\approx 10\%$ ). The purpose of this article is to provide an estimate of the direct pion production background for the  $\eta' \rightarrow 3\pi$  decays. Using the inclusive data from COSY-11 experiment we have extracted differential cross section for the  $pp \rightarrow pp$ -multipion production reactions with the invariant mass of the pions equal to the  $\eta'$  meson mass and estimated an upper limit for the signal to background ratio for studies of the  $\eta' \rightarrow \pi^+\pi^-\pi^0$  decay.

**PACS.** 13.60.Le Meson production – 13.75.-n Hadron-induced low- and intermediate-energy reactions and scattering (energy  $\leq 10$  GeV) – 13.85.Lg Total cross sections – 25.40.-h Nucleon-induced reactions – 29.20.Dh Storage rings

## 1 Motivation

### 1.1 Three pion decays of the $\eta$ and $\eta'$ mesons

The  $\eta$  and  $\eta'$  decays into three pions violate isospin and occur only due to  $u$  and  $d$  quark mass difference. The decay width is sensitive to the mass difference:  $\Gamma_{\eta(\eta') \rightarrow \pi^+\pi^-\pi^0} \propto \Gamma_0 \cdot (m_d - m_u)^2$ , where  $\Gamma_0$  term can be calculated in the isospin limit  $m_d = m_u$ . The decays might provide a precise constraint for the light quark mass ratios [1].

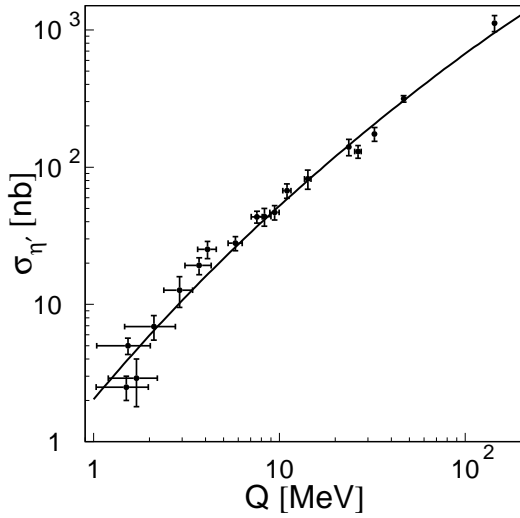
In the case of the  $\eta'$  meson the existence of the isospin conserving decays into three pseudoscalars ( $\pi\pi\eta$ ) implies that instead of the decay width for the isospin violating  $\pi\pi\pi$  channel one can measure ratio:

$$\frac{BR(\eta' \rightarrow \pi\pi\pi)}{BR(\eta' \rightarrow \pi\pi\eta)}, \quad (1)$$

as it was proposed by Gross, Treiman and Wilczek [2]. Such measurement is self contained since it does not require normalization for the partial decay width from other experiments. Additionally, simultaneous measurement of the two decays modes, with similar final states, ensures that many systematic uncertainties will cancel. The  $\eta' \rightarrow \pi\pi\pi$  decays provides also a very sensitive test of the Chiral Perturbation Theory (CHPT) framework [3,4] extensions

to the  $\eta'$  meson. Due to the large mass of the  $\eta'$  meson, the decays are strongly influenced by light vector and scalar meson resonances. Those decays cannot be studied using standard CHPT methods. An elegant method for accounting for the nonperturbative effects in two pseudoscalar meson interactions is given by unitarization procedure of the one loop CHPT result. For example in the theoretical studies of the  $\eta$  and  $\eta'$  meson decays the rescattering of any pair of the pseudoscalar mesons is described by Bethe-Salpether equations [5,6,7]. The parameters of the interactions are obtained by fits to the pseudoscalar scattering data. Predictions for many  $\eta$  and  $\eta'$  decays were given using the above technique within so called *chiral unitary approach* [8].

Experimentally determined value of the branching ratio of the  $\eta' \rightarrow 3\pi^0$  decay is  $(1.56 \pm 0.26) \times 10^{-3}$  [9]. The decay into  $\pi^+\pi^-\pi^0$  was observed in 2009 for the first time by the CLEO collaboration and the branching ratio was determined to  $(37^{+11}_{-9} \pm 4) \times 10^{-4}$  [10]. The result is in strong disagreement with the value  $10^{-2}$  predicted within the chiral unitary approach. Much more improvement on the theory and experiment side is needed to understand the three pion decays of the  $\eta'$  meson.



**Fig. 1.** Compilation of the data for the  $pp \rightarrow pp\eta'$  reaction cross section from COSY-11, DISTO and SPESIII measurements [22,23,24,26,27]. The solid line is parameterization of the data using formula (2).

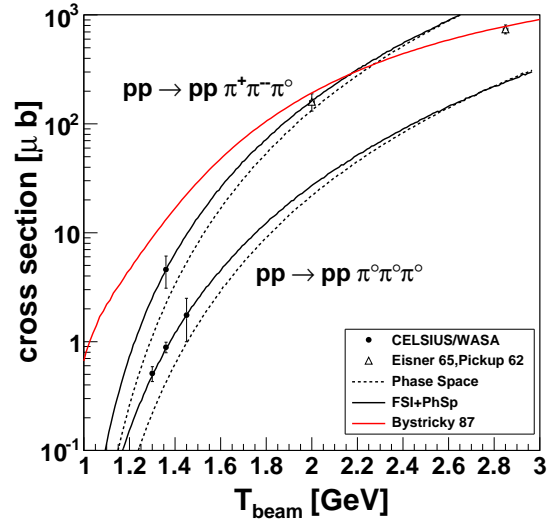
## 1.2 Experiments using $pp \rightarrow pp\eta', \eta$ reaction

The mesons for the decay studies are produced in  $\gamma p$  [11, 12],  $pp$  [13,14],  $\pi^- p$  [15,16],  $pd$  [17,18,19] or  $e^+e^-$  [20,21] interactions. For the studies at light ion storage rings as COSY the  $pp \rightarrow pp\eta'$  reaction close to threshold seems to be most promising. The cross section for  $pp \rightarrow pp\eta'$  reaction was measured by the COSY-11 [22,23,24,25], SPESIII [26] and DISTO [27] collaborations. In Fig. 1 the experimental data are compared to the analytical parameterization derived by Fäldt and Wilkin [28,29] which takes into account final state interaction of the protons:

$$\sigma_{\eta'}^{tot}(Q) = C \frac{Q^2}{m_p p_{LAB}} \frac{1}{\left(1 + \sqrt{1 + \frac{Q}{\epsilon}}\right)^2}, \quad (2)$$

where  $Q$  denotes the excess energy,  $p_{LAB}$  beam momentum and  $m_p$  proton mass. In comparison to the  $pp$  interaction the  $p - \eta'$  interaction is negligible [30]. The  $C$  and  $\epsilon$  free parameters were determined by a fit to the experimental data [31]:  $\epsilon = 0.62 \pm 0.13$  MeV and  $C = 42 \pm 7$  mb.

Experience from studies of the  $\eta \rightarrow \pi\pi\pi$  decays with  $\eta$  produced in  $pp \rightarrow pp\eta$  reaction at beam energies 1.30–1.45 GeV carried out by the CELSIUS/WASA collaboration shows that background from direct three pion production is about 15% for the  $\pi^+\pi^-\pi^0$  and about 5% for the  $3\pi^0$  channel [32,33]. This allows for precise study of the  $\eta$  decays providing a large number of events is collected. The production cross section for the  $\eta$  mesons in  $pp$  collisions [34,35,36,37,13] is about 30 times larger than the cross section for the  $\eta'$  meson [22,23,24,25,26,27] at the corresponding excess energies. At the same time the total cross section for the direct three pion production increases about two orders of magnitude between  $\eta$  and  $\eta'$



**Fig. 2.** Total cross section for three pion production: data and parameterizations. The data are from [43,44,45,46,32]. The parameterizations are from Bystricky et al. [47] and Fäldt and Wilkin [28,29]. The kinetic beam energy at thresholds for the  $\eta$  and  $\eta'$  production is equal to 1.255 GeV and 2.404 GeV respectively.

production thresholds (Fig. 2). For the  $pp \rightarrow pp\pi^+\pi^-\pi^0$  reaction total cross section there are only three experimental points in the beam kinetic energy range up to 3 GeV. The cross section for the  $pp \rightarrow pp\pi^0\pi^0\pi^0$  reaction near the  $\eta'$  meson production threshold was not measured at all. However, based on the statistical model [38, 39,40] and the isobar model [41,42] one expects the  $pp \rightarrow pp\pi^0\pi^0\pi^0$  cross section to be 6–10 times lower than for the  $pp \rightarrow pp\pi^+\pi^-\pi^0$  reaction. This is in agreement with an extrapolation of the CELSIUS/WASA measurement of the both reactions close to  $\eta$  meson production threshold. For the estimate of the background for the three pion decays of the  $\eta'$  mesons instead of the total cross section the relevant quantity is the value of the differential cross section for the invariant masses of the pions in the range of the  $\eta'$  meson mass. This quantity was not measured and in the present paper we will provide an estimate for the upper limit of the background using the COSY-11 data where only outgoing protons were registered.

## 2 General considerations

Let us consider an example analysis chain leading to a selection of the  $\eta' \rightarrow \pi^+\pi^-\pi^0$  decay from the  $pp \rightarrow pp\eta'$  reaction. In the first step all tracks are reconstructed and particles identified. The events containing two protons from the production process, two charged pions and two photons are selected. Now one can apply energy-momentum conservation and select only events consistent with  $pp \rightarrow pp\eta' \rightarrow pp\pi^+\pi^-\pi^0 \rightarrow pp\pi^+\pi^-\gamma\gamma$  reaction hypothesis. This procedure can be most generally implemented by kinematic fitting but one can use also some other method. In the end the selection could be represented by a region

in some control variable  $\mu$ . For example  $\mu$  could be missing mass squared or  $\chi^2$  value of the kinematic fit. Within the selected region, in addition to the signal, a contamination from the background events originating from reactions which have similar final states is unavoidable. The most important physics background channels for the discussed case is the direct  $pp \rightarrow pp\pi^+\pi^-\pi^0$  reaction and other  $\eta'$  decays like  $\eta' \rightarrow \pi^+\pi^-\eta \rightarrow \pi^+\pi^-\gamma\gamma$ . Candidates for the identification variable (in addition to  $\chi^2$  of the kinematic fit) are in these cases respectively: the missing mass of the two protons and the invariant mass of the two photons. In this article we focus on the first case: estimate the signal to background ratio and its implications for the statistical uncertainty of the extraction of  $BR(\eta' \rightarrow \pi^+\pi^-\pi^0)$  value.

The signal to background ratio,  $N_S/N_B$ , can be written as:

$$\frac{N_S}{N_B} = \frac{\sigma_{\eta'} \cdot BR \cdot \varepsilon_S \cdot \mathcal{L}}{\Delta\mu \cdot \rho_B \cdot \varepsilon_B \cdot \mathcal{L}}, \quad (3)$$

where the factors are:

1.  $\sigma_{\eta'}$  – the total cross section for the production reaction (here for  $pp \rightarrow pp\eta'$ ),
2.  $\rho_B$  – the differential cross section for the direct  $\pi^+\pi^-\pi^0$  production with the pions invariant mass equal to the mass of the  $\eta'$  meson:

$$\rho_B \equiv \left. \frac{d\sigma_B}{d\mu} \right|_{\mu=m_{\eta'}}, \quad (4)$$

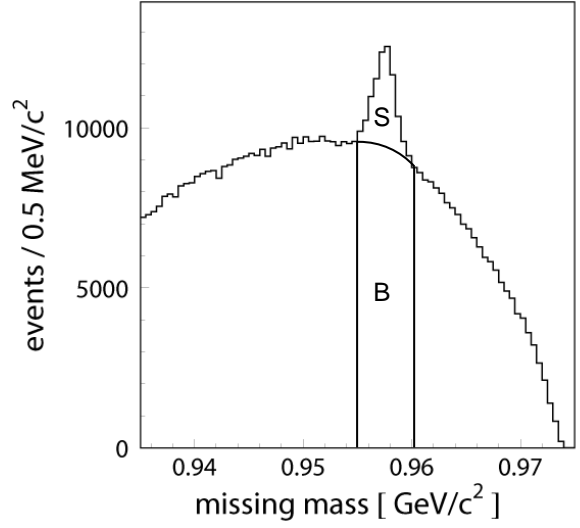
3.  $\varepsilon_S, \varepsilon_B$  – acceptances and reconstruction efficiencies for the signal and the background,
4.  $\Delta\mu$  – a range of the missing mass used for the extraction of the signal it depends on the detector resolution,
5.  $BR$  – the measured branching ratio of the  $\eta' \rightarrow \pi^+\pi^-\pi^0$  decay,
6.  $\mathcal{L}$  – stands for the integrated luminosity.

The  $N_S/N_B$  ratio depends on the beam energy through  $\sigma_{\eta'}$ ,  $\rho_B$ , the missing mass resolution and the detection efficiencies. Hereafter we derive the energy dependence of these quantities.

### 3 Background estimate

The value of the  $\rho_B$  cross section should be determined from the  $\pi^+\pi^-\pi^0$  invariant mass distributions of the direct pion production reaction. However, there is no data at beam energies near the  $\eta'$  meson threshold. Therefore, we estimate an upper limit for the  $\rho_B$  by re-evaluating the available missing mass spectra of the  $pp \rightarrow ppX$  reaction determined by the COSY-11 collaboration at several beam energies near the  $\eta'$  threshold [22,23,24,25]. In Fig. 3 an example of COSY-11 reconstructed missing mass distribution at the  $pp \rightarrow pp\eta'$  excess energy,  $Q$ , of 15.5 MeV is shown [31].

Let us consider a measurement of the two protons from the  $pp \rightarrow ppX$  reaction, where there are no constraints on other outgoing particles. In a first approximation the ratio



**Fig. 3.** An example of the missing mass distribution for the  $pp \rightarrow ppX$  reaction from the COSY-11 measurements at  $Q = 15.5$  MeV [31].  $S$  denotes the signal originating from the  $\eta'$  meson production and  $B$  indicates the background under the peak. The continuum originates from direct production of two, three and more mesons. It provides a conservative upper limit for the background from the  $pp \rightarrow pp\pi^+\pi^-\pi^0$  reaction.

of the number of the background events in a slice under the  $\eta'$  peak in the missing mass spectrum to the number of events in the peak does not depend on the detector acceptance for the protons. This assumption is valid for example if the  $\eta'$  meson and the multipion reactions are simulated according to phase space or even if an universal final state interaction between protons is introduced [48,49]. The assumption may break for example if there will be a significant difference in four momentum transfer distributions between  $\eta'$  and multimeson production. However, the dependence of the production amplitude on the momentum transfer is very weak near the kinematical threshold.

The differential cross section  $\rho_B$  for the background originating from all multimeson channels was determined from the COSY-11 data according to the formula:

$$\rho_B(Q) = \frac{N_B(Q)}{N_S(Q)} \frac{\sigma_{\eta'}(Q)}{\Delta\mu}, \quad (5)$$

which is derived from the following expressions for the  $N_S(Q)$  and  $N_B(Q)$ :

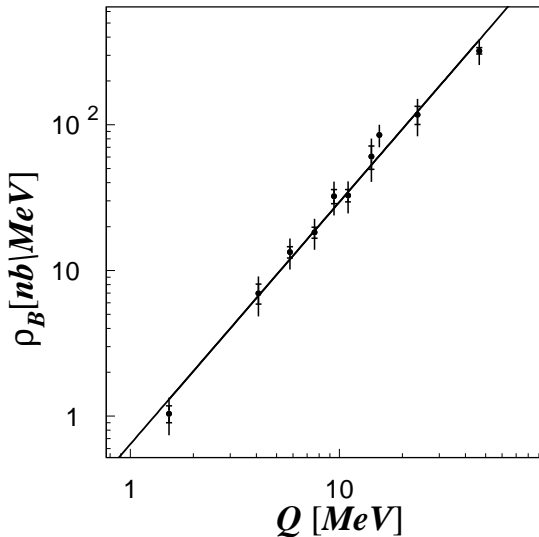
$$N_S(Q) = \sigma_{\eta'}(Q) \cdot \varepsilon(m_{\eta'}, Q) \cdot \mathcal{L}, \quad (6)$$

$$N_B(Q) = \rho_B(Q) \cdot \Delta\mu \cdot \varepsilon(m_{\eta'}, Q) \cdot \mathcal{L}, \quad (7)$$

where  $N_S$  stands for the number of the observed events in the  $\eta'$  peak,  $N_B$  number of the background events in the  $\Delta\mu$  slice under the  $\eta'$  signal,  $\sigma_{\eta'}$  denotes the total cross section for the  $pp \rightarrow pp\eta'$  reaction described according to analytical formula from Eq.2,  $\varepsilon$  denotes combined acceptance and detection efficiency of the COSY-11 detector, which, in a very good approximation, depends only on the mass of the produced system and on the excess energy [48,49],  $\mathcal{L}$  indicates the integrated luminosity. The

Q [MeV]	$\rho_B$ [nb/MeV]	$\Delta\rho_B(stat.)$ [nb/MeV]	$\Delta\rho_B(syst.)$ [nb/MeV]
1.53	1.04	0.14	0.16
4.10	7.0	1.1	1.1
5.80	13.4	1.2	2.0
7.60	18.2	1.6	2.8
9.42	32.3	3.6	4.9
10.98	32.7	3.2	4.9
14.21	60	11	9
15.50	85	2.4	13
23.64	117	17	17
46.60	322	16	48

**Table 1.** Differential cross section  $\rho_B$  for multimeson production in proton-proton collisions as a function of the  $pp \rightarrow pp\eta'$  reaction excess energy  $Q$ . The  $\rho_B$  values were extracted from the experimental data [22, 23, 24, 25] using Eq. 5.



**Fig. 4.** Inclusive differential cross section for multimeson production derived from the COSY-11 data [22, 23, 24, 25]. Statistical and systematic errors are separated by the horizontal bars. The superimposed line shows the function of Eqn. 8 fitted to the COSY-11 data.

width of the  $\Delta\mu$  slice was selected to contain nearly 100% events of the signal peak. The derived values of  $\rho_B$  as a function of  $Q$  with corresponding statistical and systematic errors are given in Table 1 and are shown in Fig. 4. The systematic uncertainties are discussed in [22, 23, 24, 25].

The  $\rho_B$  dependence on the excitation energy is well described by the following parameterization:

$$\rho_B = \alpha(Q/Q_0)^\beta \quad (8)$$

where  $Q_0 = 1$  MeV is the normalization factor and  $\alpha$  and  $\beta$  are the parameters. The fit gives  $\alpha = 0.64 \pm 0.14$  nb/MeV and  $\beta = 1.662 \pm 0.081$ .

## 4 Statistical uncertainty of the BR measurement

Assuming that the shape of the background is known and is not correlated with the signal the relative statistical uncertainty of the branching ratio can be expressed as:

$$\frac{\sigma(BR)}{BR} = \frac{\sigma(N_S)}{N_S} = \frac{\sqrt{N_S + N_B}}{N_S}. \quad (9)$$

In our case  $N_S \ll N_B$  and we have:

$$\frac{\sigma(BR)}{BR} = \frac{\sqrt{N_B}}{N_S} \quad (10)$$

Taking into account Eq. 3 and Eq. 10 one gets the formula for the statistical uncertainty:

$$\sigma(BR) \leq \frac{\sqrt{\rho_B \cdot \Delta\mu \cdot \varepsilon_B}}{\sigma_{\eta'} \cdot \varepsilon_S} \frac{1}{\sqrt{\mathcal{L}}}. \quad (11)$$

From the derived expression one sees that improved tagging resolution ( $\Delta\mu$  decreased) helps only if the detection efficiency is not worsened.

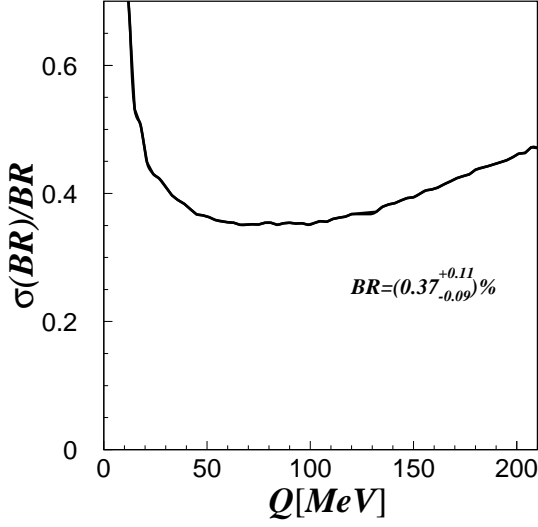
The integrated luminosity  $\mathcal{L}$  can be determined from the simultaneously measured decay  $\eta' \rightarrow \pi^+\pi^-\eta \rightarrow \pi^+\pi^-\gamma\gamma$  with well established branching ratio. Therefore the statistical uncertainty of the luminosity determination can be neglected and many contributions to the systematic uncertainty in the ratio of signal to the monitoring events will cancel.

## 5 Feasibility for a large acceptance detector

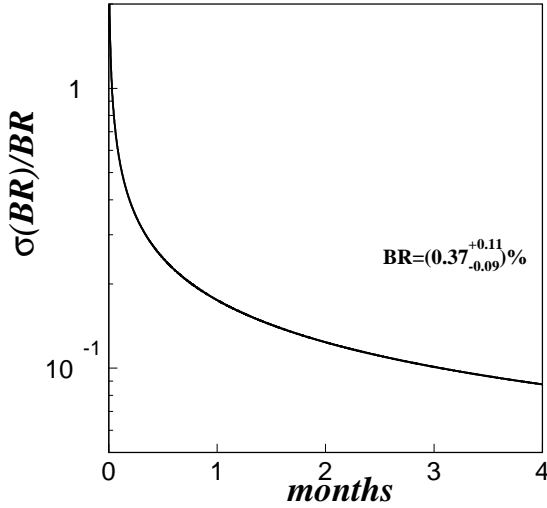
As an example application of the extracted  $\rho_B$  value and the formulas derived in the previous sections we will consider a determination of the branching ratio for the  $\eta' \rightarrow \pi^+\pi^-\pi^0$  decay using a large acceptance detector. The large acceptance is necessary for efficient identification of all outgoing particles. After selection of the  $pp\pi^+\pi^-\pi^0$  final state the direct tree pion production and the  $\eta' \rightarrow \pi^+\pi^-\pi^0$  decay can be distinguished with the best precision using the missing mass of the two forward emitted protons.

For the calculations of the missing mass resolution a typical beam and target parameters available at the Cooler Synchrotron COSY [50] were assumed: beam momentum spread  $\Delta p/p \approx 10^{-3}$  (FWHM), perpendicular beam profiles: horizontal  $\sigma_X=2$  mm, vertical  $\sigma_Y=5$  mm [51]. As a target a hydrogen stream in a cylinder with diameter of 2.5 mm was used. Effective energy resolution of the forward scattered protons from the reaction  $pp \rightarrow pp\eta'$  registered using plastic scintillators is typically in the order of few percent (3%).

The determined  $Q$  dependence of  $\sigma(BR)/BR$  is shown in Fig. 5, assuming one week experiment with luminosity of  $L = 10^{32} \text{cm}^{-2}\text{s}^{-1}$  and value of  $BR(\eta' \rightarrow \pi^+\pi^-\pi^0) = 0.37\%$  [10]. The optimum is reached for the excess energies between 50 and 100 MeV. This is a general conclusion

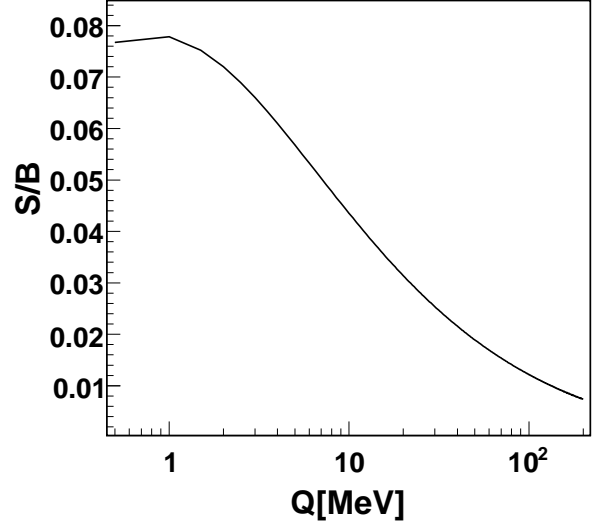


**Fig. 5.** The relative accuracy of the upper limit of the  $BR(\eta' \rightarrow \pi^+\pi^-\pi^0)$  as a function of the excess energy  $Q$  for the  $pp \rightarrow pp\eta'$  reaction.



**Fig. 6.** The relative accuracy of the upper limit of the branching ratio for the decay  $\eta' \rightarrow \pi^+\pi^-\pi^0$  as a function of measurement time in months.

for a large acceptance detection systems. The statistical uncertainty of the branching ratio improves with time of the measurement as  $1/\sqrt{t}$ . The dependence for the beam momentum of  $p_{beam} = 3.45$  GeV/c corresponding to the excess energy  $Q = 75$  MeV is shown in Fig. 6. The plot indicates that for the BR equal 0.37% to achieve the relative accuracy of 10% would require at least two month experiment. However signal to background ratio at this energy will be only about  $10^{-3}$  what puts extreme requirements for the understanding of the systematic effects. Therefore the other strategy for the experiment would be to find a



**Fig. 7.** The signal to background ratio  $S:B$  calculated taking into account the natural width of the  $\eta'$  meson.

compromise between the statistical and systematic uncertainties by going to lower excitation energies where the signal to background ratio increases (Fig.7).

An additional source of background, not discussed here, comes from other decays of  $\eta'$  involving similar particles:  $\eta' \rightarrow \pi^+\pi^-\eta$  and  $\eta' \rightarrow \omega\gamma$ . This background cannot be suppressed using the missing mass method and the invariant masses of the decay products should be used instead.

## 6 Summary

Using the COSY-11 data for the  $pp \rightarrow ppX$  reaction near the  $\eta'$  meson production threshold we extracted an upper limit for the background from the  $pp \rightarrow pp\pi^+\pi^-\pi^0$  reaction for  $\eta' \rightarrow \pi^+\pi^-\pi^0$  decay studies. This and the parameterization of the total cross section energy dependence for the  $pp \rightarrow pp\eta'$  reaction permit us to estimate that two months of the beam time with average luminosity of  $10^{32}\text{cm}^{-2}\text{s}^{-1}$  would be sufficient to reach statistical accuracy of the previous experiments for the studies of  $\eta' \rightarrow \pi^+\pi^-\pi^0$  using a large acceptance detector. However since signal to background ratio for the optimal energy is only about  $10^{-3}$  one may expect much larger systematic uncertainty. Since even taking the natural width of the  $\eta'$  meson the  $S : B$  ratio is about  $10^{-2}$ , this points to inherent limitations of the  $pp \rightarrow pp\eta'$  reaction for the  $\eta' \rightarrow \pi^+\pi^-\pi^0$  decay shown in Fig. 7. Situation is expected to be at least one order of magnitude better for the  $\eta' \rightarrow \pi^0\pi^0\pi^0$  case. Also "not rare" decays  $\eta' \rightarrow \pi\pi\eta$  can be studied in the  $pp \rightarrow pp\eta'$  reaction.

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