PROCEEDINGS OF SCIENCE

Measurements of Meson Polarizabilities

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The EM polarizability of the charged pion ranks among the most important tests of low-energy QCD presently unresolved by experiment. It makes a potentially significant contribution to hadronic light-by-light scattering impacting the uncertainty in the SM. Experimentally, the electromagnetic polarizability has been accessed using various reactions which include Compton scattering and the Primakoff effect. Recently, interest in meson polarizabilities has been renewed with a recent COMPASS experiment(2015) and an approved experiment at Jefferson Lab. A brief status of the current experimental landscape of meson polarizabilities is presented.

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1. Charged Pion Polarizability

Recent activity has renewed interest in the polarizability of mesons[1][2][3] with charged pions being the most easily accessible via experiment. Several experiments have measured the charged pion polarizability[4][5][6][7] while a higher precision new measurement has been approved using the GlueX detector at Jefferson Lab[8]. These are summarized in figure 1. The horizontal solid line represents the $O(p^4)$ ChPT prediction[9][10] with the horizontal dashed lines representing the uncertainty of that prediction. LO ChPT predicts the electric (α_π) and magnetic (β_π) polarizabilities are equal in magnitude and opposite in sign as given in equation1.1 where F_π is the pion form factor and L_9^r and L_{10}^r are Low Energy constants from the ChPT effective Lagrangian. It is common to quote the "polarizability" as $\alpha_\pi - \beta_\pi$ (=5.6 $\times 10^{-4} fm^3$ LO ChPT). This is the value plotted in figure1 and used throughout this paper.

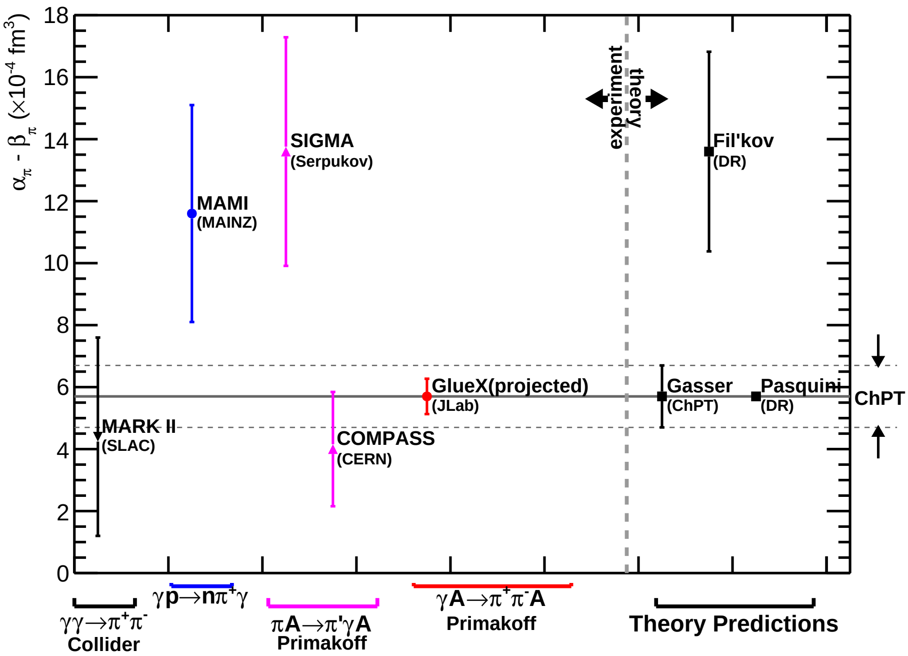

Figure 1: Current experimental and theoretical landscape of charged pion polarizability.

$$\alpha_\pi = -\beta_\pi = \frac{4\alpha}{m_\pi F_\pi^2}(L_9^r - L_{10}^r) = (2.78 \pm 0.1) \times 10^4 fm^3 \tag{1.1}$$

The following sections highlight three of the experiments, including the planned experiment using the GlueX detector at JLab.

1.1 MARK II

Figure 2 shows the $\gamma\gamma \to \pi^+\pi^-$ cross section as a function of the $\pi^+\pi^-$ invariant mass as measured by the MARK II experiment. The experiment was performed at SLAC using the $e^+e^- \to \pi^+\pi^-$ reaction. The main focus of the original MARK II paper[4] was on the $f0(975)$ and $f2(1260)$ while the polarizability was determined from the measured cross section by a lter analysis. The open circle markers in the low invariant mass region are where the cross section is sensitive to the polarizability. The markers differ in this region because a different detector type was used for pion identification in this region compared $M_{\pi\pi} > 0.5$ region. The polarizability was extracted from only the open markers in a later paper[11] yielding a value of $\alpha_\pi - \beta\pi = 4.4 \pm 3.2_{stat+syst} \times 10^{-4} fm^3$. The measurement consisted of a few thousand events in the region of $M_{\pi\pi} < 0.5$.

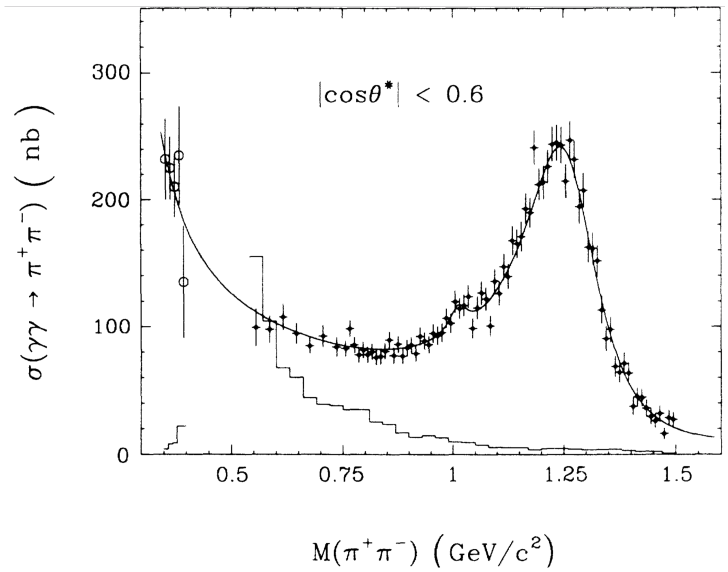

Figure 2: MARK II measurement. Reprinted from [4] DOI: https://doi.org/10.1103/PhysRevD.42.1350 by permission via APS Reuse and Permissions License.

1.2 COMPASS

The most recent and most precise measurement of the charged pion polarizability to date was performed at COMPASS[7]. There, a 190 GeV/c π^- beam was incident on a stationary Ni target. Only ultra-peripheral events were used which reduced meson exchange and final state interaction effects. The resulting dataset was approximately 60k events. The polarizability was extracted using a novel analysis technique where the LO ChPT prediction of $\alpha_\pi = -\beta_\pi$ was assumed and the ratio of the cross section to the predicted cross section for zero polarizability was fit. Equation 1.2 gives this ratio as a function of the electric polarizability α_π with x_γ representing the fraction of the beam energy carried by the final state photon. Figure 3 shows the resulting fit with the band representing the statistical uncertainty. A similar analysis was performed using data taken with a muon beam to help control systematics. The final result of the measurement was $\alpha_\pi - \beta\pi = 4.0 \pm 1.2_{stat} + 1.4_{syst} \times 10^{-4} fm^3$.

$$R_\pi = \left(\frac{d\sigma_{\pi\gamma}}{dx_\gamma}\right) \Big/ \left(\frac{d\sigma^o_{\pi\gamma}}{dx_\gamma}\right) = 1 - \frac{3}{2}\frac{m_\pi^3}{\alpha}\frac{x_\gamma^2}{1-x_\gamma}\alpha_\pi \tag{1.2}$$

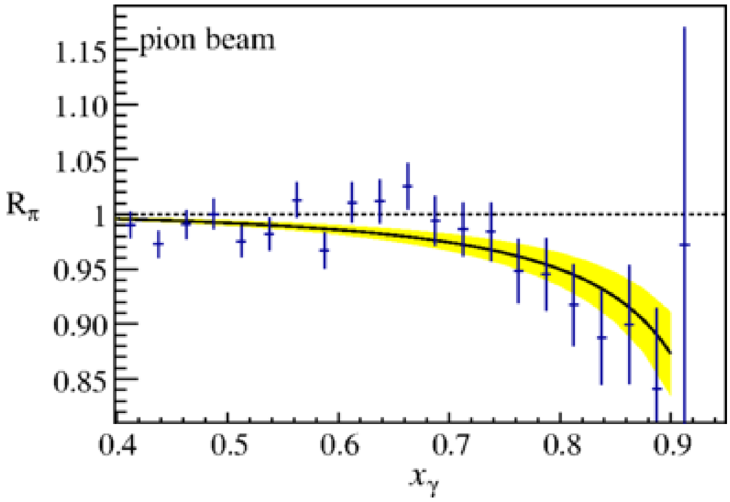

Figure 3: COMPASS measurement adapted from [7]. R_π is ratio of measured cross section to predicted cross section with no polarizabiity. x_γ is the fraction of the beam energy carried by the final state photon in the $\pi^- Ni \rightarrow Ni\pi^-\gamma$ reaction. DOI: https://doi.org/10.1103/PhysRevLett.114.062002 via Creative Commons License v3.

1.3 GlueX

A new experiment to measure the charged pion polarizability has been approved to run at Jefferson Lab using the GlueX detector[8]. The experiment will use an approximately 6 GeV linearly polarized photon beam incident on a Pb target in the $\gamma Pb \rightarrow Pb\pi^+\pi^-$ reaction. The forward drift chambers(FDC), time of flight(TOF) and forward lead-glass Cerenkov calorimeter(FCAL) from the GlueX detector will be used. In addition, another detector consisting of a set of drift chambers sandwiched between thick iron absorbers will be installed to help distinguish $\pi^+\pi^-$ events from $\mu^+\mu^-$ background. Figure 4 shows a diagram of the experimental setup. Another large background for this experiment will come from $\rho \rightarrow \pi^+\pi^-$ decays. These form a part of the cross section that is not sensitive to the polarizability and so must be separated in order to measure the Primakoff-only part of the cross section which is sensitive to the polarizability. This will be done statistically using the linear polarization of the incident photon beam relative to the angles of the final state $\pi^+\pi^-$ particles. Figure 5 shows the overlap of the Primakoff and ρ distributions in the invariant mass of the $\pi\pi$ system ($W_{\pi\pi}$). It also defines the scattering angles including $\phi_{\pi\pi}$ and $\psi_{\pi\pi}$. The Primakoff events will have an asymmetry in the angle $\phi_{\pi\pi}$ while the ρ events will have an asymmetry in $\psi_{\pi\pi}$. These asymmetries will be used to separate Primakoff and ρ contributions to the measured cross section. The sensitivity of the Primakoff cross section to the polarizability can be seen in figure 6. There, the $\gamma\gamma \rightarrow \pi^+\pi^-$ cross section is shown for three different values of the polarizability. The polarizability is expected to have an uncertainty that is approximately ten times larger than the uncertainty of the measured cross section[12][13]. With the expected yield of $\sim$200k events, for the GlueX experiment, the uncertainty of the polarizability from the measurement will be at the 10% level. This will be the first experiment to measure this quantity at a level comparable to the uncertainty of the LO ChPT prediction.

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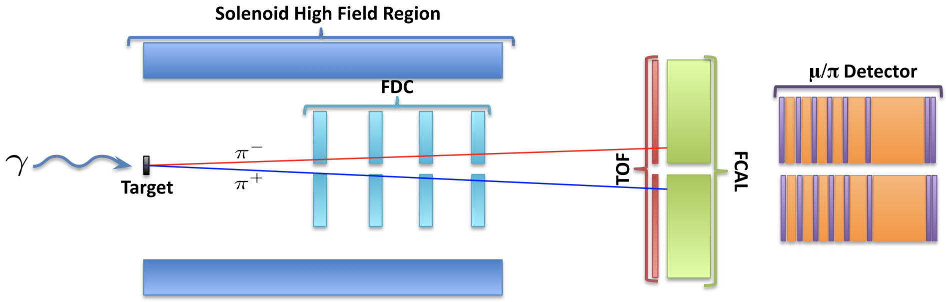


Figure 4: Geometry of the parts of GlueX detector that will be used in the JLab experiment plus the supplemental muon detection chambers.

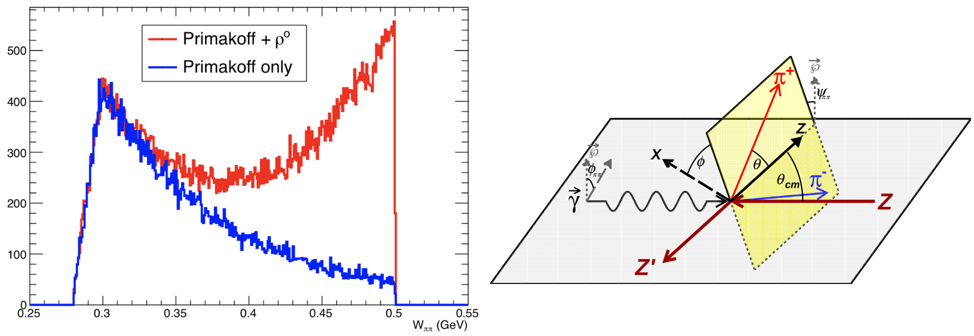


Figure 5: Left: $\pi^+\pi^-$ invariant mass spectra for Primakoff and ρ events. Right: Diagram of scattering angles that can be used to statistically separate ρ and Primakoff contributions to the measured cross section.

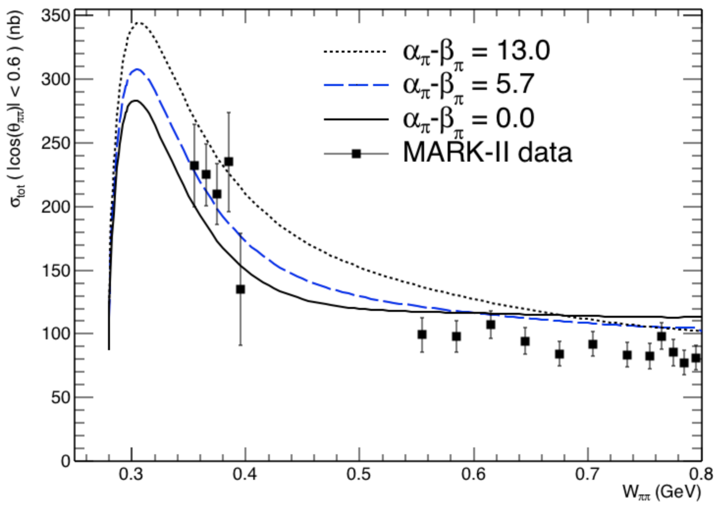
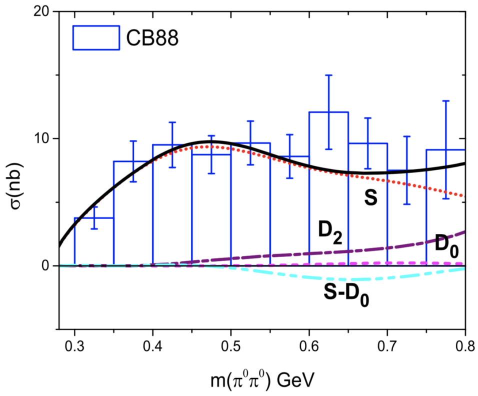


Figure 6: Cross section for $\gamma\gamma \to \pi^+\pi^-$ reaction as a function of the $\pi^+\pi^-$ invariant mass for multiple values of the polarizability. Reprinted from [12] DOI: https://doi.org/10.1103/PhysRevC.77.065211 by permission via APS Reuse and Permissions License.

2. Neutral Pion Polarizability

There currently exists only one direct measurement of the neutral pion polarizability. It comes via the $e^+e^- \to e^+e^-\pi^\circ\pi^\circ$ reaction using the Crystal Ball detector at DESY[14]. More recently, Dai and Pennington have related the uncertainty of the charged pion polarizability to that of the neutral pion polarizability[13]. Figure 7 shows the Crystal Ball measurement of the $\pi^\circ\pi^\circ$ cross section as well as a table of values from[13] relating the uncertainty of the polarizability to that of the measured cross section for both the neutral and charged cases. Their conclusion states that a measurement of the charged polarizability at the 10% level will fix the neutral polarizability to be $0.9 \pm 0.2 \times 10^{-4} fm^3$ (or 22%).



Polarizability	For an uncertainty of	Accuracy required of $\gamma\gamma \to \pi\pi$ cross section at 450 MeV	Uncertainty required in the integrated cross section
$(\alpha_1-\beta_1)_{\pi^+}$	100%	10%	20 nb
$(\alpha_2-\beta_2)_{\pi^+}$	100%	17%	34 nb
$(\alpha_1-\beta_1)_{\pi^0}$	100%	13%	1.2 nb
$(\alpha_2-\beta_2)_{\pi^0}$	100%	132%	12 nb
$(\alpha_1+\beta_1)_{\pi^+}$	100%	1%	2 nb
$(\alpha_2+\beta_2)_{\pi^+}$	100%	1%	2 nb
$(\alpha_1+\beta_1)_{\pi^0}$	100%	1%	0.08 nb
$(\alpha_2+\beta_2)_{\pi^0}$	100%	1%	0.07 nb

Figure 7: LEFT: $e^+e^- \to e^+e^-\pi^\circ\pi^\circ$ cross section as a function of the $\pi^\circ\pi^\circ$ invariant mass from the 1988 Crystal Ball experiment. RIGHT: Table relating uncertainty in cross sections to uncertainty of polarizabilities. The red and blue boxes indicated the dipole polarizabilities of the charged and neutral pion respectively. Reprinted and adapted from [13] by permission via APS Reuse and Permissions License. DOI: https://doi.org/10.1103/PhysRevD.94.116021

3. Future Measurements

In addition to the approved charged pion polarizability measurement at Jefferson Lab, there are a couple of other notable measurements currently in the planning stages. One is a measurement of the Kaon polarizability at an upgraded COMPASS detector[2]. There has been only one previous measurement of this using kaonic atoms from 1973[15]. The Letter of Intent promoting the COMPASS upgrade as part of a new facitlity on the M2 beam line of the CERN SPS indicates the earliest data would not come before 2026. A Letter of Intent is also being developed for a direct measurment of the neutral pion polaizability using the GlueX detector at Jefferson Lab. This will be submitted to the Program Advisory Committee in 2019 with hopes of developing a full proposal by 2020.

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