PROCEEDINGS OF SCIENCE

Measuring the charged pion polarizability in the $\gamma\gamma \to \pi^+\pi^-$ reaction

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Development has begun of a new experiment to measure the charged pion polarizability $\alpha_\pi - \beta_\pi$. The charged pion polarizability ranks among the most important tests of low-energy QCD presently unresolved by experiment. Analogous to precision measurements of $\pi^\circ \to \gamma\gamma$ that test the intrinsic odd-parity (anomalous) sector of QCD, the pion polarizability tests the intrinsic even-parity sector of QCD. The measurement will be performed using the $\gamma\gamma \to \pi^+\pi^-$ cross section accessed via the Primakoff mechanism on nuclear targets using the GlueX detector in Hall D at Jefferson Lab. The linearly polarized photon source in Hall-D will be utilized to separate the Primakoff cross-section from coherent ρ° production.

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1. Motivation

Electric and magnetic polarizabilities (α_π and β_π respectively) are fundamental properties of particles with structure such as the charged pion. They become particularly important in the low energy sector of QCD where they can be related to the pion form factors F_V and F_A. Leading order $\mathscr{O}(p^4)$ calculations in Chiral Perturbation Theory (ChPT) indicate that the electric and magnetic polarizabilties are equal in magnitude ($\alpha_\pi = -\beta_\pi$) and that their value is[1]:

$$\alpha_\pi = -\beta_\pi = \frac{4\alpha_{EM}}{m_\pi F_\pi^2}(L_9^r + L_{10}^r) \propto \frac{F_A}{F_V}$$

$$\alpha_\pi = -\beta_\pi = 2.78 \pm 0.1 \times 10^{-4} fm^3$$

where L_9^r and L_{10}^r are low-energy constants of the Gasser-Leutwyler effective Lagrangian.

A summary of the current experimental and theoretical landscape of $\alpha_\pi - \beta_\pi$ can be seen in figure 1. From there it can be seen that the landscape of experimental values is quite poor with values for $\alpha_\pi - \beta_\pi$ ranging from 4×10^{-4} to 52×10^{-4} fm^3.

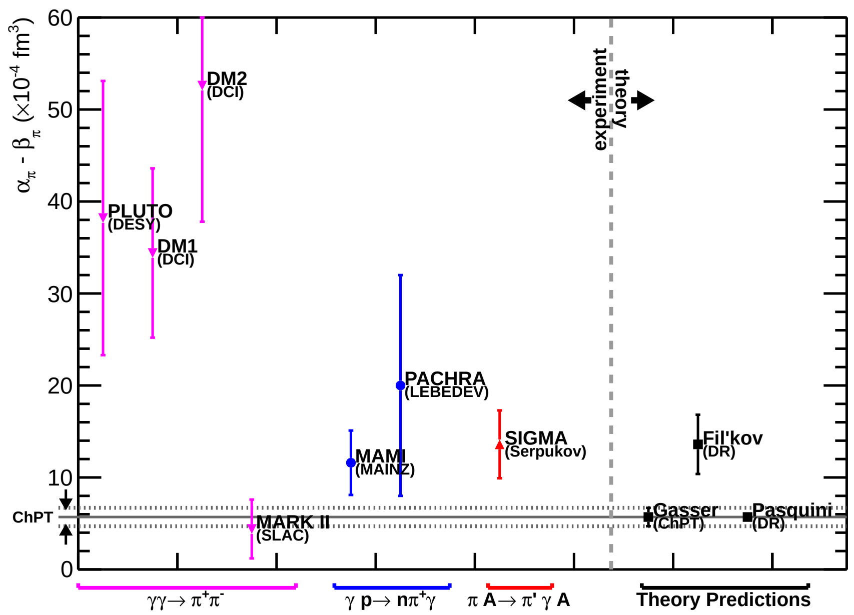

Figure 1: Current experimental and theoretical landscape of π polarizability. [2] [3] [4] [5] [6] [7]

The next to leading order $\mathscr{O}(p^6)$ corrections to the polarizabilities in ChPT are relatively small giving[8]:

$$\alpha_\pi - \beta_\pi = 5.7 \pm 1.0 \times 10^{-4} fm^3$$

$$\alpha_\pi + \beta_\pi = 0.16 \pm 0.1 \times 10^{-4} fm^3.$$

Dispersion relation calculations have also been made using data from $\gamma\gamma \to \pi^+\pi^-$ to fix the dispersion integrals, but with some discrepancy:

$$\alpha_\pi - \beta_\pi = 13.0^{+2.6}_{-1.9} \times 10^{-4} fm^3 \qquad \text{(Fil'kov [6])}$$

$$\alpha_\pi - \beta_\pi = 5.7 \times 10^{-4} fm^3. \qquad \text{(Pasquini [7])}$$

With the construction of the new experimental Hall-D at Jefferson lab which includes a high energy (8.5GeV) linearly polarized photon source, the prospect of a new, more accurate measurement is presented.

2. Previous Experiments

Three categories of experiments have been performed in the past to access the polarizability of the pion. These are:

Primakoff Effect The Primakoff effect[9] involves scattering from a virtual photon that is part of the Coulomb field of a nucleus. The most recent experiment using this mechanism was done at Serpukov using SIGMA[4]. There, a π^- beam was radiatively scattered from the field of a heavy nucleus. The reaction is equivalent to Compton scattering. The measurement resulted in a value of $\alpha_\pi - \beta_\pi = 13.6 \pm 2.8$. While consistent with the calculation by Fil'kov, this is inconsistent with the ChPT calculations and the dispersion relation calculation by Pasquini.

Radiative pion photo-production In radiative photo-production, an incident photon interacts with a virtual pion in the field of a nucleus, knocking it on shell. This technique was used most recently at Mainz using MAMI[3] and resulted in a value of $\alpha_\pi - \beta_\pi = 11.6 \pm 1.5_{stat} \pm 3.0_{syst} \pm 0.5_{mod}$, a value $> 1.7\sigma$ away from the ChPT calculation.

Light-by-light scattering Here, two virtual photons interact to produce a $\pi^+\pi^-$ final state. The most compelling measurement of this type was done at SLAC using MARK-II[2]. The measurement resulted in a value of $\alpha_\pi - \beta_\pi = 4.4 \pm 3.2$ which is consistent with the most recent theory calculations. However, the number of events was quite small (≈ 400) leading to a relatively large experimental uncertainty.

3. Measurement at Jefferson Lab Hall-D

The Primakoff mechanism will be used in the proposed experiment. Here, an incident beam of linearly polarized photons is incident on a heavy nuclear target ($\gamma Pb \to Pb\pi^+\pi^-$). The GlueX detector will be used to detect the final state $\pi^+\pi^-$ particles using primarily the Forward Drift Chamber (FDC) and Time-Of-Flight (TOF) detectors and the Forward Electromagnetic calorimeter (FCAL) for triggering. Figure 2 shows a diagram of the GlueX detector in its nominal configuration used for GlueX running. In the proposed measurement, the target will be replaced with a thin (5% rad. len.) Pb target and the start-counter may be removed.

The low-t reaction gives most of the energy to the two charged pions, which will be very forward going, leaving the target with very little momentum. Figure 3 shows the angular and momentum distributions of the final state pions for incident photons with an energy of 8.5 GeV.

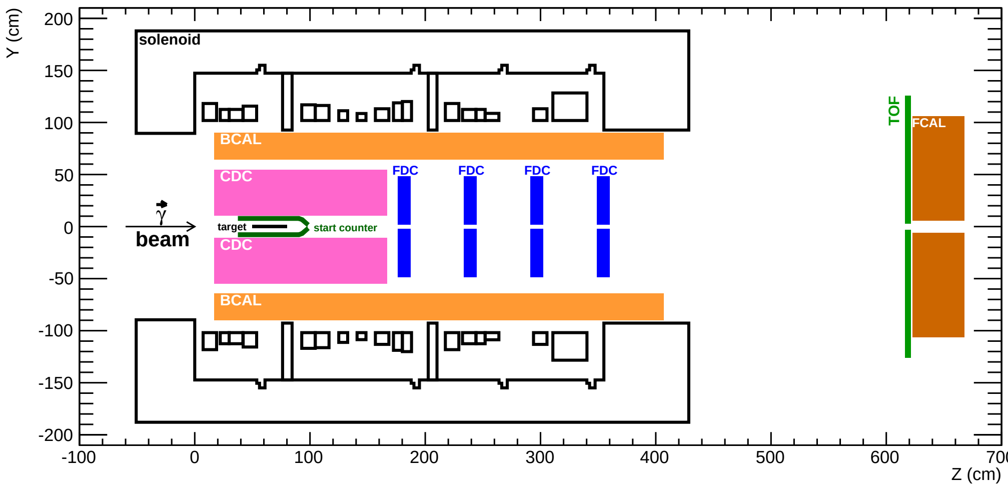

Figure 2: Side view drawing of the GlueX detector. For the proposed measurement, the 30cm long LH2 target shown here will be replaced with a thin (5% rad. len.) Pb target placed slightly upstream. The kinematics of the $\gamma\gamma \to \pi\pi$ reaction are such that the final state pions will go forward through the FDC detectors and into the TOF and FCAL detectors downstream. Shapes with black outlines and white fill color represent the solenoidal magnet (yoke and coils).

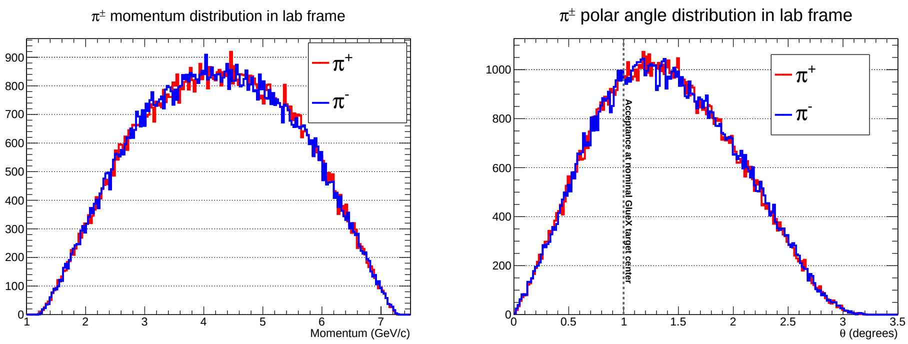

Figure 3: Expected momentum (left) and polar angle (right) distributions for pions in the $\gamma\gamma \to \pi^+\pi^-$ reaction for a 8.5GeV incident photon energy. Kinematics are limited to $W_{\pi\pi} < 400 MeV/c$ and only Primakoff and coherent ρ° production are included. The GlueX detector accepts particles with θ >1 degree.

The value of $\alpha_\pi - \beta_\pi$ will be obtained through its influence on the $\gamma\gamma \to \pi^+\pi^-$ cross section. For the values of $\alpha_\pi - \beta_\pi = 5.7$ and $\alpha_\pi - \beta_\pi = 13.0$, the cross section differs on the order of 10% (see figure 5 of [7]). This cross section will therefore need to be measured to within a few percent. The primary background will be from coherent ρ° production followed by $\rho \to \pi^+\pi^-$ decay. Figure 4 shows the expected invariant mass distribution of the $\pi\pi$ system for signal events (Primakoff) and signal + background(ρ°) events from threshold up to $400 MeV/c$. Primkoff production dominates at lower values of $W_{\pi\pi}$.

Separation of signal and background will be done via the pion angular distributions relative to the polarization direction. The kinematics and relevant angles are illustrated in figure 5. For Primakoff produced events, the cross-section has a $\cos 2\phi_{\pi\pi}$ dependence:

$$\frac{d\sigma_{Primakoff}}{d\Omega} \propto 1 + P_\gamma \cos 2\phi_{\pi\pi},$$

where $\phi_{\pi\pi}$ is the azimuthal angle of the $\pi\pi$ system in the lab frame. For coherent ρ° production, the cross-section has a $\cos 2\psi_{\pi\pi}$ dependence

$$\frac{d\sigma_{coherent\ \rho}}{d\Omega} \propto 1 + P_\gamma \cos 2\psi_{\pi\pi},$$

where $\psi_{\pi\pi}$ is the angle of the π^+ in the helicity frame. Figure 6 shows the angular distributions of $\phi_{\pi\pi}$ and $\psi_{\pi\pi}$ for 3 regions of $W_{\pi\pi}$ (see figure 4). The blue and red regions show the dependence on Primakoff-dominated and coherent ρ°-dominated regions of $W_{\pi\pi}$ respectively. The dependence on $\cos 2\phi_{\pi\pi}$ and $\cos 2\psi_{\pi\pi}$ will be used to extract the relative fractions of Primakoff and coherent ρ° events.

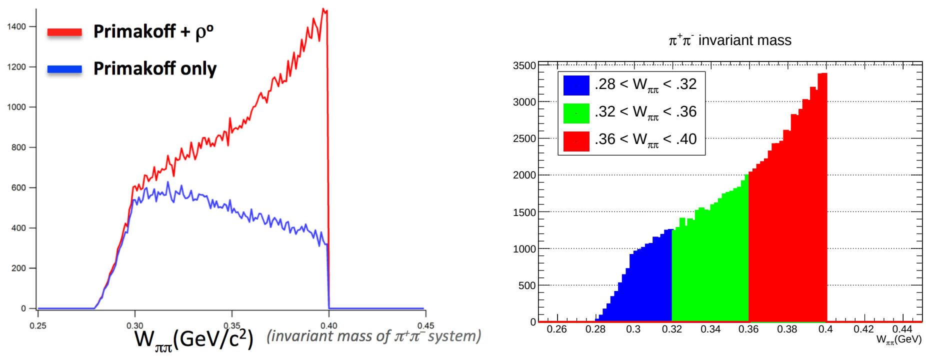

Figure 4: Expected $W_{\pi\pi}$ distribution from 2π production threshold up to 400MeV/c. The left plot shows the contribution from Primakoff only (blue) and the Primakoff+Coherent ρ° production (red). The plot on the right shows the same total spectrum, but with regions color coded to correspond to the angular distribution in figure 6.

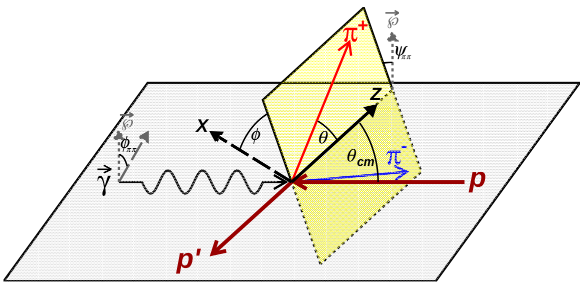

Figure 5: Scattering angle definitions for the $\gamma\gamma \to \pi^+\pi^-$ reaction.

Assuming a 5% radiation length Pb target and a rate of 10^7 tagged photons per second and 500 hours of running time, we can expect to produce $\sim 36k$ Primakoff events.

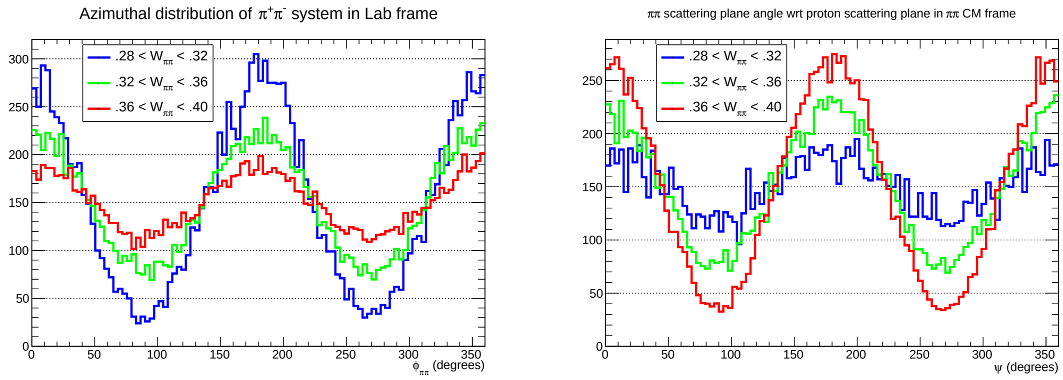

Figure 6: Expected $\phi_{\pi\pi}$ (left) and $\psi_{\pi\pi}$ (right) angular distributions for different ranges in $W_{\pi\pi}$.

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