

## PION POLARIZABILITIES MEASUREMENT AT COMPASS

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The electromagnetic structure of pions is probed in  $\pi^- + (A, Z) \rightarrow \pi^- + (A, Z) + \gamma$  Compton scattering in inverse kinematics (Primakoff reaction) and described by the electric ( $\overline{\alpha}_\pi$ ) and the magnetic ( $\overline{\beta}_\pi$ ) polarizabilities that depend on the rigidity of pion's internal structure as a composite particle. Values for pion polarizabilities can be extracted from the comparison of the differential cross section for scattering of pointlike pions with the measured cross section. The pion polarizability measurement was performed with a  $\pi^-$  beam of 190 GeV. The high beam intensity, the good spectrometer resolution, the high rate capability, the high acceptance and the possibility to use pion and muon beams, unique to the COMPASS experiment, provide the tools to measure precisely the pion polarizabilities in the Primakoff reaction. The preliminary result for pion polarizabilities under the assumption of  $\overline{\alpha}_\pi + \overline{\beta}_\pi = 0$  is  $\overline{\alpha}_\pi = -\overline{\beta}_\pi = (2.5 \pm 1.7_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-4} \text{ fm}^3$ .

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### 1. Introduction

Pion polarizabilities characterize the pion interacting as a complex  $q\bar{q}$  system with external electromagnetic fields. They are fundamental parameters of pion physics and the comparison of theoretically predicted and directly measured values provides a stringent test for various theoretical models. Among different models, chiral perturbation theory ( $\chi PT$ ) is one of the most successful tools in describing low-energy hadron properties and provides predictions for these two parameters [1]:  $\overline{\alpha}_\pi = 2.93 \pm 0.5 \times 10^{-4} \text{ fm}^3$ ,  $\overline{\beta}_\pi = -2.77 \pm 0.5 \times 10^{-4} \text{ fm}^3$ . The predictions of other theoretical models, like dispersion sum rules, QCD sum rule and quark confinement

model lie in the range  $(2 - 8) \times 10^{-4} \text{ fm}^3$  for the absolute values of  $\bar{\alpha}_\pi$  and  $\bar{\beta}_\pi$  (see Refs. [2] and [3]). Several attempts were already done using different approaches to measure these quantities (see Table 1 and Ref. [12]). The results obtained are affected by large uncertainties and there are large discrepancies between them and the  $\chi PT$  prediction. The new measurement performed with the COMPASS spectrometer will contribute to clarify the situation.

TABLE 1. Experimental values of  $\bar{\alpha}_\pi$ ,  $(\bar{\alpha}_\pi + \bar{\beta}_\pi)$  and  $(\bar{\alpha}_\pi - \bar{\beta}_\pi)$ .

Data	Reaction	$\bar{\alpha}_\pi$ [ $10^{-4} \text{ fm}^3$ ]
Lebedev [4]	$\gamma + N \rightarrow \gamma + N + \pi$	$20 \pm 12$
PLUTO [5]	$\gamma\gamma \rightarrow \pi^+\pi^-$	$19.1 \pm 4.8 \pm 5.7$
DM1 [6]	$\gamma\gamma \rightarrow \pi^+\pi^-$	$17.2 \pm 4.6$
DM2 [7]	$\gamma\gamma \rightarrow \pi^+\pi^-$	$26.3 \pm 7.4$
Mark II [8]	$\gamma\gamma \rightarrow \pi^+\pi^-$	$2.2 \pm 1.6$
Serpukhov [9]	$\pi + Z \rightarrow \pi + Z + \gamma$	$6.8 \pm 1.4 \pm 1.2$
Data	Reaction	$(\bar{\alpha}_\pi + \bar{\beta}_\pi)$ [ $10^{-4} \text{ fm}^3$ ]
Serpukhov [10]	$\pi + Z \rightarrow \pi + Z + \gamma$	$1.4 \pm 3.1 \pm 2.8$
Data	Reaction	$(\bar{\alpha}_\pi - \bar{\beta}_\pi)$ [ $10^{-4} \text{ fm}^3$ ]
Mami A2 [11]	$\gamma + p \rightarrow \gamma + \pi^+ + n$	$11.6 \pm 1.5 \pm 3.0 \pm 0.5$

## 2. The Primakoff reaction

The Primakoff reaction  $\pi^-(A, Z) \rightarrow \pi^-(A, Z) + \gamma$  can be treated as Compton scattering on the pion of a virtual photon, provided by the nucleus. The momentum transferred to the nucleus in a Primakoff reaction is very small ( $Q \ll m_\pi$ ).

In the anti-laboratory system, the differential cross section is described by the formula:

$$\frac{d^3\sigma}{dQd\omega_1d(\cos\theta)} = \frac{2\alpha^3 Z^2}{m_\pi^2 \omega_1} \frac{Q^2 - Q_0^2}{Q^4} |F_A(t)|^2 \cdot \left( F_{\pi\gamma}^{Pt} + \frac{m_\pi \omega_1^2}{\alpha} \cdot \frac{\bar{\alpha}_\pi(1 + \cos^2\theta) + 2\bar{\beta}_\pi \cos\theta}{(1 + (\omega_1/m_\pi)(1 - \cos\theta))^3} \right) \quad (1)$$

where  $Q_0^2 = (m_\pi \omega_1)/p_{\text{beam}})^2$ ,  $m_\pi$  is the pion mass,  $\omega_1$  the energy of the virtual photon,  $\theta$  the angle between the real photon and the virtual photon directions and  $F_A(t)$  the electromagnetic form factor of the nucleus ( $F_A(t) \approx 1$  for  $Q \ll m_\pi/c$ ).

Here,  $F_{\pi\gamma}^{Pt}$  [13] describes the differential Compton cross section for the scattering of photons on a point-like spin-0 particles. The main characteristic of the cross

section (Eq. (1)) is that it depends on  $(\bar{\alpha}_\pi + \bar{\beta}_\pi)$  at forward angles and on  $(\bar{\alpha}_\pi - \bar{\beta}_\pi)$  at backward angles.

### 3. Primakoff reaction studies at COMPASS.

The Primakoff reaction studies at COMPASS during the pilot hadron run in 2004 were performed with the 190 GeV  $\pi^-$  beam and a Pb target. Additional samples with Cu, C and empty targets and a 190 GeV  $\mu^-$  beam were used to study background processes and estimate systematic errors. COMPASS provides unique conditions for the investigation of the Primakoff process: silicon detectors (spacial resolution better than  $16\mu\text{m}$ ) for the vertex position reconstruction and for the measurement of the pion scattering angle, an electromagnetic calorimeter for the photon 4-momentum reconstruction and a magnetic spectrometer for the determination of the scattered pion's momentum (see Refs. [14], [15], [16], [18] and [17]). Primakoff triggers were mainly based on the usage of the electromagnetic calorimeter and hodoscopes.

In our analysis, we selected events with one primary vertex in the target region, one well measured outgoing track and one cluster in the central region of the electromagnetic calorimeter. The exclusivity of Primakoff events is guaranteed by cuts on the total energy and  $Q^2$ . In addition to the electromagnetic scattering, we have diffractive scattering processes with the same signature, for which the momentum transfer is not zero. The diffractive scattering produces a significant background in the region of large  $Q^2$ , while the peak at  $Q^2 = 0$  corresponds to the Primakoff events. The contribution of the pion diffractive scattering can be deduced from the comparison of the  $Q^2$ -distributions for pions and muons (see Fig. 1). In our analysis, we used events with  $Q^2 < Q_{\text{max}}^2 = 6.5 \times 10^{-3}(\text{GeV}/c)^2$ . To take

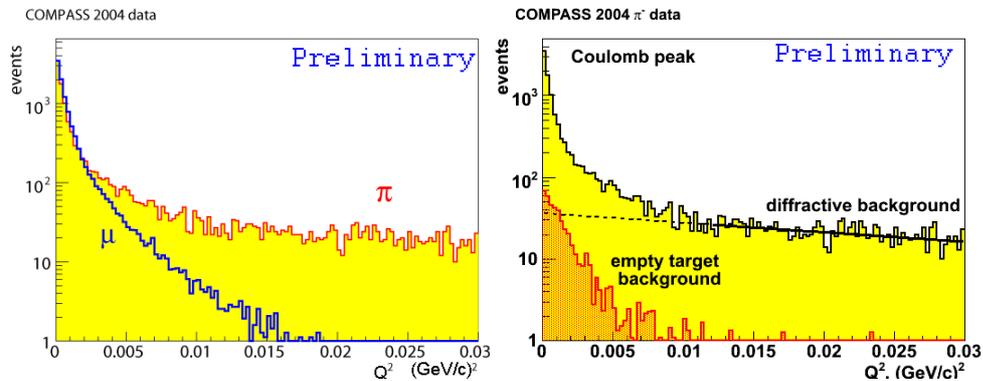


Fig. 1 (left).  $Q^2$ -distribution for pions and muons.

Fig. 2.  $Q^2$ -distribution for 2+1 mm lead target. Diffractive and empty target backgrounds are shown.

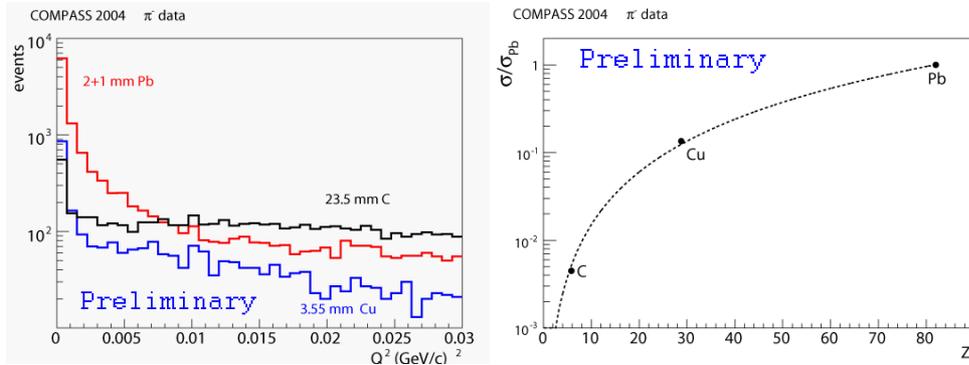


Fig. 3 (left).  $Q^2$  distributions for lead, copper and carbon targets.

Fig. 4.  $Z^2$ -dependence of Primakoff cross section.

into account the background from diffractive scattering in the Primakoff sample, we fitted it with an exponential function in the range  $(2 \times 10^{-2} - 1 \times 10^{-1})(\text{GeV}/c)^2$  and extrapolated the fitted curve to  $Q^2 = 0$ . We also excluded the events with a  $\pi\gamma$  invariant mass  $M_{\pi\gamma} > 3.75 \times m_\pi$  to prevent misidentification of  $\rho^-$ -meson decay events due to the missing reconstruction of one of the photons from the  $\pi^0 \rightarrow \gamma\gamma$  decay as Primakoff events. Due to similar reasons, we have some background from the decay of beam kaons (up to 4% in the beam) from  $K^- \rightarrow \pi^- + \pi^0$ . It was estimated and subtracted using the data with beam kaon decays up- and downstream of the target. The contribution of kaon, the so-called empty target background, is shown in Fig. 2.

#### 4. Primakoff scattering on different nuclear targets

The comparison of data samples collected with different targets provides the possibility to study the behavior of the signal/background ratio (ratio of the Primakoff signal versus the diffractive scattering background) for different materials and to check the  $Z^2$  dependence for the Primakoff cross section. In Fig. 3 are shown the  $Q^2$ -distributions for lead, copper and carbon. We observe that, compared to the other targets with smaller  $Z$ , the ratio of the Primakoff signal over the diffractive background is larger for lead. This confirms the goodness of our choice of lead as the main target material.

To check the  $Z^2$ -dependence, we measured the total Primakoff cross sections for copper and carbon normalized by the measured cross section for lead  $\sigma/\sigma_{Pb}$ . The test for the  $Z^2$  dependence of the Primakoff cross section is presented in Fig. 4. We can observe that the measured values satisfy the  $Z^2$  dependence rule for a wide range of  $Z$ . This proves that our selection criteria effectively select Primakoff events and reject background events.

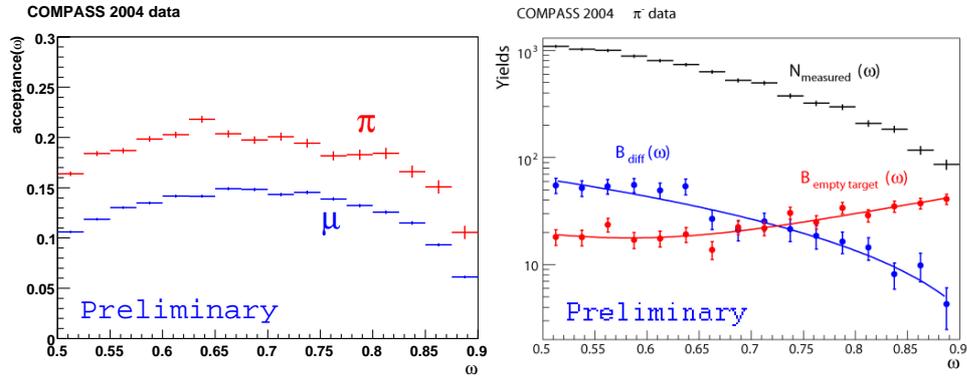


Fig. 5 (left). Acceptance for pions and muons as a function of  $\omega$ .

Fig. 6.  $\omega$ -distributions for pions for measured signal, diffractive and kaon backgrounds.

### 5. Pion polarizability extraction under the assumption of $\overline{\alpha_\pi} + \overline{\beta_\pi} = 0$

For a preliminary result on polarizabilities under the assumption of  $\overline{\alpha_\pi} + \overline{\beta_\pi} = 0$ , we compared the shapes of the differential cross sections  $d\sigma/d\omega$  measured and theoretically predicted for a point-like pion, where  $\omega = E_\gamma/E_{\text{beam}}$  is the relative energy of emitted photon. Only part of the total statistics for Pb target was used (about 7500 events in selected  $\omega$ -range). For the calculation of the acceptance, we used a Monte Carlo simulation based on the Primakoff event generator POLARIS ([19]) and GEANT3 for the COMPASS setup description. The acceptance function (Fig. 5) has a smooth shape in the selected  $\omega$ -range and a similar behavior for pions and muons. That means that the COMPASS geometry and selection criteria are convenient to study the Primakoff reaction, and the muon events can be used as a reference. Since the simulation was based on the Born approximation for the cross section, radiative corrections for Compton vertex, multiple photon exchange, vacuum polarization and nuclear charge screening by electrons were taken into account. Figure 6 shows the  $\omega$ -distributions for the measured signal, diffractive and empty target backgrounds. The ratio of the measured cross section to the prediction for a point-like particle is presented in Figs. 7 and 8 for pions and muons. In both cases it was fitted by a function with two free parameters: the absolute normalization and  $\overline{\beta_\pi}$ . In the case of muons, the result of the fit is consistent with the hypothesis of unstructured particles, while for pions the preliminary result is  $\overline{\alpha_\pi} = -\overline{\beta_\pi} = 2.5 \pm 1.7 \times 10^{-4} \text{ fm}^3$ . We estimated that the main contribution to the systematic uncertainty comes from the MC description and the total systematic uncertainty is  $\pm 0.6 \times 10^{-4} \text{ fm}^3$ .

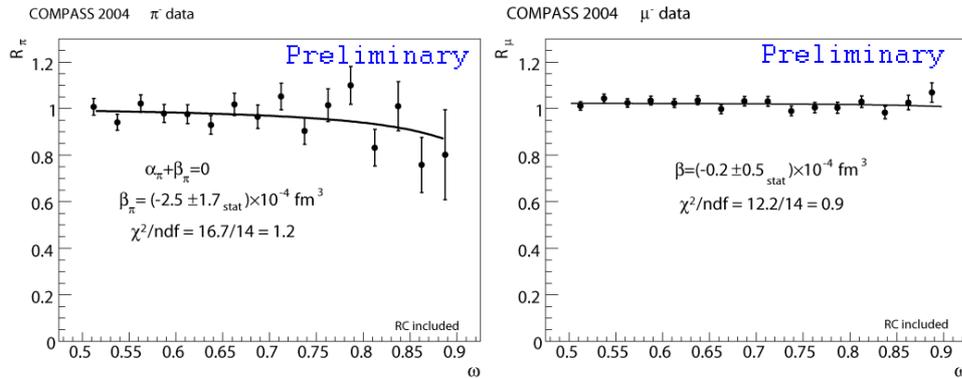


Fig. 7 (left). Ratio of Primakoff cross sections for pions as function of  $\omega$ .

Fig. 8. Ratio of Primakoff cross sections for muons as function of  $\omega$ .

## 6. Conclusion

The preliminary result of the COMPASS experiment for the pion polarizability is  $\overline{\alpha}_\pi = -\overline{\beta}_\pi = (2.5 \pm 1.7_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-4} \text{fm}^3$ . It is consistent with the prediction of  $\chi$ PT, but present statistical and systematic uncertainties do not exclude completely from consideration the predictions of other theoretical models. COMPASS has the potential to reduce uncertainties using more statistics in the analysis, and final result should be more promising.

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## MJERENJE PIONSKE POLARIZIVOSTI NA COMPASS-U

Elektromagnetska građa piona istražuje se Comptonovim raspršenjem  $\pi^- + (A, Z) \rightarrow \pi^- + (A, Z) + \gamma$  u obrnutoj kinematici (Primakoffova reakcija) i opisuje se električnom ( $\overline{\alpha}_\pi$ ) i magnetskom polarizivošću ( $\overline{\beta}_\pi$ ). One ovise o krutosti piona kao složene čestice. Vrijednosti pionske polarizivosti izvode se usporedbom diferencijalnih udarnih presjeka za točkaste pione s eksperimentalnima. Mjerenje pionske polarizivosti načinili smo sa snopom  $\pi^-$  energije 190 GeV. Snažan snop, dobro razlučivanje spektrometra, velika moć brzog bilježenja i veliko prihvaćanje podataka, te primjena pionskog i mionskog snopa jedinstvene su odlike eksperimenta COMPASS, i to omogućuje točna mjerenja polarizivosti piona Primakoffovom reakcijom. Prethodni ishodi mjerenja za pionske polarizivosti, uz pretpostavku  $\overline{\alpha}_\pi + \overline{\beta}_\pi = 0$ , su  $\overline{\alpha}_\pi = -\overline{\beta}_\pi = (2.5 \pm 1.7_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-4} \text{ fm}^3$ .