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QCD Studies in Two-Photon Collisions at CLEO

Vladimir Savinov
University of Pittsburgh, Pittsburgh

We review the results of two-photon measurements performed up to date by the CLEO experiment at Cornell University, Ithaca, NY. These measurements provide an almost background-free virtual laboratory to study strong interactions in the process of the e^+e^- scattering. We discuss the measurements of two-photon partial widths of charmonium, cross sections for hadron pairs production, antisearch for glueballs and the measurements of $\gamma^*\gamma \to$ pseudoscalar meson transition form factors. We emphasize the importance of other possible analyses, favorable trigger conditions and selection criteria of the presently running experiment and the advantages of CLEOc—the future τ-charm factory with the existing CLEO III detector.

1. INTRODUCTION

One of the ways to study properties of strong interactions, surprisingly, is to collide high energy photons. Photons do not interact strongly, however, in the presence of other photons they can fluctuate into quark pairs that have a sizable probability to realize as hadrons. Space-like photons of relatively high energies can be obtained in the process of the e^+e^- scattering, that is, in the $e^+e^- \to e^+e^-$hadrons reactions, where hadrons are produced in charge-even, that is, $C = +1$ state. These processes proceed mainly by a two-photon fusion therefore telling us about the strength of relevant $\gamma\gamma$ couplings and the properties of particles born in such reactions. When a single hadron is born, the production cross section is proportional to its two-photon partial width thus allowing the measurement of this quantity in the time-reversed two-photon decay. When (at least) one of the photons is substantially off-mass shell, we can measure the form factors associated with two-photon transitions that probe spatial distribution of electric charge inside of produced hadrons thus telling us about respective wave functions, that is, details of binding potential. The kinematics of two-photon collisions in the e^+e^- scattering is described elsewhere [1, 2].

2. CLEO EXPERIMENT

The results discussed in this short review were obtained from the data collected at the Cornell Electron Storage Ring (CESR) with the CLEO detector. The results are based on statistics that correspond to an integrated e^+e^- luminosity of up to $9.2 fb^{-1}$ collected at the Υ(4S) energy of 10.58 GeV and up to $4.6 fb^{-1}$ collected approximately 60 MeV below the Υ(4S) energy. Our data sample was recorded with two configurations of the CLEO detector. The first third of the data were recorded with the CLEO II detector [3] which consisted of three cylindrical drift chambers placed in an axial solenoidal magnetic field of 1.5T, a CsI(Tl)-crystal electromagnetic calorimeter, a time-of-flight (TOF) plastic scintillator system and a muon system (proportional counters embedded at various depths in the steel absorber). Two thirds of the data were taken with the CLEO II.V configuration of the detector where the innermost drift chamber was replaced by a silicon vertex detector [4] and the argon-ethane gas of the main drift chamber was changed to a helium-propane mixture. This upgrade led to improved resolutions in momentum and specific ionization energy loss (dE/dx) measurements.

The three-tier CLEO trigger system [5] complemented by the software filter for beam-gas rejection utilizes the information from the two outer drift chambers, the TOF system and electromagnetic calorimeter. The response of the detector is modeled with a GEANT-based [6] Monte Carlo (MC) simulation program. The data and simulated samples are processed by the same event reconstruction program. Whenever possible the efficiencies are either calibrated or corrected for the difference between simulated and actual detector responses using direct measurements from independent data. This is especially important for understanding the trigger efficiency as most two-photon events experience strong Lorentz boost along the e^+e^- collision axis often missing detection and failing to trigger data taking.

All analyses presented in this summary employ complete reconstruction of hadronic final states born in the process of two-photon fusion. In all but the form factor measurements, final state leptons escape detection in the beam pipe because of kinematics of two-photon collisions that favors small scattering angles for electron and positron. The detailed descriptions of the reviewed CLEO analyses can be found in the references to CLEO papers provided in the bibliography section. Relevant theoretical references can be found in the CLEO papers.

3. CHARMONIUM MEASUREMENTS

CLEO measured two-photon partial widths of χ_{c_2} in the $J/\psi\gamma$ final state [7], and, more recently, of the η_c in the

$K_s K^{\pm}\pi^{\mp}$ final state [8] and χ_{c0} and χ_{c2} in the $\pi^+\pi^-\pi^+\pi^-$ decays [9]. The most recent results are $\Gamma_{\gamma\gamma}(\chi_{c0}) = (3.76 \pm 0.65(\text{stat}) \pm 0.41(\text{syst}) \pm 1.69(\text{br}))$ keV, $\Gamma_{\gamma\gamma}(\chi_{c2}) = (0.53 \pm 0.15(\text{stat}) \pm 0.06(\text{syst}) \pm 0.22(\text{br}))$ keV and $\Gamma_{\gamma\gamma}(\eta_c) = (7.6 \pm 0.8(\text{stat}) \pm 0.4(\text{syst}) \pm 2.3(\text{br}))$ keV.

Our results on two-photon partial widths of charmonium are consistent with some of the theoretical predictions we refer to in our publications. It should be emphasized that the extraction of α_s from our data presented in our papers was done mainly to compare our results with other similar measurements. As became known recently [10], theoretical attempts to include next-to-next to leading order corrections in α_s to perturbative Quantum Chromodynamics (pQCD) predictions for two-photon partial widths diverge and fail thus making such α_s extraction poorly defined. Another important aspect of the analyses presented in our papers on charmonium is the assumption about absence of the interference between resonant and continuum two-photon production of the studied final states. In the new η_c analysis where we had sufficient statistics to study possible effect of such interference, we found no convincing indication of this effect. Therefore, no interference was taken into account when estimating systematic effects in either of our charmonium analyses.

Our new result for the χ_{c0} is consistent with the previous result [7] obtained in the $J/\psi\gamma$ mode. Also, our measurement of the product of η_c two-photon partial width and $\eta_c \to K_s K\pi$ branching fraction is consistent with our preliminary results [11]. We would like to alert the reader to the fact that there is a large uncertainty in our measurements of two-photon partial widths as we measure the products of these with the branching fractions for the final states where we reconstruct charmonium. Therefore we inherit large uncertainties in the experimental values for these branching fractions when we convert the measured products to the measurements of two-photon partial widths. Great care should be executed when comparing the results of different experiments as a more recent experiment often uses an updated value for the final state branching fraction as an older one. A good strategy would be to have old editions of the review of particle properties available for such comparisons.

In our η_c analysis we also measured the mass and (total) width of this charmonium state: $M(\eta_c) = (2980.4 \pm 2.3(\text{stat}) \pm 0.6(\text{syst}))$ MeV and $M(\eta_c) = (27.0 \pm 5.8(\text{stat}) \pm 1.4(\text{syst}))$ MeV. While we did a thorough study of systematics that could be a source of experimental error, we have to emphasize that we have no calibration channel that would be a "golden-bullet" kind of a *proof* that we understand the mass and width measurements around 3 GeV in the four charged tracks final states at CLEO. This is to provide the reader with more information, not to give an impression that we have any doubts in our results. We refer the reader to our publication on the subject [8] for more information.

4. HADRON PAIR PRODUCTION

CLEO measured a number of cross sections for two-photon production of hadron pairs. These include combined measurement for $\pi^+\pi^-$ and K^+K^- pairs [12], $p\bar{p}$ pairs[13] and $\Lambda\bar{\Lambda}$ pairs[14]. Our results agree well with the predictions of perturbative QCD and diquark model, especially at higher invariant masses of produced pairs. The agreement for the values and shapes of the cross sections is also reasonable in the region of relatively low pair masses and this fact is quite surprising because predictions based on perturbative QCD are not expected to hold there. However, and more important, our result proves that there is a qualitative difference between hadron pairs produced at lower masses and at higher masses where the definitions of lower and higher are CLEO-specific and are determined by energies available to us in our experiment. This qualitative difference is demonstrated in Figure 1(a) and Figure 1(b) for $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to pp$ measurements, respectively. These figures show efficiency-corrected and background-subtracted distributions of our data (points with the error bars) for several intervals of hadron pairs invariant mass versus $|\cos\theta^*|$, where θ^* is helicity angle. Curves in figures show (a) perturbative prediction [15] made by Brodsky and Lepage assuming their mechanism $\gamma\gamma \to q\bar{q}g \to \pi^+\pi^-$ (BL) for pion pairs production and (b) diquark model [16] and perturbative [17] predictions for $p\bar{p}$ production. Theoretical curves shown in Figure 1(b) are normalized to our data and are displayed only for $p\bar{p}$ invariant mass above 2.5 GeV. Notice that there are two vertical scales for two distributions shown in Figure 1(b), the right-side scale is for the events collected at higher invariant mass. Helicity angle is measured between the direction of one of the hadrons in the rest frame of two photons and the momentum direction for a pair in the laboratory reference frame. Notice that the range of the helicity angle-related variable is restricted to be below 0.6 which is a typical acceptance region for a two-photon experiment. It would take photons to be highly off-mass shell to extend the range of non-zero acceptance for cosine of helicity angle. This analysis is being planned, meanwhile, notice that the distribution for the hadron pairs in the region of higher invariant mass shows a clear transition to the diffractive (that is, perturbative) behavior when compared to that for the pairs in the region of lower invariant mass.

5. GLUEBALL ANTISEARCH

The possible existence of glueballs, that is, hadrons made of constituent glue, does not contradict to known experimental and theoretical facts. More important, such states are predicted to exist by calculations on the lattice (LQCD). The main caveat here is that these predictions are made in the so-called quenched approximation, when quenching is removed, there is no consensus yet if the predictions are going to hold. Therefore, the possible discovery of glueballs should help to advance the theory. On the other hand, it is also possible that no glue bound states could ever exist and this scenario would not be a great disappointment, neither a catastrophe for LQCD. If the latter non-existence scenario realizes in nature, it is still possible that glueball-like field configurations play an important role in non-perturbative QCD processes acting as a mass scale that modifies predictions for cross sections at relatively low

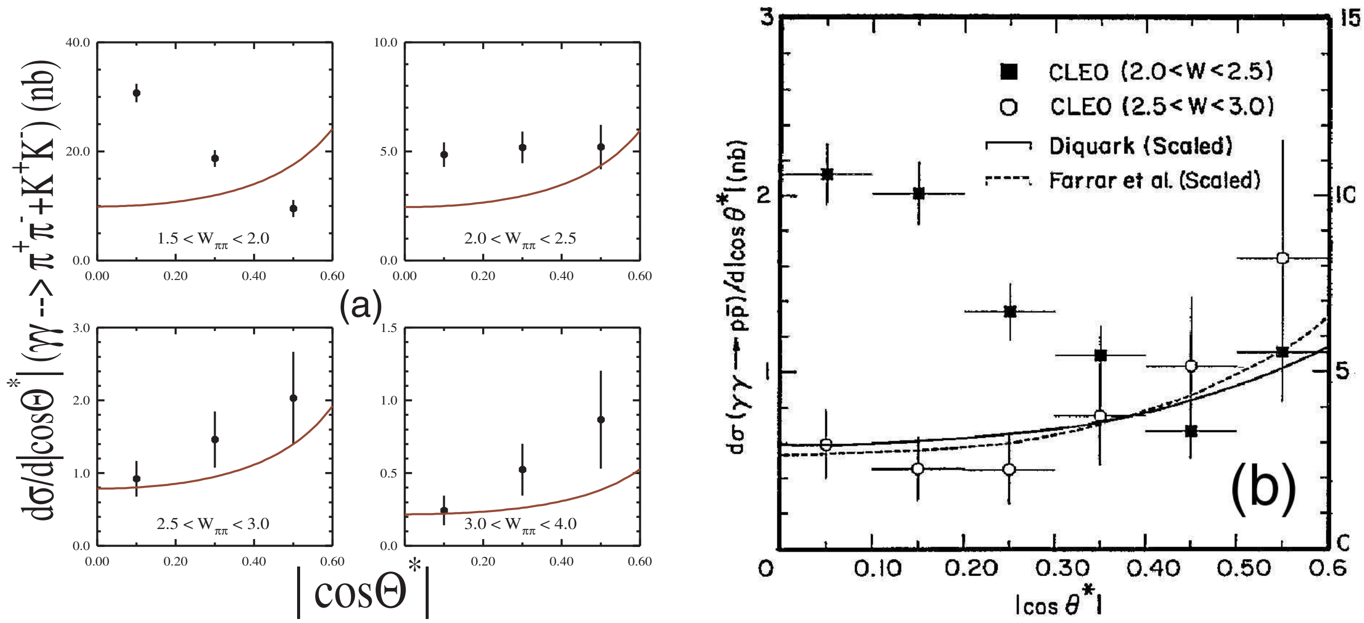

Figure 1: CLEO results on (a) $\pi\pi$ and (b) $p\bar{p}$ pairs production. See the text for more information.

energies, that is, below 10 GeV.

So far CLEO has only searched for the most famous glueball candidate, $f_j(2220)$ observed a few years ago in radiative J/ψ decays at BES. We searched for this resonance in the K_sK_s and $\pi\pi$ final states and set 95% CL upper limits on the products of its two-photon partial width and relevant branching fractions of $\Gamma_{\gamma\gamma}(f_j(2220))\mathcal{B}(f_j(2220) \to K_sK_s) < 1.3$eV and $\Gamma_{\gamma\gamma}(f_j(2220))\mathcal{B}(f_j(2220) \to \pi^+\pi^-\pi^+\pi^-) < 2.5$eV, respectively. Small values of these upper limits are not surprising as if the $f_j(2220)$ state existed, its electromagnetic coupling would be very small because gluons do not couple to photons directly. Invariant mass plots for relevant final states from our analyses are shown in Figures 2(a) and 2(b). Figure 2(a) shows a histogram for our data, a curve approximating the experimental line shape for the not-found in our analyses $f_j(2220)$ and the analytical shape chosen to approximate combinatorial and two-photon continuum backgrounds, arrows show the signal region used to estimate the upper limit. Figure 2(b) shows points with the errors for our data, a histogram describing the $f_j(2220)$ experimental line shape obtained from our signal MC simulation, a curve that shows the result of binned maximum likelihood fit to separate the sample into signal and background contributions, the insert shows the signal region. More information on CLEO antisearches for glueballs can be found in publications that describe these analyses [18, 19].

6. TRANSITION FORM FACTORS

In 1998 we published the results of our extensive analysis [20] of the $\gamma^*\gamma \to \mathcal{R}$ transition form factors for three resonances $\mathcal{R}$: π^0, η and η'. It turned out to be an important publication providing data that helped, among other applications, to reduce theoretical uncertainties in form factors predictions for semileptonic and hadronic decays of B and D mesons. Fixing these form factors is necessary for extracting the values of CKM matrix elements from data collected at existing and future experimental facilities. Our data were also used to reduce the theoretical uncertainty in hadronic contribution from light-by-light scattering to the result of the Muon $g-2$ experiment. According to a number of theoretical papers, our π^0 result proves the transition to perturbative QCD region at relatively low momentum transfer (negative squared mass of the highly off-shell photon). Our publication [20] also has references to theoretical papers where this conclusion has been challenged. We compare our π^0 result with some of the available theoretical predictions in Figure 3. This figure also shows the results of the CELLO experiment [21] at lower values of momentum transfer Q^2. The horizontal axis is momentum transfer Q^2 and the vertical axis is the product of Q^2 with the absolute value of the $\gamma^*\gamma \to \pi^0$ transition form factor. Notice that this form factor is proportional to the square root of the observed cross section after effects of the $e^+e^- \to e^+e^-\pi^0$ kinematics are removed. The horizontal line shows the well-defined $Q^2 \to \infty$ limit of pQCD [15]. Figure 3(a) compares our results with pQCD-inspired prediction [22] that uses (the unique) asymptotic [15] wave function (shown with solid curve) and Chernyak-Zhitnitsky (CZ) model [23] wave function (shown with dashed curve) to approximate non-perturbative effects. The dotted curve shows the effect of running α_s on the latter prediction. Figure 3(b) compares our results with another pQCD-based prediction [24], the solid curve is for asymptotic wave function and the dashed curve employs the CZ model distribution amplitude. Figure 3(c) compares our results with the theoretical prediction [25] based on QCD sum rules method [26]. Eventually, such methods should help to describe strong interactions in non-perturbative domain from first principles. Figure 3(d) compares our results with interpolation [15] sug-

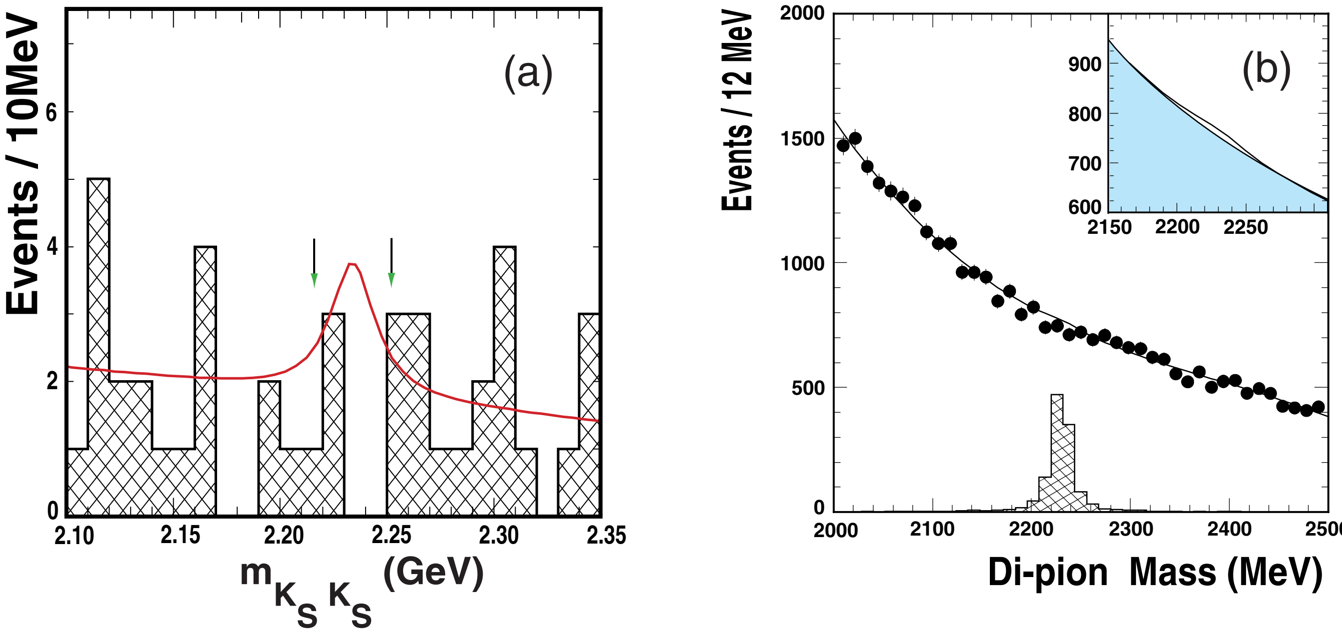

Figure 2: CLEO antisearch for $f_j(2220)$ in (a) $K_s K_s$ and (b) $\pi^+\pi^-$ channels. See the text for more information.

gested by Brodsky and Lepage (solid curve) that obeys both $Q^2 \to 0$ and $Q^2 \to \infty$ QCD limits. Amazingly, our results agree well with the $Q^2 \to \infty$ pQCD prediction corrected to first order in α_s (not shown in figure). The dashed curve shows the result of a phenomenology-based pole-mass fit to our data that does not obey $Q^2 \to \infty$ pQCD limit. Many other theoretical predictions are available in the literature. More information is available in our publication [20].

Our results for $\gamma^*\gamma \to \eta$ and $\gamma^*\gamma \to \eta'$ transition form factors (plots are not shown in this review) are in full agreement with the prediction based on mixing measured from two-photon partial widths for these resonances [27]. More interestingly, the η' result was utilized [28] to challenge the hypothesis of possible intrinsic charm [29] in η' suggested to explain the anomalously large branching fraction [30] discovered and measured by CLEO for the decay $B \to K\eta'$.

7. OTHER OPPORTUNITIES

Existing CLEO II and II.V data could be used for a variety of other interesting two-photon analyses probing dynamics of strong interactions. These include detailed analyses of $K_s K\pi$, $\eta\pi\pi$, $\pi^0\pi^0$ final states at invariant masses below 2.5 GeV/c^2 where glueball searches could be greatly extended, a study of a quantum mechanical interference between two-photon and bremsstrahlung production mechanisms for $\pi\pi$ pairs sensitive to relative strong phase between corresponding amplitudes, possible search for the η_c', analyses of axial-vector mesons produced when at least one of the photons is off-mass shell and many other projects. Possible analysis of π^0 production by two off-shell photons deserves special mention as this study could give a definitive answer about pQCD applicability at moderately high momentum transfer.

The specifics of the new CLEO III data could allow us to probe the threshold behavior of a number of two-photon hadronic cross sections. The optimistic prognosis here comes from the fact that no filtering has been done on CLEO III to reduce beam-gas contamination, courtesy of the powerful data acquisition system and event storing capabilities of the new experiment. It should be noted, however, that the new data samples of low final state particle multiplicities will not be ready for the CLEO user-level analysis for some time.

8. ADVANTAGES OF CLEOC

As the B factories at SLAC and in Japan came on-line and proved to be a great success, the CLEO experiment is changing the priorities and is about to start the new experimental program in the region of e^+e^- center-of-masses energies between 3 and 5 GeV. While the range of invariant masses of two-photon systems accessible at this new facility is going to be below ≈1.5 GeV, there are certain benefits associated with reduced Lorentz boost for low-mass two-photon production. For example, our estimates show that with the same detector geometry, the number of detected and reconstructed π^0 events accompanied by a detected electron or a positron per unit of e^+e^- luminosity could be by the order of magnitude higher than at $\Upsilon(4S)$ energies. The same estimate applies to $\pi\pi$ pairs that should allow us to probe the threshold production important for chiral perturbation theory predictions. The increase in the number of events is achieved by becoming sensitive to the region of lower momentum transfer. Therefore, at CLEOc we lose sensitivity in the perturbative region of high momentum transfer but become able to probe the highly non-perturbative

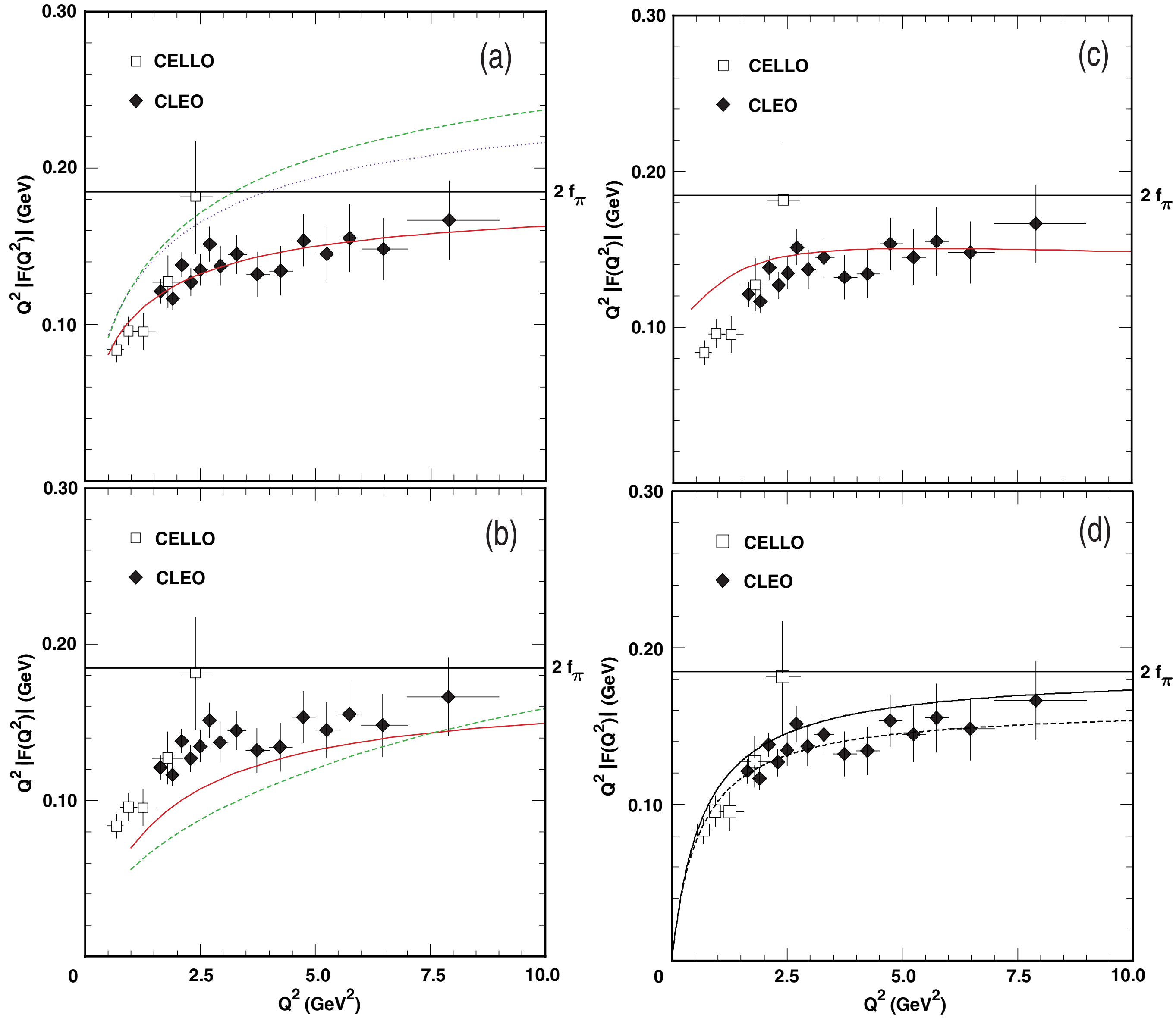

Figure 3: CLEO results on $\gamma^*\gamma \to \pi^0$ production. See the text for more information.

region of low momentum transfer. The measurements of the $\gamma^*\gamma^* \to \pi^0$ transition form factor and $\gamma^*\gamma \to \pi\pi$ cross sections at threshold are highlights among the two-photon program at CLEOc. We would like to emphasize that these measurements are also among interesting opportunities potentially available at the PEP-N experiment.

9. CONCLUSIONS

It has been known for a long time that two-photon processes provide a clean laboratory to study properties of strong interactions. The measurements of two-photon partial widths allow us to test the models of binding potential and mesons decays. When combined with results from radiative decays of J/ψ and, in the near future, of Υ resonances, two-photon partial widths can tell us about the possible mixing of mesons with glueballs. Extending $\gamma^*\gamma$-meson transition form factors measurements to the axial-vector sector should allow more tests of model wave functions and theoretical predictions eventually derived from the first principles. These measurements help to fix hadronic uncertainties in precise measurements of CKM matrix elements and in searches for new physics at existing and future experiments. Two-photon measurements at the e^+e^- machines continue to play an important role in learning about properties of strong interactions.

The credit for the analyses summarized in this short review belongs to the members of the CLEO collaboration, past and present. These usually challenging physics analyses are the product of thorough studies done by many people. Besides efforts of my CLEO colleagues, CESR accelerator physicists and support personnel, I would like to acknowledge interesting and stimulating discussions with Stanley Brodsky, Thorsten Feldman, Iliya Ginzburg, Peter Kroll, Kirill Melnikov, Valery Serbo and Arkady Vainshtein. It is my pleasure to thank the organizers of the PEP-N workshop for creating a productive and stimulating atmosphere.

REFERENCES

[1] V. M. Budnev *et al.*, *Phys. Rep.* **C15** (1975), 181.
[2] M. Poppe, *Int. J. Mod. Phys.* **1** (1986), 545.
[3] CLEO Collaboration, Y. Kubota *et al.*, *Nucl. Instrum. Methods* **A320** (1992), 66.
[4] T. Hill, *Nucl. Instrum. Methods* **A418** (1998), 32.
[5] CLEO Collaboration, C. Bebek *et al.*, *Nucl. Instrum. Methods* **A302** (1992), 261.
[6] R. Brun *et al.*, GEANT 3.15, CERN Report No. DD/EE/84-1 (1987).
[7] CLEO Collaboration, J. Dominick *et al.*, *Phys. Rev.* **D50** (1994), 4265.
[8] CLEO Collaboration, G. Brandenburg *et al.*, *Phys. Rev. Lett.* **85** (2000), 3095.
[9] CLEO Collaboration, B. I. Eisenstein *et al.*, hep-ex/0104042, submitted to *Phys. Rev. Lett.*
[10] Private communication with Kirill Melnikov from SLAC.
[11] V. Savinov and R. Fulton (CLEO Collaboration), Proceedings of the PHOTON95 conference, edited by David J. Miller *et al.*, World Scientific, 1995.
[12] CLEO Collaboration, J. Dominick *et al.*, *Phys. Rev.* **D50** (1994), 3027.
[13] CLEO Collaboration, M. Artuso *et al.*, *Phys. Rev.* **D50** (1994), 5484.
[14] CLEO Collaboration, S. Anderson *et al.*, *Phys. Rev.* **D56** (1997), 2485.
[15] S. J. Brodsky and G. P. Lepage, *Phys. Rev.* **D24** (1981), 1808.
[16] P. Kroll *et al.*, *Phys. Lett.* **B316** (1994), 546.
[17] G. Farrar *et al.*, *Nucl. Phys.* **B259** (1985), 702.
[18] CLEO Collaboration, R. Godang *et al.*, *Phys. Rev. Lett.* **79** (1997), 3829.
[19] CLEO Collaboration, M. S. Alam *et al.*, *Phys. Rev. Lett.* **81** (1998), 3328.
[20] CLEO Collaboration, J. Gronberg *et al.*, *Phys. Rev.* **D57** (1998), 33.
[21] CELLO Collaboration, H.-J. Behrend *et al.*, *Z. Phys.* **C49** (1991), 401.
[22] R. Jakob *et al.*, *J. Phys.* **G22** (1996), 45.
[23] V. L. Chernyak and A. R. Zhitnitsky, *Phys. Rep.* **D112** (1984), 173.
[24] F.-G. Cao *et al.*, *Phys. Rev.* **D53** (1996), 6582.
[25] A. V. Radyushkin and R. Ruskov, *Phys. Lett.* **B374** (1996), 173.
[26] M. A. Shifman *et al.*, *Nucl. Phys.* **B147** (1979), 385.
[27] T. Feldmann and P. Kroll, *Phys. Rev.* **D58** (1998), 057501.
[28] T. Feldmann and P. Kroll, *Eur. Phys. J.* **C5** (1998), 327.
[29] I. Halperin and A. Zhitnitsky, *Phys. Rev.* **D56** (1997), 7247.
[30] CLEO Collaboration, B. H. Behrens *et al.*, *Phys. Rev. Lett.* **80** (1998), 3710.