MEASUREMENTS OF π AND K POLARIZABILITY @ COMPASS

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Abstract

The COMPASS spectrometer is specially suited to perform a precise measurement of the pion-polarizabilities through the Primakoff reaction $\pi + Z \to \pi + Z + \gamma$. The results of a simulation are presented. An overall error of the measured polarizabilities comparable with the theoretical uncertainty can be obtained, making possible a clean test of the chiral symmetry polarizability prediction.

1. INTRODUCTION

The response of a particle, thought of as a composite structure of quarks, to an external electromagnetic field is described by its electric $\overline{\alpha}$ and magnetic $\overline{\beta}$ polarizabilities. These are fundamental quantities whose understanding is of great importance in any model or theory of the strong interactions, because the knowledge of these two quantities is an essential piece of information to check fundamental symmetry relations like the chiral symmetry.

The Chiral Perturbation Theory, χPT, based on the assumption of the chiral symmetry conservation, predicts for the two pion polarizabilities the values [1]:

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

The error on $\overline{\alpha_\pi}$ and $\overline{\beta_\pi}$ is due to the uncertainty in the knowledge of the axial and vector coupling constants that were measured in the radiative pion decay, where the polarizability can be expressed [2] as:

$$\overline{\alpha_\pi} = \frac{4\alpha_F}{m_\pi f_\pi^2}(L_r^9 - L_r^{10}),$$

where L_r^i are the chiral Lagrangian renormalization coupling constants.

Different experimental approaches have been used to deduce the pion polarizabilities. An approach involves the production of a $\pi^+\pi^-$ pair in e^+e^- collisions as a way to study the reaction $\gamma\gamma \to \pi^+\pi^-$, as shown in Fig. 1. The result [3]:

$$\overline{\alpha_\pi} = (2.2 \pm 1.6_{stat+sys}) \cdot 10^{-4}\ \mathrm{fm}^3$$

is obtained using dispersion relation. This result is, however, based on some model-dependent assumption and has, therefore, not to be considered as a pure experimental result.

Polarizabilities can also be measured via 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.

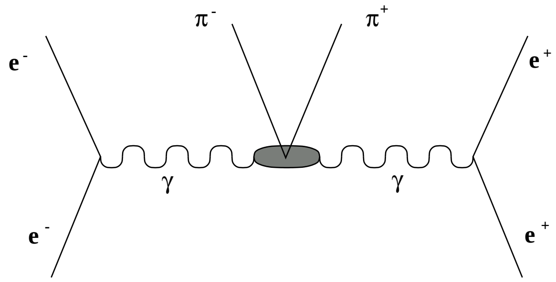

Fig. 1: Photon–photon collision.

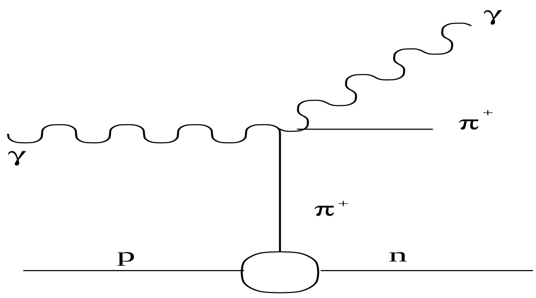

Fig. 2: Radiative pion photoproduction.

In the pion photoproduction a real photon scatters on a virtual pion $\gamma p \rightarrow \gamma\pi^+ n$ (see Fig. 2). With this process the following result was obtained [4]:

$$\overline{\alpha_\pi} = (20 \pm 12_{stat}) \cdot 10^{-4}\ \mathrm{fm}^3$$

The problem with such an approach is how to handle the final-state interaction between the produced pion and the scattered neutron.

Another way to deduce the pion polarizability is to make use of the radiative pion scattering $\pi^- Z \rightarrow \pi^- Z\gamma$, where the problem of final-state interactions, discussed before, is not present, because of the different interaction lengths of the strong and electromagnetic interactions. In the process considered here, also called Primakoff reaction, a real pion scatters on a virtual photon provided by the nuclear field (see Fig. 3). This approach allows for a simultaneous measurement of $\overline{\alpha_\pi}$ and $(\overline{\alpha_\pi} + \overline{\beta_\pi})$, therefore a check of the chiral symmetry relation between $(\overline{\alpha_\pi}$ and $\overline{\beta_\pi})$. This reaction has been used by the Serphukov group [5–7], studying the scattering of 40 GeV/c pion on a ^{12}C target. The result obtained is:

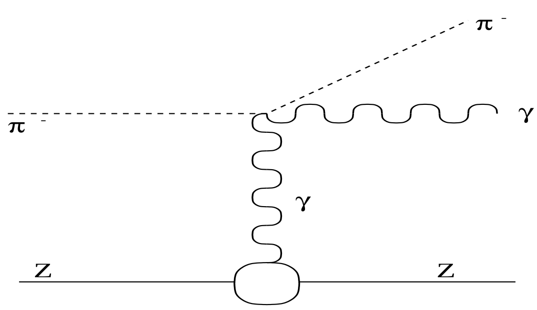

Fig. 3: Radiative pion scattering.

$$\overline{\alpha_\pi} = (6.8 \pm 1.4_{stat} \pm 1.2_{sys}) \cdot 10^{-4}\ \mathrm{fm}^3$$

assuming $(\overline{\alpha_\pi} + \overline{\beta_\pi}) = 0$ [5] and

$$(\overline{\alpha_\pi} + \overline{\beta_\pi}) = (1.4 \pm 3.1_{stat} \pm 2.5_{sys}) \cdot 10^{-4}\ \mathrm{fm}^3$$

without this assumption [6]. The value of $(\overline{\alpha_\pi} + \overline{\beta_\pi})$, here obtained as an independent measurement, is compatible with zero. The value of $\overline{\alpha_\pi} = 6.8 \cdot 10^{-4}\ \mathrm{fm}^3$ substantially differs from the χPT prediction $\overline{\alpha_\pi} = 2.4 \cdot 10^{-4}\ \mathrm{fm}^3$.

The experimental results of different experiment given here are very different and disagree with the χPT predictions, with the exception of [3], where the error bar is significantly larger than the theoretical uncertainty. Therefore new experiments are needed to measure $\overline{\alpha_\pi}$ and $\overline{\beta_\pi}$ with a statistical significance comparable with the uncertainty estimated by the theory. The COMPASS spectrometer is specially suited to perform a precise measurement of these two quantities, as part of the global Primakoff programme [8]. For this purpose we plan to measure the polarizabilities $\overline{\alpha_\pi}$ and $\overline{\beta_\pi}$ with a 190 GeV pion beam scattered on a lead target. The choice of the energy and the target will be discussed in Section 2.

2. THE PRIMAKOFF REACTION

A characteristic of the Coulomb scattering is the sharp dependence of the cross section on t, the four-momentum transfer from the incoming pion to the target nucleus. The t-dependence of $d\sigma/dt$, measured at the Serphukov experiment [7], is presented in Fig. 4. The dominance of the Coulomb amplitude for $t \leq 10^{-3}(\mathrm{GeV}/c)^2$ is evident, while the background coming from the strong interactions remains small.

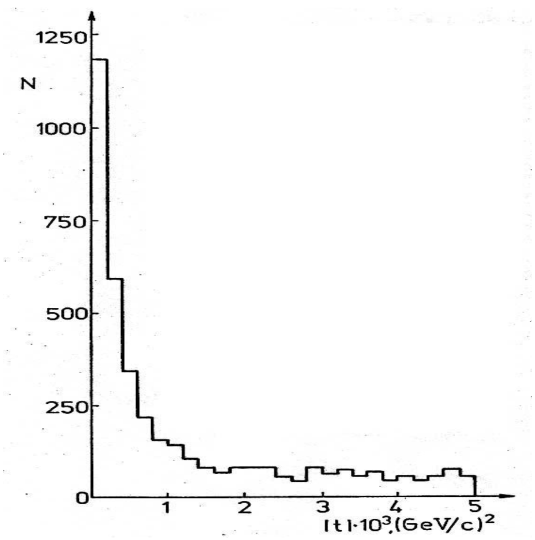

Fig. 4: t-dependence of $d\sigma/dt$ measured at Serphukov.

The Primakoff differential cross section for a pion scattering on a nucleus in the anti-laboratory frame (alab), the pion rest frame, is described by this formula:

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

where t is the four-momentum transfer, $t_0 = (\frac{m_\pi \omega}{p_{beam}})^2$, m_π is the pion mass, ω is the energy of the virtual photon in the alab system, p_{beam} is the momentum of the incoming pion in the laboratory frame, θ is the

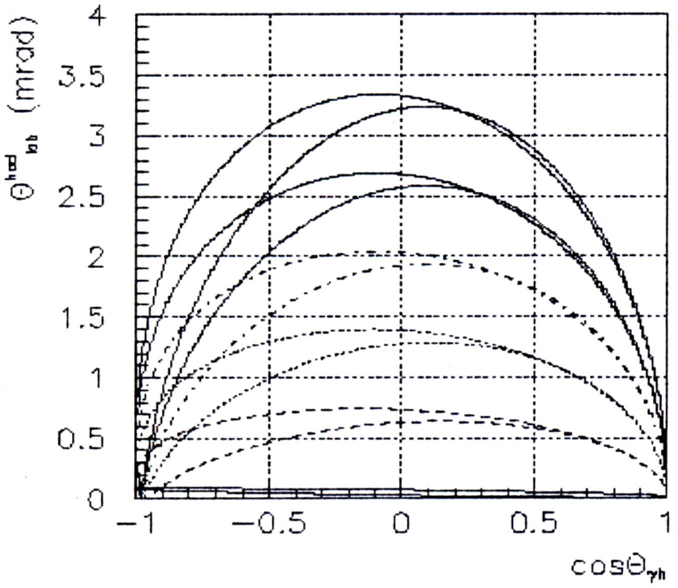

Fig. 5: Pion scattering angle in the lab system vs pion-photon angle in the alab system. The different curves correspond to increasing photon energies in the alab system from the lowest (dashed curve) to the highest value (full curve).

scattering angle of the real photon relative to the incident virtual photon direction in the alab system, α_f is the fine structure constant, Z is the charge of the nuclear target, $F_A(t)$ is electromagnetic form factor of the nucleus ($F_A(t) \approx 1$ in the range of $t < 10^{-3}(\mathrm{GeV}/c)^2$). In Eq. (1) the dependence on the pion polarizability is included in the cross section $\frac{d\sigma_{\gamma\pi}}{d\cos\theta}$, given by:

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

The first term in the parenthesis represents the Thomson cross section for the γ scattering on a point-like particle given by:

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

The second term expresses the correction for a non-pointlike particle. It describes the structure of the pion through the polarizabilities $\overline{\alpha_\pi}$ and $\overline{\beta_\pi}$.

The general behaviour of this cross section is characterized by the dependence on ($\overline{\alpha_\pi} + \overline{\beta_\pi}$) at forward angles and on ($\overline{\alpha_\pi} - \overline{\beta_\pi}$) at backward angles in the alab system.

In the COMPASS experiment this measurement will be performed at the beam momentum of 190 GeV/c, higher than that used at Serphukov. This choice allows for lower t values, where the cross section is higher. For the first measurement we have chosen a lead target, instead of carbon, because of the Z^2 dependence in the cross section. We can also use an higher beam intensity (up to 2×10^7 π's per second) and therefore collect a statistics significantly larger than that collected in the Serphukov experiment.

The kinematics of the scattering of a 190 GeV/c pion beam on a lead target shows the existence of a limit angle for the pion. In Fig. 5 the relation between the pion angle in the laboratory system versus the angle between the scattered pion and photon in the alab system is shown. The different lines correspond to different energies for the virtual photon hitting the pion in the alab system. The limit angle is about 3.5 mrad.

For small t values the scattered pion is close to the non-scattered pion beam, therefore to identify the Primakoff reaction it is mandatory to reconstruct the complete final state, measuring simultaneously the pion momentum components, the energy and the emission angle of the photon. A good resolution on the reconstructed momentum transfer is one of the most stringent experimental requirements in order to well separate this reaction from the background due to the strong interactions.

3. TRIGGER

The COMPASS experimental setup has already been described in detail in other contributions. Therefore we give here in Fig. 6 a schematic view of the apparatus as needed to study $\overline{\alpha_\pi}$ and $\overline{\beta_\pi}$ polarizabilities. To select the Primakoff reaction, we need to identify and reconstruct the complete final state, detecting and measuring both the pion and the photon.

The total cross section for the Primakoff scattering is small, if compared to the total inelastic cross

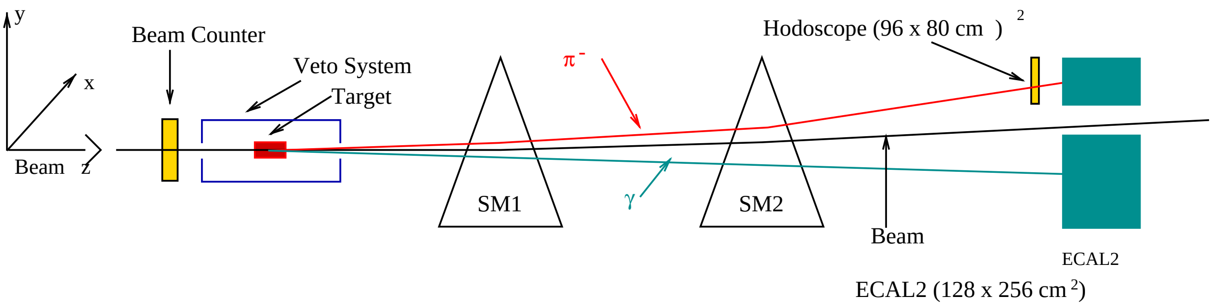

Fig. 6: The trigger.

section. Therefore, to get the high statistics needed to extract the polarizabilities, a high-intensity beam and a good acceptance are required. This implies for the trigger system, that it should act as a beam killer by accepting only the Primakoff scattered pions, and suppressing the large background associated with the non-interacting pions of the beam. In addition it should not cut the acceptance for the photon emitted at backward angles in the alab system, where the effects of the polarizabilities are more evident.

Trigger studies were performed during the test runs. The setup is illustrated in Fig. 6. It consists of a beam counter upstream of the target, a veto system around the target, a beam veto counter (beam killer) in front of ECAL2, and a hodoscope situated in front of ECAL2, displaced by 20 cm from the centre of the deflected beam. The trigger used was the coincidence of a signal in the beam counter with a photon that left an energy larger than $((0.2 \div 0.3) \times E_{beam})$ in ECAL2 and with a charged particle in the hodoscope.

From the test runs, with a beam intensity of $6 \cdot 10^6$ π/spill on a 3 mm lead target, the trigger rate was 2.5×10^5 events/spill [9]. This result is obtained without the beam killer and the veto counter. Their inclusion in the trigger does not decrease significantly the trigger rate. A further reduction of the number of events will be done offline using the target veto to reject background reactions with large momentum transfer to the target. The trigger rate reached is fully compatible with the capability of the data taking.

4. MONTE CARLO SIMULATION

To check the feasibility of our experiment, we [8, 10–12] made a Monte Carlo simulation with the following assumption: the pion and photon pass through the setup simulating the response of the apparatus to their interactions. The hits produced in the detectors are then used by the track reconstruction software to get the pion momentum components and the photon energy and emission angle at the target. The event

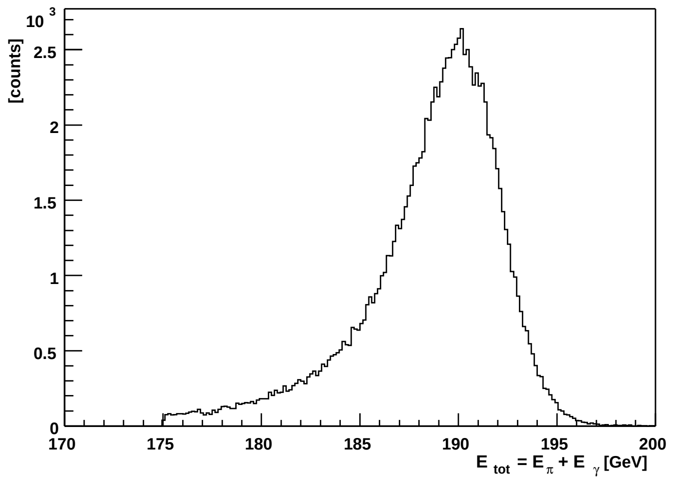

Fig. 7: Total energy of the $\pi\gamma$ pair.

generator was the program POLARIS [13] that produced Primakoff events according to the cross section given in Eq. (1) with $p_{beam} = 190$ GeV/c and with a lead target 1.7 mm thick. Only the events satisfying that, the photon energy $E_\gamma > 90$ GeV, were kept. With this cut the contribution of the polarizability term [see Eq. (1)] is emphasized versus the pointlike term $F^{Th}_{\pi\gamma}$.

These events were then processed by the POLTOGEA interface to adapt the database configuration to that required as an input to COMGEANT. COMGEANT [14] is a simulation software based on GEANT 3.21 [15] and developed according to the COMPASS Initial Layout requirements. This code traces the pion and the photon throughout the whole apparatus taking into account all the possible interactions with the detectors and with any other material they cross. The hits corresponding to the interaction points in the sensitive detectors were stored in a ZEBRA file that is the input for the reconstruction program CORAL: COMPASS Reconstruction and AnaLysis program [16], developed using object-oriented techniques. In CORAL, this input is digitized taking into account the proper experimental resolution of each detector. Then the retracking of the pion and the photon is performed to get at the target their kinematics variables. The sets of the generated (MC) and the reconstructed (RC) variables are then compared to evaluate the performance of our apparatus for the study of this specific reaction.

A first consistency check was made on the energy conservation. The energy E_γ of the photon detected in the electromagnetic calorimeter ECAL2 and the energy of the pion E_π obtained through the retracking were summed up and compared to the beam energy. The result is shown in Fig. 7. It can be seen that the peak is correctly centred at the beam energy of 190 GeV. The asymmetric tail on the low-energy side reflects the energy loss in the interactions with the apparatus. We selected only the events following the (180÷196) GeV cut. The reconstruction efficiency versus the four-momentum transfer squared for these events is plotted in Fig. 8.

The efficiency distribution is flat in the region of interest of t. There is no need for a t-dependent correction where the Primakoff cross-section varies very rapidly with t, as show in Fig. 4. So any cut on the t variable will not affect the detection efficiency.

To distinguish the Coulomb scattering from the strong interaction and in particular from the diffractive scattering $\pi Z \to \pi Z \gamma\gamma$, a good resolution on the transverse transfer momentum is necessary. A good selection between the single and multiple photons is also required by ECAL2. Typical values of the transverse momentum are: 0.1 GeV/c for the Primakoff reaction and 1 GeV/c for the diffractive scattering.

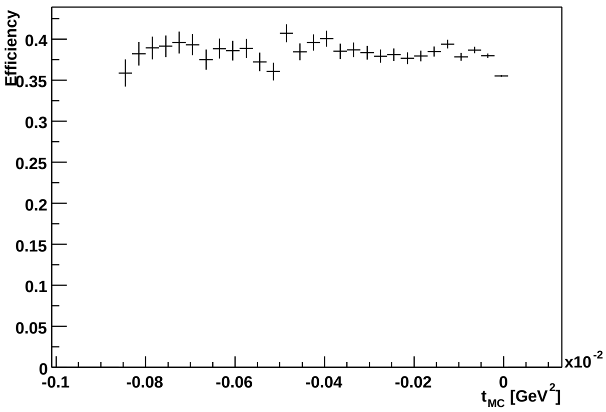

Fig. 8: Total efficiency vs t.

The transverse transfer momentum can be expressed in the following way:

$$p_T = \sqrt{(p_{x_\pi} + p_{x_\gamma})^2 + (p_{y_\pi} + p_{y_\gamma})^2} \tag{4}$$

id est

$$p_T = \sqrt{(p_X)^2 + (p_Y)^2} \quad . \tag{5}$$

In Figs. 9, 10 are reported the resolution for the transverse component of the four-momentum transfer. The resolution found on p_T was $\sigma(p_T) \approx 18\ \mathrm{MeV}/c$. This resolution is sufficient to clearly distinguish the Primakoff and the diffractive process. The effect of this resolution on p_T on the t dependence in the cross section is shown in Fig. 11.

5. CONCLUSION

If we compare our results with the corresponding data obtained by the Serphukov experiment, we can infer the expected precision of the polarizabilities. In that experiment the statistical precision in $\overline{\alpha_\pi}$ was $\pm 1.4 \cdot 10^{-4}\ \mathrm{fm}^3$ with the total flux of $2 \cdot 10^{11}$ pions. Assuming a lead target, a beam momentum of $190\ \mathrm{GeV}/c$ and a pion flux of $2 \cdot 10^7\ \pi/\mathrm{s}$ we expect to measure $\overline{\alpha_\pi}$ with an overall error of $\approx 0.4 \cdot 10^{-4}\ \mathrm{fm}^3$. This error is comparable with the theoretical error computed for pion polarizability. We hope to get a similar error also for the sum $(\overline{\alpha_\pi} + \overline{\beta_\pi})$. To get this number we made the following assumption: an overall flux of $3.2 \cdot 10^{11}$ pions per day, an interaction probability $R = \sigma N_T \ = \ 5 \cdot 10^{-6}$, computed

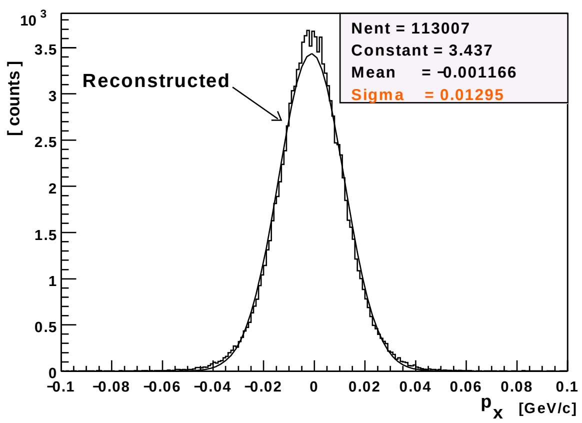

Fig. 9: p_X resolution.

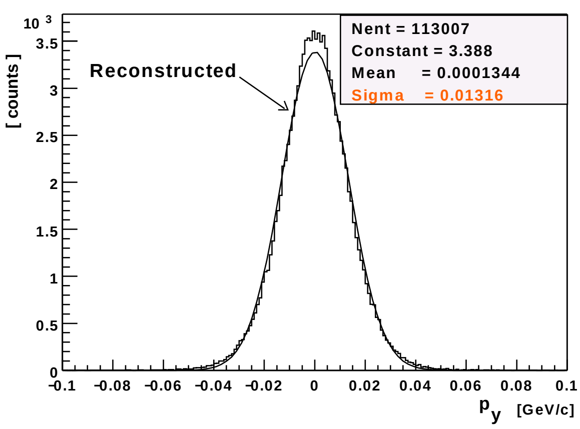

Fig. 10: p_Y resolution.

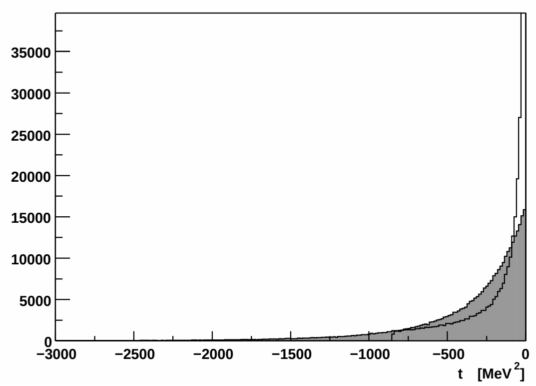

Fig. 11: Generated (white) and reconstructed (shaded) t distribution.

assuming $\sigma = 0.5$ mbarn and $N_T = 10^{-22}\mathrm{cm}^{-2}$, that gives $1.6 \cdot 10^6$ Primakoff polarizability events per day. Other input were tracking efficiency (92%), photon detection (58%), accelerator and COMPASS operation (60%), cuts to reduce background (75%), so a global efficiency of 24%. The result is that we expect to get $4 \cdot 10^5$ useful events per day, which is more then the total statistic, 7000 events, collected by the Serphukov experiment during the whole data taking. With such a statistical significance the measurement of the pion polarizabilities with the Primakoff reaction at COMPASS will allow to test:

1. the value of $\overline{\alpha_\pi}$ as compared with the existing data and with the theoretical prediction
2. the value of the sum ($\overline{\alpha_\pi} + \overline{\beta_\pi}$) with the existing data and the theoretical χPT prediction.

With the kaon beam we could also study the kaon polarizability, never measured until now. Since the cross section for kaon scales down as the inverse of the mass [Eq. (2)] at the first order approximation, this means that the cross section is three times smaller compared to the pion one. Also the values of the polarizability decrease by a factor 5.4 because of the ratio of the masses and the decay constant squared between the two mesons.

$$\overline{\alpha}_h = \frac{4\alpha_f}{m_h F_h^2}(L_r^9 \; + \; L_r^{10}) \rightarrow \overline{\alpha}_K = \frac{\overline{\alpha}_\pi}{5.4} \quad . \tag{6}$$

Assuming such figure and the same conditions as in the pion case, but a flux of $3 \cdot 10^5$ kaons per second, we expect to collect $2 \cdot 10^4$ events per day. With such statistics an overall resolution of $0.6 \cdot 10^{-4}\ \mathrm{fm}^3$ is estimated. This resolution takes into account both the statistical and systematic error.

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