Measurement of electric and magnetic polarizabilities with Primakoff reaction at COMPASS

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The COMPASS spectrometer is well suited to perform precise measurements of the pion polarizabilities via the Primakoff reaction $\pi+(Z,A) \rightarrow \pi+(Z,A)+\gamma$. The electric ($\overline{\alpha}_\pi$) and magnetic ($\overline{\beta}_\pi$) polarizabilities characterize the response of the pion quark substructure to the electromagnetic field of the γ during the $\pi\gamma$ scattering. The results of a simulation for the foreseen 2004 setup are presented. The measurement of the pion polarizabilities allows for a test of the chiral perturbation theory (χPT) predictions.

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1 Introduction

The pion electric and the magnetic polarizabilities $\overline{\alpha_\pi}$ and $\overline{\beta_\pi}$ relate the response of the $q\overline{q}$ system to the presence of an external electromagnetic field, providing important information on the internal structure and dynamics of the pion, like its radius or charge [1, 2]. Many different values for the pion polarizabilities have been predicted theoretically. All predictions agree that the sum of $\overline{\alpha_\pi}$ and $\overline{\beta_\pi}$ is a small value, while the difference of these two numbers strongly depends on the theoretical model.

The chiral perturbation theory χPT [3, 4, 5] has been very successful in predicting several low energy ($t < 1(GeV/c)^2$) hadronic properties [1] that, compared with the experimental results, show a good agreement except in the case of the pion polarizabilities. To predict those values χPT expands the $\gamma\pi$ scattering amplitude into powers of photon momenta. The results of the χPT calculation for the pion polarizabilities are:

$$\begin{aligned} \overline{\alpha_\pi} &= (2.4 \pm 0.5) \cdot 10^{-4} \quad fm^3 \\ \overline{\beta_\pi} &= (-2.1 \pm 0.5) \cdot 10^{-4} \quad fm^3 \qquad [6]. \end{aligned}$$

The errors derive from the uncertainties in the low energy constants that are used in the Lagrangian to compute them. Knowledge of the Lagrangian structure in recent years has improved, and an update [7] of these results is needed before comparison with the new data to be produced by the COMPASS experiment. Unfortunately this update is not yet available.

Alternative theoretical approaches use, for example, the application of the dispersion sum rules (DSR)[8, 9, 2], of a QCD sum rule [10], lattice calculations [11] and several models based on the Weinberg [12] and Das-Mathur-Okubo (DMO) sum rules [13], like in the Nambu-Jona-Lasinio (NJL) model [14] or in an extended version of it (ENJL)[15]. The theoretical predictions for $\overline{\alpha_\pi}$ fall in the range $(2.4 - 8.0) \cdot 10^{-4} fm^3$, whereas for $\overline{\beta_\pi}$ vary between $(-8.0 - -2.1) \cdot 10^{-4} fm^3$. A more detailed review of the current status of the theory is given in [16, 17].

2 Previous experimental results

Several attempts have already been made to measure the pion polarizabilities. One is based on the study of the production of $\pi^+\pi^-$ pairs by virtual photon-photon collisions generated in e^+e^- scattering. The result obtained from this measurement is:

$$\overline{\alpha_\pi} = [2.2 \pm 1.6(stat + sys)] \cdot 10^{-4} \quad fm^3 \quad [18]$$

Another approach involves the pion Compton scattering. Since a pion target is not available, the Compton scattering is only indirectly accessible through the radiative pion-photoproduction and the pion radiative scattering. In the radiative pion-photoproduction a real photon scatters on a virtual pion provided by a proton target. This reaction can be clearly distinguished from the background and the result obtained is:

$$\overline{\alpha_\pi} = [20 \pm 12(stat)] \cdot 10^{-4} \quad fm^3 \quad [19]$$

With the same method a high precision experiment was made recently at MAMI [20]. The difference $(\overline{\alpha_\pi} - \overline{\beta_\pi}) = [11.6 \pm 1.5(stat) \pm 3.0(sys) \pm 0.5(mod)] \cdot 10^{-4} fm^3$ [21] was measured. Assuming $\overline{\alpha_\pi} = -\overline{\beta_\pi}$, the value of

$$\overline{\alpha_\pi} = [5.6 \pm 0.75(stat) \pm 3.0(sys) \pm 0.5(mod)] \cdot 10^{-4} fm^3$$

can be deduced.

In the radiative pion scattering a real pion scatters on a virtual photon provided by the nuclear target field. This process is also called the Primakoff reaction. This approach was used by the Serpukhov group [22, 23], to deduce the pion polarizabilities making use of a 40 GeV/c pion beam incident on a carbon target. The results obtained are:

$$\overline{\alpha_\pi} = [6.8 \pm 1.4(stat) \pm 1.2(sys)] \cdot 10^{-4} \quad fm^3 \ [22],$$

assuming $\overline{\alpha_\pi} = -\overline{\beta_\pi}$, and

$$\overline{\alpha_\pi} = [8.5 \pm 4.8(stat) \pm 3.5(sys)] \cdot 10^{-4} \quad fm^3 \ [23],$$

when in the fit of the data $\overline{\alpha_\pi}$ and $\overline{\beta_\pi}$ are taken as independent variables. Both values differ substantially from the χPT predictions $\overline{\alpha_\pi} = 2.4 \cdot 10^{-4} \ fm^3$.

There is no agreement between the experimental results obtained with these different methods [18, 19, 22, 23]. Only [18] fits with the χPT prediction [6]. However to extract this value model dependent assumptions have to be made, that make this agreement doubtful [18, 24].

There is one more way to get pion polarizabilities without measuring directly the $\gamma\pi$ interaction: the use of the DMO sum rule [25]. This method was used by the OPAL and PIBETA collaborations. The results found are respectively: $\overline{\alpha_\pi} = (2.71 \pm 0.88) \cdot 10^{-4} fm^3$ [26] and $\overline{\alpha_\pi} = (2.9 \pm 0.6) \cdot 10^{-4} fm^3$ [27], obtained however implying ($\overline{\alpha_\pi} + \overline{\beta_\pi}$=0). This assumption is not required by χPT [7].

To measure independently $\overline{\alpha_\pi}$ and $\overline{\beta_\pi}$, to be free from any assumption on the value of their sum, high statistics is needed. We plan to extract at COMPASS both quantities separately from the Primakoff reaction data. Therefore the scattering of a 190 GeV/c pion beam on a lead target will be studied, as described in the next section.

3 The Primakoff reaction

A characteristic feature of the Primakoff process, illustrated in Fig. 1, is the sharp dependence of the cross section on t, the square of the four-momentum transferred to the target nucleus. A similar dependence can be seen in the Fig. 2, where

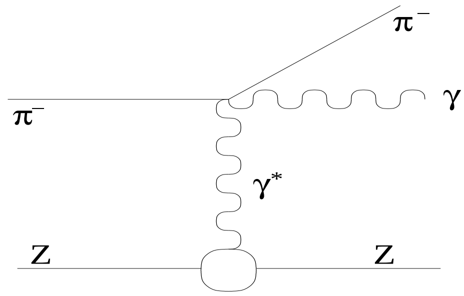


Fig. 1. Radiative pion scattering or Primakoff reaction.

the data collected by the Serpukhov group [29] are plotted, for the expected Primakoff signal. The dominance of the Coulomb amplitude for very small values of t, $t \leq 10^{-3}(GeV/c)^2$, is clear, while the background coming from the strong interaction remains small.

The Primakoff differential cross-section is usually expressed in the rest frame of the incoming pion. In this system, also called anti-laboratory system (alab), this quantity is given by:

$$\frac{d^3\sigma}{dt d\omega dcos\theta} = \frac{\alpha Z^2}{\pi\omega} \frac{t - t_0}{t^2} \frac{d\sigma_{\gamma\pi}(\omega, \theta)}{dcos\theta} |F_A(t)|^2 \tag{1}$$

where $t_0 = (\frac{m_\pi \omega}{p_{beam}})^2$, m_π is the pion mass, ω is the energy of the virtual photon in the alab system obtained through the measurement of the momenta of the incoming (p_{beam} in the laboratory frame) and scattered pions and the energy of the real photon. θ is the angle between the real photon and the virtual photon directions

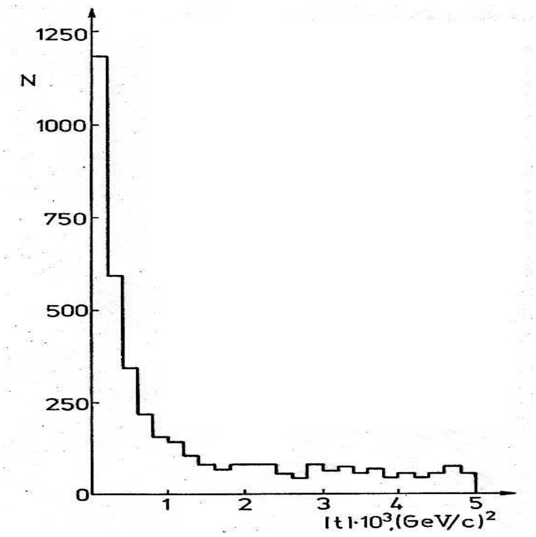


Fig. 2. t-dependence of the yield measured at Serpukhov [29].

in the alab system, α is the fine structure constant, Z is the charge of the nuclear target, $F_A(t)$ is the electromagnetic form factor of the nucleus ($F_A(t) \approx 1$ in the range of $t < 10^{-3}(GeV/c)^2$). The $d\sigma_{\gamma\pi}/dcos\theta$ describes the $\gamma\pi$ scattering at the upper vertex of Fig. 1. It contains the pion polarizabilities $\overline{\alpha}_\pi, \overline{\beta}_\pi$:

$$\frac{d\sigma_{\gamma\pi}(\omega,\theta)}{dcos\theta} = \frac{2\pi\alpha^2}{m_\pi^2} \cdot \left(F_{\pi\gamma}^{Co} + \frac{m_\pi \omega^2}{\alpha} \cdot \frac{\overline{\alpha_\pi}(1+cos^2\theta) + \overline{\beta_\pi} cos\theta}{(1+\frac{\omega}{m_\pi}(1-cos\theta))^3} \right) \tag{2}$$

Here $F_{\pi\gamma}^{Co}$ describes the differential Compton cross section for a photon scattering on a pointlike spin-0 particle, and is given by:

$$F_{\pi\gamma}^{Co} = \frac{1}{2} \cdot \frac{1+cos^2\theta}{\left(1+\frac{\omega}{m_\pi}(1-cos\theta)\right)^2}. \tag{3}$$

The second term in the brackets of eq. 2 is the correction for a non-pointlike pion. The pion structure is described by the electric ($\overline{\alpha}_\pi$) and magnetic ($\overline{\beta}_\pi$) polarizabilities. The cross section mainly depends on ($\overline{\alpha}_\pi + \overline{\beta}_\pi$) at small angles and on ($\overline{\alpha}_\pi - \overline{\beta}_\pi$) at large θ angles in the alab system.

From eq. 1 it can be deduced that the t-dependence of the cross section favours the choice of higher pion beam momenta where smaller values of t_0 can be reached, whereas the Z^2 dependence in the cross section supports the choice of a heavy target. At COMPASS we plan to perform the measurement with a negative pion beam of 190 GeV/c and with a Pb target. The target thickness will be limited to 0.5 radiation length (X_0) to minimize the multiple scattering effects. For consistency additional targets (Cu, C) will be used to check systematics e. g. for background subtraction. With a beam intensity up to 2×10^7 π per second we will collect a statistics significantly larger than that obtained at Serpukhov.

The reconstruction of the complete final state, measuring simultaneously the pion momentum components, the energy and the emission angle of the photon, is mandatory to select this reaction from the background. A very good resolution in t is the most stringent requirement for the data analysis. All the features of the COMPASS setup that will be used for this measurement can be found elsewhere [30]. The details on the test runs for the trigger and on trigger setup can be found respectively in [31] and in A. Ferrero's report written for this conference [32].

4 The Monte Carlo simulation

To check the feasibility of the Primakoff measurement at COMPASS, Monte Carlo simulations [28, 33, 34, 35, 36] were performed. The events were generated by the Polaris software [37] according to the cross section reported in eq. (1) in the alab system, with a 190 GeV/c negative pion beam, then transformed to the lab system. The photon energy in the lab was required to be $E_\gamma > 90$ GeV in order to study the response of the apparatus to the so called "hard-events". This kinematical region corresponds to the backward events in the alab system where the influence on the cross section due to the second term in eq. (2) becomes more evident. The events produced were processed by COMGEANT [38], a simulation program based on GEANT [39], developed in accordance with the COMPASS apparatus requirements. Then the hits left in the detectors, digitalized with the their typical resolution were inserted into the reconstruction software CORAL [40]. After this the kinematical parameters of the beam, the scattered pion and the photon are available at the target point.

A typical reconstructed event, in the COMPASS experimental setup, can be seen in Fig. 3. Only charged tracks are displayed.

The energy spectra of the pion and the photon are shown in Fig. 4 and 5 respectively. To produce them a coincidence is required between a pion hit in the Primakoff hodoscope (Fig. 3) and a photon in the electromagnetic calorimeter (ECAL2) . As we can see from Fig. 4, the very low momentum pions ($0 \div 20$ GeV/c) fall outside the acceptance of the Primakoff hodoscope. Therefore to recover them a second trigger (not requiring the hodoscope information, but asking for a photon energy deposit into ECAL2 greater than 100 GeV) has been introduced.

The overall resolution was $\frac{\delta p}{p} = 0.35\%$ on the pion momenta and $\frac{\delta E}{E} = 2.5\%$ for the photon energy. The corresponding resolution on the t variable is $3 \cdot 10^{-4} (GeV/c)^2$, as illustrated in Fig. 6.

This resolution is sufficient to clearly separate the Primakoff reaction from the strong process. The reconstruction efficiency for the Primakoff events is plotted in Fig. 7. The efficiency distribution is flat in the region of interest, where the cross

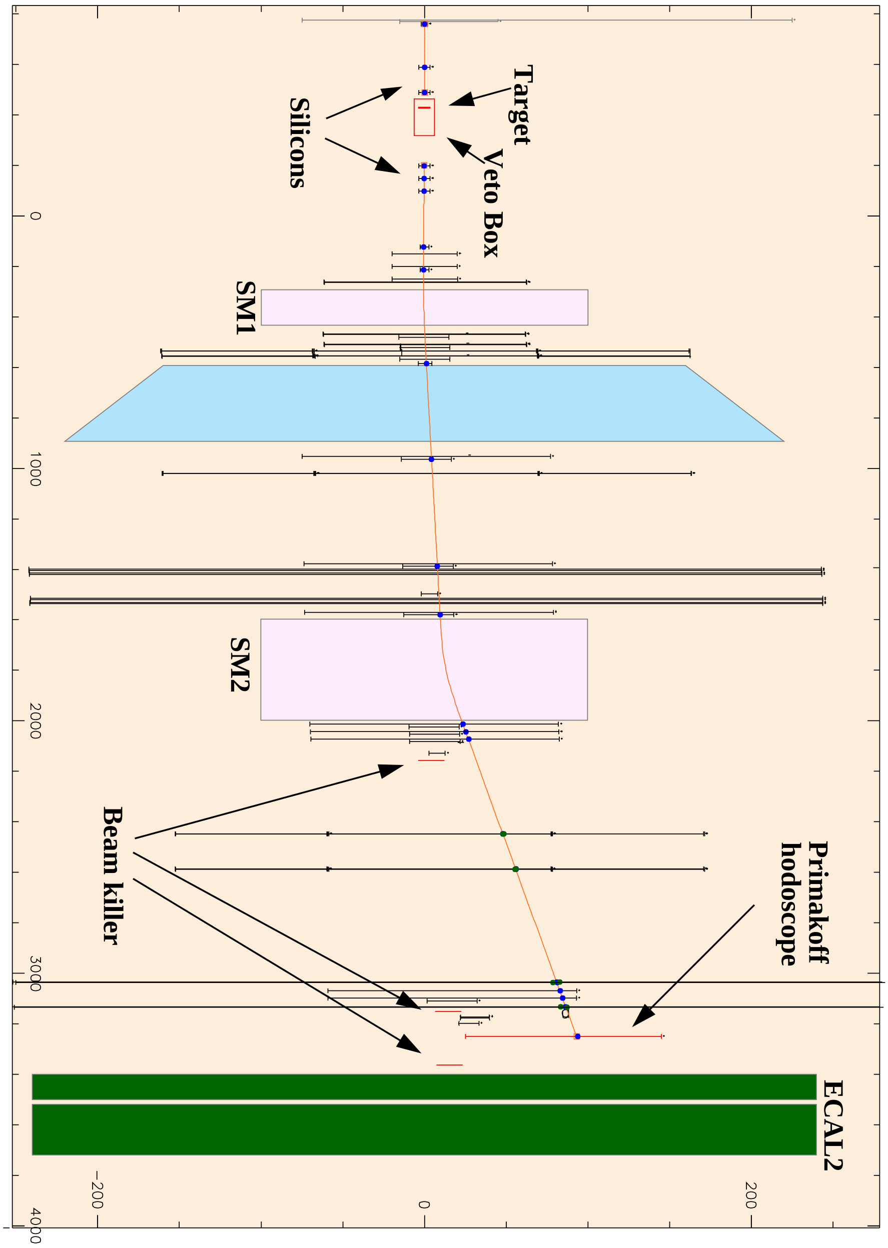


Fig. 3. A typical reconstructed event in COMPASS hadron setup.

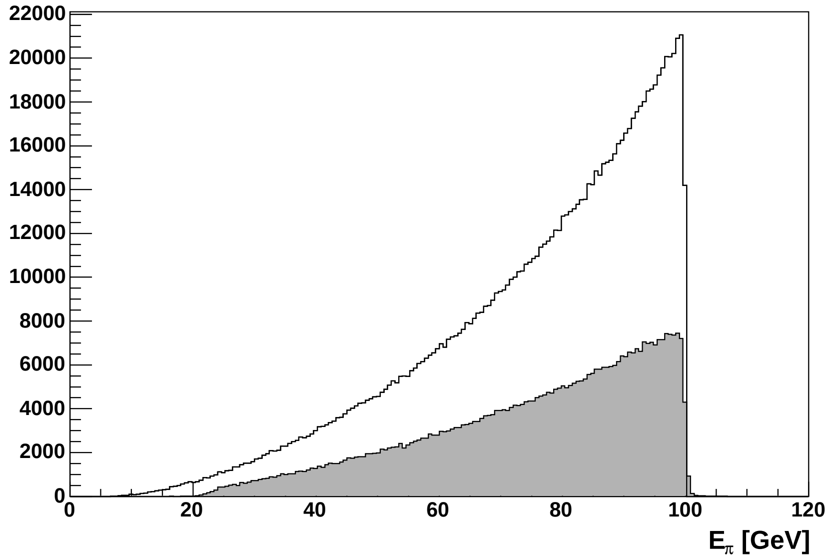


Fig. 4. Distributions of the pion momentum generated (white) and reconstructed (shaded) in the lab system.

section varies rapidly with t. Therefore the apparatus acceptance does not bias the distribution.

5 Expected statistics for the pion polarizabilities measurement

The precision on the measurement of the pion polarizabilities ($\overline{\alpha_\pi}, \overline{\beta_\pi}$) we want to achieve, can be inferred from the comparison with the Serpukhov data. In that experiment the statistical precision on $\overline{\alpha_\pi}$ was $\pm 1.4 \cdot 10^{-4} fm^3$ for a total flux of $2 \cdot 10^{11}$ pions. Assuming a beam momentum of 190 GeV/c and pion beam flux of $2.47 \cdot 10^{11} \pi$/day, an interaction probability $R = \sigma N_T = 5 \cdot 10^{-6}$, computed assuming a total cross section of σ =0.5 mbarn for the region of interest ($E_\gamma > 90$ GeV) and a number of Pb nuclei $N_T = 10^{-22}$ cm^{-2} in the target, we get $1.24 \cdot 10^6$ Primakoff events per day. This number has to be corrected for: the track reconstruction efficiency (92%), the photon detection efficiency (58%), the accelerator and COMPASS availability (60%), cuts to reduce background (25 % - 75%), resulting in a global efficiency of 8% - 24%. Therefore at least 10^5 useful events/day are expected, which is more than the total statistics of $6 \cdot 10^3$ events collected at Serpukhov [22]. With the foreseen amount of data the fit can be performed with and without the constraint ($\overline{\alpha_\pi} = -\overline{\beta_\pi}$), allowing for an independent measurement of these two values with a statistical error negligible versus the systematical one, that is estimated to be of the order of $0.4 \cdot 10^{-4} fm^3$ [30]. The COMPASS spectrometer

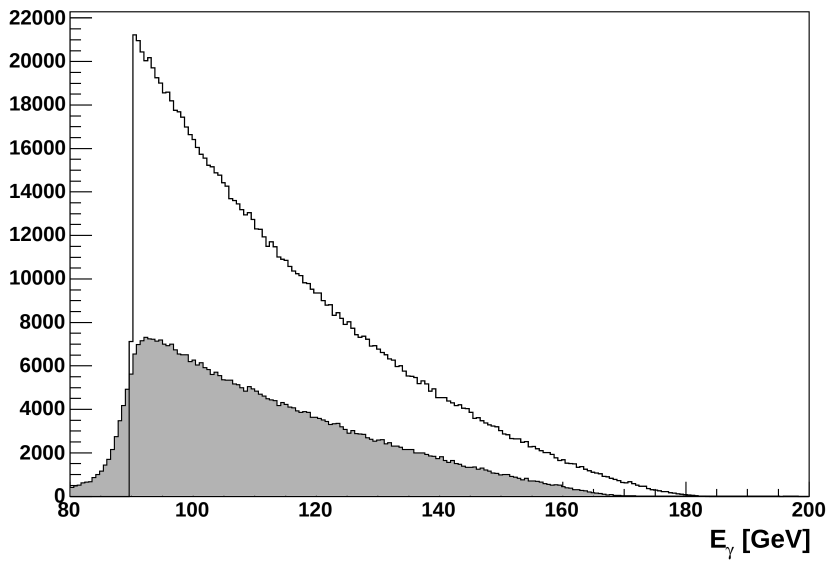


Fig. 5. Distributions of the photon energy generated (white) and reconstructed (shaded) in the lab system.

offers the possibility to measure independently the pointlike factor of eq. 2 using a muon beam without further change in the apparatus. This fact will allow for a better study of the systematic effects in the data analysis.

6 The measurements of the kaon polarizabilities

The beam contains also about 4.5% of kaons, that can be selected with Cerenkov detectors, allowing to measure for the first time the kaon electric and magnetic polarizabilities [41]. We plan to tag the kaons using the Cerenkov Differential counters with Achromatic Ring focus (CEDAR)[42] already available on the beam line. Assuming a CEDAR efficiency of 0.5, a kaon flux of $4.5 \cdot 10^5$K/s, we hope to get $\simeq 2 \cdot 10^3$ events/day. This number has been computed scaling eq. (2) with the kaon mass. A measurement of the kaon polarizabilities with good statistical significance could then be performed at COMPASS at the same time of the pion data taking.

7 The chiral axial anomaly

In addition to the single photon detection and because of the good spatial resolution ($\sigma = 2mm$) of the ECAL2, we can detect events with two photons in coincidence to reconstruct the π^0 mass. This allows us to study the process $\pi^- + (Z, A) \rightarrow \pi^- + (Z, A) + \pi^0$ (see Fig. 8) in parallel to the polarizability data

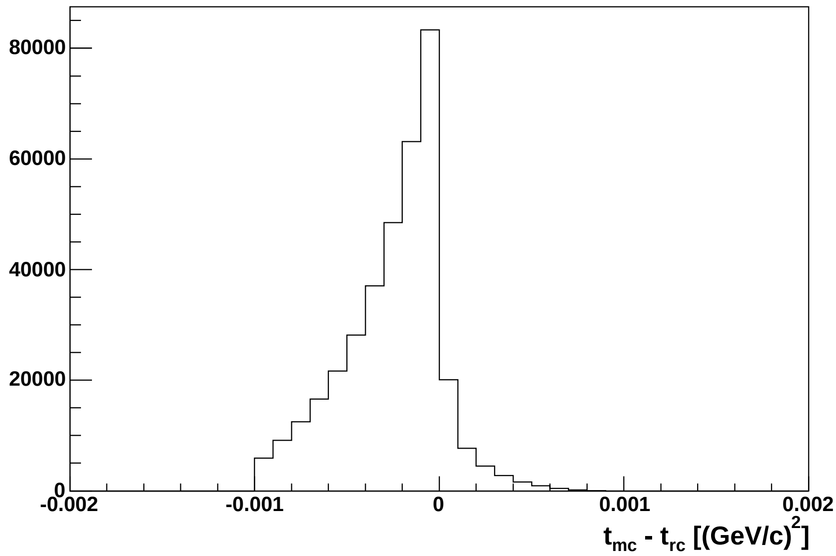


Fig. 6. Resolution in the four-momentum transfer t.

taking and to measure the production cross section [43] for this reaction given by the following formula in the center of mass system of $\gamma\pi$:

$$\frac{d\sigma}{dsdtdq^2} = \frac{Z^2\alpha}{\pi}\left(\frac{q^2 - q^2_{min}}{q^4}\right)\frac{1}{s - m^2_\pi}\frac{d\sigma_{\gamma\pi\to\pi\pi}}{dt} \tag{4}$$

This cross section is expected to be large, since it is proportional to the square of the nucleus charge Z. The term $d\sigma_{\gamma\pi\to\pi\pi}$ represents [44] the elementary process $\gamma\pi \to \pi\pi$ illustrated in the upper vertex of the diagram in Fig. 8, where the relevant kinematical variables are also defined. Its expression is given by:

$$\frac{d\sigma_{\gamma\pi\to\pi\pi}}{dt} = \frac{(F_{3\pi})^2}{128\pi}\frac{1}{4}(s - 4m^2_\pi)sin^2\theta \tag{5}$$

where θ is the π^- scattering angle in the center of mass system, $F_{3\pi}$ is the coupling constant for the $\gamma \to 3\pi$ process, related to F_π, the coupling constant of $\pi^0 \to \gamma\gamma$, through the low energy theorem [46]. The π^0 lifetime results given by the chiral anomaly hypothesis are in excellent agreement with the experimental data [45]. Therefore a confirmation of the chiral anomaly hypothesis by means of $F_{3\pi}$ is important and can be done studying this reaction channel.

The theoretical prediction is: $F_{3\pi} = 9.7 \pm 0.2$ GeV^{-3}[47], while in an experiment performed at Serpukhov [48] $F_{3\pi} = 12.9 \pm 0.9 \pm 0.5$ GeV^{-3} was found from a sample of only 200 events. The discrepancy between the theoretical and the experimental

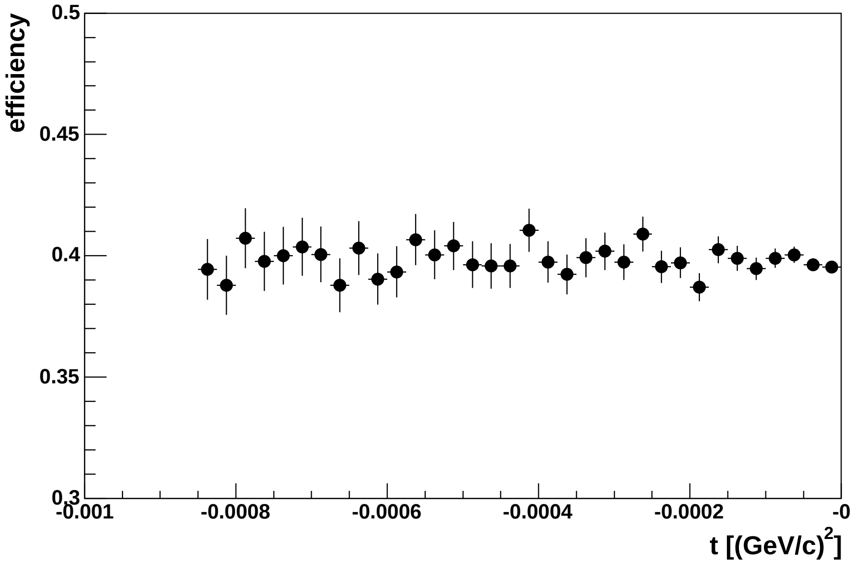
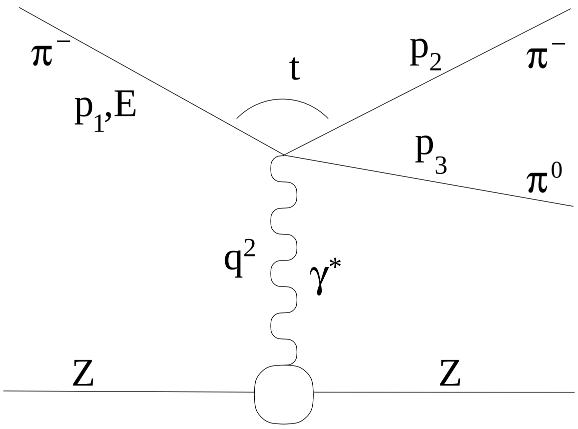


Fig. 7. Total detection efficiency vs the t-variable.



$$t = (p_1 - p_2)^2$$

$$s = (p_2 + p_3)^2$$

$$q_{min} = \left(\frac{s - m_\pi^2}{2E}\right)$$

Fig. 8. The reaction $\pi^- + (Z, A) \rightarrow \pi^- + (Z, A) + \pi^0$.

values of $F_{3\pi}$ is larger than 2.3 σ. Therefore new high precision experiments are needed to clarify the situation.

The event rate expected at COMPASS is of about $5 \cdot 10^3$/day, which is more than 25 times what was collected in the Serpukhov experiment. The 4.5% contamination of kaons in the beam will be tagged by the CEDAR detectors to avoid the $K^- \rightarrow$

$\pi^- + \pi^0$ decay, that is a major background at small t. The error on $F_{3\pi}$ will be considerably reduced and we will be able to make a comparison with the theoretical prediction at the level of the theoretical error.

8 Conclusion

The Primakoff program of the COMPASS experiment is scheduled to run in 2004 with a possible extension in 2006 as part of a wider hadron program. The COMPASS experiment can provide a more precise measurement of the pion polarizabilities, the first measurement of kaon polarizabilities and an important check of the chiral anomaly hypothesis.

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