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e^+e^- Annihilations into Quasi-two-body Final States at 10.58 GeV

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We report the first observation of e^+e^- annihilations into hadronic states of positive C-parity, $\rho^0\rho^0$ and $\phi\rho^0$. The angular distributions support two-virtual-photon annihilation production. We also report the observations of $e^+e^- \to \phi\eta$ and a preliminary result on $e^+e^- \to \rho^+\rho^-$.

Keywords: Exclusive; High momentum; C parity; Helicity amplitude.

1. Introduction

The large datasets collected by the B factories provide unique opportunities for studying rare processes and discovering new states. We report several observations of e^+e^- annihilations into quasi-two-body hadronic final states with $C = \pm 1$ at *BABAR* [?,?,?]. A new avenue for the study of hadron production mechanisms is opened with these observations, and a testing ground for QCD at the amplitude level is provided.

2. $e^+e^- \to \rho^0\rho^0, \phi\rho^0$

The process $e^+e^- \to$ hadrons at center-of-mass (c.m.) energy $\sqrt{s}$ far below the Z^0 mass is dominated by annihilation via a single virtual photon, thus yielding final state charge-conjugation parity $C = -1$. The Two-Virtual-Photon-Annihilation (TVPA) process, depicted in Fig. **??**, with positive final state C parity, has been ignored in incorporating the total hadronic cross section in e^+e^- annihilations into calculations [?] of muon g–2, and the running of the QED coupling constant, α.

The present analysis uses a 205 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance, and 20 fb^{-1} collected at c.m. energy 40 MeV lower, using the *BABAR* detector at the SLAC PEP-II asymmetric-energy e^+e^- collider.

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The *BABAR* detector is described in detail elsewhere [**?**].

Events with four well-reconstructed charged tracks and net charge zero are selected. The χ^2 probability of the fitted four track vertex is required to exceed 0.1%, and two oppositely charged tracks must be identified as pions; the other pair must be identified as two pions or two kaons. We accept events with four-particle invariant mass within 170 MeV/c^2 of the nominal c.m. energy. Loose signal regions are defined by the mass ranges $0.5 < m_{\pi^+\pi^-} < 1.1$ GeV/c^2 and $1.008 < m_{K^+K^-} < 1.035$ GeV/c^2. The extracted $\rho^0\rho^0$ and $\phi\rho^0$ yields in these intervals are 1243 ± 43 and 147 ± 13 events, respectively.

The efficiency-corrected production angular distributions are shown in Fig. **??**, where θ^* is defined as the angle between the ρ^0_f (ϕ) direction and the e^- beam direction in the c.m. frame. The observed sharply peaking $|\cos\theta^*|$ distributions are consistent with the TVPA expectation [**?**], which is approximated by:

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{1+\cos^2\theta^*}{1-\cos^2\theta^*}. \tag{1}$$

For the signal mass regions defined above, and $|\cos\theta^*| < 0.8$, we obtain the following results for the TVPA cross sections near $\sqrt{s} = 10.58$ GeV:

$$\sigma_{\rm fid}(e^+e^- \to \rho^0\rho^0) = 20.7 \pm 0.7({\rm stat}) \pm 2.7({\rm syst})\ {\rm fb}$$
$$\sigma_{\rm fid}(e^+e^- \to \phi\rho^0) = 5.7 \pm 0.5({\rm stat}) \pm 0.8({\rm syst})\ {\rm fb}.$$

The measured cross sections are in good agreement with the calculations [?, **?**]. The Standard Model calculations of the anomalous magnetic moment of the muon and of the QED coupling constant rely on measurements of low-energy e^+e^- hadronic cross sections, which are assumed to be entirely due to single-photon exchange. We have estimated the effect due to the TVPA processes [?] and find it to be small compared with the current precision [?].

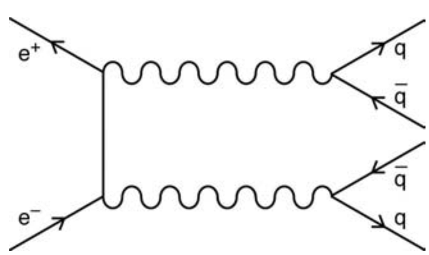

Fig. 1. The two-virtual-photon annihilation diagram.

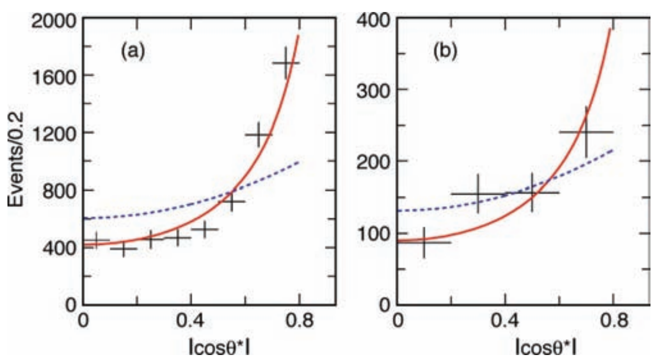

Fig. 2. Production angle distributions, after correction for efficiency, for a) $\rho^0\rho^0$ and b) $\phi\rho^0$. The solid and dashed lines are the normalized $\frac{1+\cos^2\theta^*}{1-\cos^2\theta^*}$ and $1+\cos^2\theta^*$ distributions, respectively.

3. $e^+e^- \to \phi\eta$

The process $e^+e^- \to J/\psi\eta_c$ and other double charmonium processes are observed [?] at rates approximately ten times larger than expected from QCD-based models [?]. Various theoretical efforts to understand this have been made recently [?]. An alternate avenue of investigation is provided by the process $e^+e^- \to \phi\eta$, which also involves a vector – pseudoscalar (VP) final state. Different models predict different s dependences for the cross section, and so it is interesting to investigate this by comparing a measurement at $\sqrt{s} = 10.58$ GeV to the CLEO measurement at $\sqrt{s} = 3.67$ GeV [?].

This analysis uses 204 fb^{-1} of e^+e^- colliding beam data collected on the $\Upsilon(4S)$ resonance at $\sqrt{s} = 10.58$ GeV and 20 fb^{-1} collected 40 MeV below. Events with exactly two well-reconstructed, oppositely charged kaon tracks and at least two well-identified photons are selected. We fit the two tracks to a common vertex, and require the χ^2 probability to exceed 0.1%. Each photon candidate is required to have a minimum laboratory energy of 500 MeV. Events with a reconstructed $K^+K^-\gamma\gamma$ invariant mass within 230 MeV/c^2 of the e^+e^- c.m. energy are accepted for further study.

We define the ϕ mass window as $1.008 < m_{KK} < 1.035$ GeV/c^2, and extract 24 ± 5 $\phi\eta$ signal events in the ϕ mass window, with $\eta \to \gamma\gamma$. The significance is estimated to be 6.5 sigma.

The final radiation-corrected cross section for $1.008 < m_\phi < 1.035$ GeV/c^2 within $|\cos\theta^*| < 0.8$ near $\sqrt{s} = 10.58$ GeV is:

$$\sigma_{\rm fid}(e^+e^- \to \phi\eta) = 2.1 \pm 0.4({\rm stat}) \pm 0.1({\rm syst})\ {\rm fb}.$$

The cross section, extended to the full range of $\cos\theta^*$ by assuming a $1 + \cos^2\theta^*$ distribution, is:

$$\sigma(e^+e^- \to \phi\eta) = 2.9 \pm 0.5(\text{stat}) \pm 0.1(\text{syst})\ \text{fb}.$$

There is currently no direct prediction for the cross section of this process at this energy, but the $e^+e^- \to$ VP cross section is expected to have a $1/s^2$ [**?**] or $1/s^4$ [**?**,**?**] dependence in QCD-based models. A comparison between our result and that of CLEO, ($\sigma = 2.1^{+1.9}_{-1.2} \pm 0.2$ pb) at $\sqrt{s} = 3.67$ GeV (continuum) [?], favors a $1/s^3$ dependence (Fig. **??**).

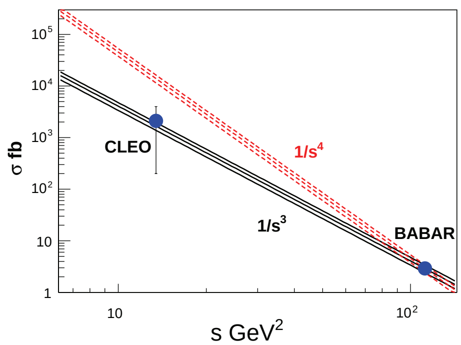

Fig. 3. Cross section extrapolations based on *BABAR*'s measurement at $\sqrt{s} = 10.58$ GeV assuming a $1/s^3$ (black) or $1/s^4$ (red) energy dependence. The bands show one standard deviation uncertainties in the extrapolations. The CLEO measurement at $\sqrt{s} = 3.67$ GeV is also shown.

4. $e^+e^- \to \rho^+\rho^-$ (preliminary result)

Since charged ρ's are involved, the $e^+e^- \to \rho^+\rho^-$ process is unlikely to occur through TVPA [?,?,?], unless there is significant final quark recombination between the products of the two virtual photons, or unless there is significant final state interaction ($e^+e^- \to \rho^0\rho^0 \to \rho^+\rho^-$) [**?**]. Assuming a one-photon production mechanism, this VV ($\rho^+\rho^-$) final state is described by three helicity amplitudes. A study of this reaction can then provide an experimental test of QCD at the amplitude level [?] [?] through investigation of the final states angular correlations.

This analysis uses 343 fb^{-1} of e^+e^- colliding beam data collected on the $\Upsilon(4S)$ resonance at $\sqrt{s} = 10.58$ GeV and 36 fb^{-1} collected 40 MeV lower. Events with exactly two well-reconstructed, oppositely charged tracks identified as pions and at least two well-reconstructed π^0s are selected. We fit

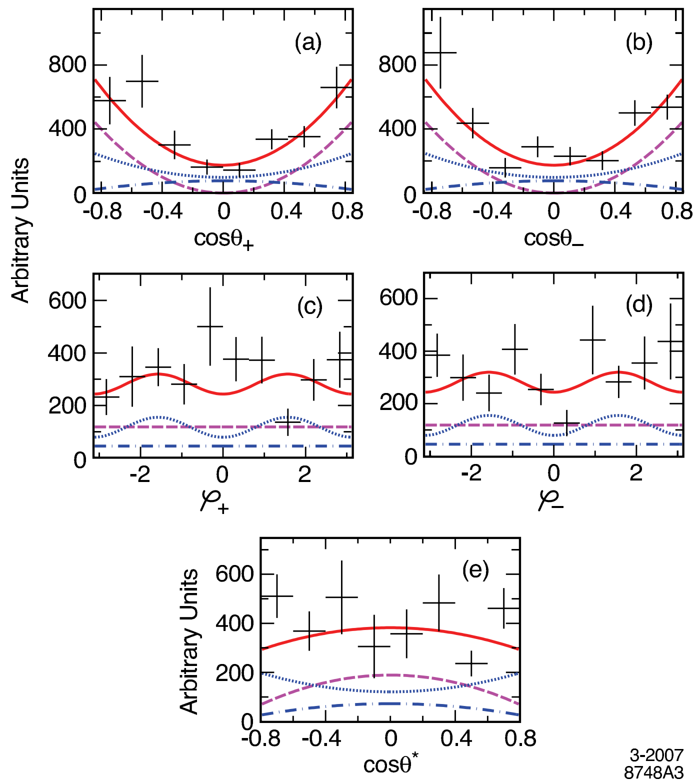

Fig. 4. The s-weighted and efficiency corrected a) $\cos\theta_+$ b) $\cos\theta_-$ c) φ_+ d) φ_- e) $\cos\theta^*$ distributions for $e^+e^- \to \rho^+\rho^-$. The magenta dashed curves show the contributions from F_{00}, the blue dotted curves are F_{10}, the blue dashed-dotted curves are F_{11}, and the solid red curves show the total result.

the charged tracks to a common vertex, and require the χ^2 probability to exceed 0.1%. Each π^0 is reconstructed through its $\gamma\gamma$ decay channel by requiring the two photon invariant mass to be within the range [0.1,0.16] GeV/c^2, and then constraining its mass to the nominal value. We accept events with $|m_{\pi^+\pi^0\pi^-\pi^0} - E_{cm}| < 0.28$ GeV and $|\Delta p| < 0.2$ GeV/c, where E_{cm} is the total c.m. energy, and Δp is the momentum difference between the $\pi^+\pi^0\pi^-\pi^0$ system and the e^+e^- system.

We define the $\rho^\pm$ mass intervals as [0.5,1.1] GeV/c^2, and extract 308±25 $\rho^+\rho^-$ signal events in the defined mass region. The significance is estimated to be 9.5 sigma.

Assuming $\rho^+\rho^-$ is produced through one photon or $\Upsilon(4S)$, there are three independent helicity amplitudes ($\mathrm{F}_{\mu\nu}$, μ/ν is the helicity of ρ^+/ρ^-), F_{00}, F_{10}, and F_{11} ($\mathrm{F}_{10} = \mathrm{F}_{-10} = \mathrm{F}_{0\pm1}$, $\mathrm{F}_{11} = \mathrm{F}_{-1-1}$) [**?**]. The one-dimensional projections for the decay angles involved can be expressed as:

$$\frac{dN}{d\cos\theta^*} \propto (\sin^2\theta^*|F_{00}|^2 + 2(1+\cos^2\theta^*)|F_{10}|^2 + 2\sin^2\theta^*|F_{11}|^2) \qquad (2)$$

$$\frac{dN}{d\cos\theta_\pm} \propto (\cos^2\theta_\pm|F_{00}|^2 + (1+\cos^2\theta_\pm)|F_{10}|^2 + \sin^2\theta_\pm|F_{11}|^2) \qquad (3)$$

$$\frac{dN}{d\varphi_\pm} \propto (|F_{00}|^2 + (4-\cos 2\varphi_\pm)|F_{10}|^2 + 2|F_{11}|^2) \qquad (4)$$

where θ^* is the ρ production angle, $\theta_\pm$ ($\varphi_\pm$) is the helicity (azimuthal) angle of the pion from ρ decay. From the two dimensional mass fit ($\pi^+\pi^0$ and $\pi^-\pi^0$), we can calculate a $\rho^+\rho^-$ signal sWeight [**?**] for each event (including those events outside the defined $\rho^\pm$ mass window) and use it to produce signal angular distributions. We fit the five angular distributions to Equs. **??**, **??** and **??** simultaneously by minimizing χ^2. The correlations among the five angles are neglected; this is justified by means of fits to events generated according the assumed PDFs (toy MC). We normalize the amplitudes such that $|F_{00}|^2+4|F_{10}|^2+2|F_{11}|^2 = 1$ since we have 1 F_{00}, 4 F_{10} and 2 F_{11} amplitude contributions. The normalized amplitudes from the fit are found to be in the ratio: $|\mathrm{F}_{00}|^2 : |\mathrm{F}_{10}|^2 : |\mathrm{F}_{11}|^2 = 0.51 \pm 0.14(\mathrm{stat}) \pm 0.02(\mathrm{syst}) : 0.10 \pm 0.04(\mathrm{stat}) \pm 0.01(\mathrm{syst}) : 0.04 \pm 0.03(\mathrm{stat}) \pm 0.00(\mathrm{syst})$, and $|\mathrm{F}_{00}|^2$ deviates from 1 with significance more than 3 sigma. This disagrees with a QCD prediction [?], and suggests that either the decay is not dominated by single-photon exchange as naively expected, or that the QCD prediction does not apply to data in our energy region. The final radiation-corrected cross section for $0.5 < m_{\rho^\pm} < 1.1$ GeV/c^2, and within $|\cos\theta^*| < 0.8$, $|\cos\theta_\pm| < 0.85$, at near $\sqrt{s} = 10.58$ GeV (assuming only one-photon production) is:

$$\sigma_{\mathrm{fid}}(e^+e^- \to \rho^+\rho^-) = 8.5 \pm 0.7(\mathrm{stat}) \pm 1.5(\mathrm{syst})\ \mathrm{fb}.$$

We extend the cross section calculation from our acceptance region to the full phase space using the fitted amplitude values, and find $20.0 \pm 1.6(\mathrm{stat}) \pm 3.6(\mathrm{syst}) \pm 1.7(\mathrm{ampl})$ fb; the third uncertainty is due to the amplitude uncertainties.

5. Conclusion

We report the first observation of e^+e^- annihilations into hadronic states of positive C-parity, $\rho^0\rho^0$ and $\phi\rho^0$. We also report the observation of the process $e^+e^- \to \phi\eta$, and obtain preliminary results on $e^+e^- \to \rho^+\rho^-$. The measured helicity amplitude magnitudes from $e^+e^- \to \rho^+\rho^-$ contradict a QCD prediction at a significance of more than 3 sigma.

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