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Two-Photon Physics in the 1990's †

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ABSTRACT

The successful exploitation of e^+e^- storage rings for the study of two-photon interactions over the past decade will continue with exclusive measurements at the high luminosity frontier with CLEO-II and inclusive studies at the high-energy frontier with experiments at LEP and TRISTAN. Specialized contributions can be expected from the KEDR experiment (double-tagging and low-Q^2 measurements), the HERA ep collider (gluon distribution in the photon), and heavy ion colliders such as RHIC (contrasting pomeron-pomeron with photon-photon collisions). Construction and operation of a B Factory will allow very large increases in two-photon rates, extending the exclusive mass reach up to 5 GeV. Production of higher mass states will require development of very high energy linear colliders. Either the use of virtual bremsstrahlung or beamstrahlung at such machines will allow measurements of the C=+1 bottomonium states. To reach the weak mass scale and toponium, it will be necessary to use high-power lasers and Compton back scattering to convert electron beams to photon beams and collide them.

1. Introduction

1.1. Present Status

The study of two-photon interactions has proven to be a very productive source of information[1] about QED, QCD, and hadron spectroscopy. The two-photon reaction is accessible via the emission of virtual photons (i.e. virtual bremsstrahlung) from the $e^\pm$ circulating in storage rings. When neither of the scattered leptons is detected (untagged reactions), the virtual photons are nearly real and can produce C=+1, even-spin, hadronic resonances not easily studied in e^+e^- interactions. A measurement of the two-photon coupling, $\Gamma\gamma\gamma \propto (e_q)^4$, determines the quark content of the produced meson and can indicate the presence of exotic states. Also of interest is the untagged production of hadron pairs and inclusive jet production, since perturbative QCD makes explicit predictions about the rates for these processes. Detection of either of the scattered $e^\pm$ (i.e. single-tagged reactions) allows the production of spin-1 mesons (including $J^{PC}=1^{-+}$ $q\bar{q}g$ hybrids) and invites comparison to QCD predictions for the photon structure functions and meson transition form factors. Detection of both scattered leptons (double-tagging) provides

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reconstruction of the final state kinematics without the need for detection of all of the hadrons, leading to sensitive measurements of cross sections and structure functions, along with searches for exotic, high-mass resonances. Unfortunately, the advantages of tagging are partially offset by the sharp decline in rate with increasing tag angle.

The first generation of experiments[2] have accumulated 100-500 pb^{-1} of data with detectors optimized for e^+e^- annihilation reactions, and thus acceptances for the boosted system produced in two-photon reactions have been rather low. Still most of the ground state pseudoscalar and tensor meson nonets have been measured, with upper limits for radial excitations and $s\bar{s}$ mesons of order BR * $\Gamma\gamma\gamma \sim 0.1$ keV. There are some hints of exotic states, although nothing conclusive as of yet. Many exclusive channels have been examined and the rates compared to perturbative QCD predictions with varying success. Often the shape of the cross section with mass agrees but the normalization doesn't, indicating we are still in the region where resonances give large contributions. The photon structure function and the total cross section have been measured well at low two-photon c.m. energy (W) and virtual photon mass ($q^2 = -Q^2$), where vector dominance is most important, but only limited data is available at higher Q^2 where perturbative QCD should apply. First measurements have been made of pseudoscalar meson transition form factors but again statistics are lacking in the high Q^2 region where QCD predictions should be reliable. Only a few double-tagged measurements exist, mainly of the total two-photon cross section and a search for high mass resonances using the missing mass technique.

1.2. Interesting Questions

There are still many intriguing problems to be understood in two-photon physics, most of which have been highlighted by presentations at this workshop. In the inclusive area, the focus at present is on the whole issue of 'minijets', or more generally, on the parton distributions inside the photon. It may well be that the contributions from 'resolved' photons can help explain the long-standing excess of jet events at moderate p_t in two-photon reactions. Since this issue looms large for future colliders, it has attracted considerable interest[3] from both theorists and experimentalists. Although the pace of results on the photon structure function has slowed in recent years, contributions[4] from LEP and TRISTAN at high Q^2 may be able to improve our understanding of the sensitivity to the QCD parameter Λ_{MS}. A strong case can be made[5] for double-tagged measurements of the virtual photon structure function, which should allow a much cleaner test of QCD. There is also the question of the size of charm cross sections from two-photon reactions[6].

In the exclusive arena, the issue of $\gamma\gamma \longrightarrow \pi\pi$ at low mass has received considerable attention, both experimentally and theoretically[7]. However, in order to resolve which of the models best explains the cross section, there is a real need for substantially more data from a larger angular range. There has been some recent measurements of high-mass hadron pair production, but the data are still at relatively low W and thus do not pose a real challenge to the fundamental QCD predictions for these processes[8]. The real source of the large disparity in cross sections[9] between $\rho^0\rho^0$ and $\rho^+\rho^-$ is still not understood, although it is consistent with the production of interfering four-quark states[10]. There has also been the recent challenge from theorists to try to isolate 'semihard' processes from the data[11].

The last few years have seen the first measurements[12] of $J^{PC}=2^{-+}$ meson states with $\gamma\gamma$ reactions, along with theoretical predictions that radially and orbitally excited states should not have depressed two-photon couplings[13]. Other recent efforts have involved attempts to isolate scalar meson states[12], searches for exotics[14], and further measurements of the charmonium system[15]. The whole E/iota region (1400-1500 MeV) remains a mystery, although recent J/Psi[16] and hadron[17] data may aid in untangling the many states seen there. Finally, there is the conundrum of how to extend the mass reach of two-photon reactions to the bottomonium and toponium[18] systems.

2. The Next Few Years

Further progress in most of two-photon physics hinges on reaching higher W and Q^2 regimes. The problem is that the $\gamma\gamma$ luminosity from virtual bremsstrahlung decreases rapidly with both Q^2 and W. Also, the moving $\gamma\gamma$ system throws the (often low-multiplicity) final state into the forward regions of detectors, leading to low acceptances and high backgrounds. The best way to beat these problems for the near-term future is to boost the e^+e^- luminosity and to maximize the detector efficiency at low angles where the two-photon rates are largest. Clearly this is easiest at low energy storage rings such as CESR, where the two-photon system is not so severely boosted and the achievement of high luminosity has already been demonstrated. Thus resonance studies and, to a large extent, exclusive hadron production will likely be the focus there[19]. On the other hand, there are significant advantages to higher beam energies for the study of inclusive phenomena, since the kinematic range is larger and backgrounds from annihilation are less troublesome. LEP (especially LEP200) and TRISTAN should do much to improve our knowledge of structure functions and jets from two-photon interactions[20].

While it is unlikely that HERA will pursue two-photon physics *per se* (except for the possibility[21] of $\gamma\gamma \longrightarrow \mu\mu$), it may be the ideal place to study, using photon-gluon fusion, the structure of the photon at low Bjorken x values, where the contribution from gluons should be maximal[22]. Such measurements are vitally needed to predict hadronic rates from very high energy photon interactions in both particle physics and astrophysics[23].

2.1. Monte Carlo methods for event rate projections

In order to compare the capabilities of present and future experiments for two-photon work, I used a Monte Carlo generator which calculates the $e^+e^- \rightarrow e^+e^-X$ cross section and the exact $\gamma\gamma$ luminosity, given inputs of $\Gamma\gamma\gamma$ for resonances and the W dependence for continuum production. This Monte Carlo can apply kinematic cuts during the generation so as to simulate important geometrical acceptance factors such as angular and energy coverage of the detectors. Table 1 shows the definitions I used for the various facilities considered. TPC/$\gamma\gamma$ is shown because it is an example of present data and supplied a normalization for the event rate predictions. In the case of LEP and TRISTAN, I used a generic 'detector' which is really the most favorable geometry of the real detectors; note the somewhat arbitrary assumption that at least some of the LEP experiments will use their luminosity monitors for tagging, while the TRISTAN experiments will not.

I have not tried to simulate the KEDR detector[24], to be used with the upgraded VEPP4M

storage ring (with beam energies ~ 5 GeV), due to its very unusual small-angle tagging arrangement. Assuming it can get sufficient running time, this facility, with its state-of-the-art detector and dedication to two-photon physics, should produce good measurements of the two-photon cross section in double-tagged mode, and perform studies which require low-Q^2 coverage (e.g. spin-1 meson production). However, the expected luminosity (~ 4 x 10^{31} cm^{-2} s^{-1}) is much lower than at Cornell (> 2.5 x 10^{32} cm^{-2} s^{-1}) so it will not be competitive for many processes.

Table 1 Definition of experiments for Monte Carlo rate studies

Experiment (Beam Energy)	*Expected Luminosity* [25] *(pb^{-1})*	*Min. Hadron Angle (mrad)*	*Min. Tag Angle (mrad)*	*Min. Tag Energy (GeV)*
TPC/Two-Gamma (14.5 GeV)	*140 (untagged)* *120 (single-tagged)*	*300*	*20*	*2.0*
TRISTAN (30 GeV)	*300*	*300*	*250*	*5.0*
LEP (46 GeV)	*50*	*300*	*30*	*5.0*
LEP200 (100 GeV)	*500*	*300*	*30*	*5.0*
CLEO-II (5.2 GeV)	*5000*	*220*	*220*	*0.5*
Asym. B Factory (3.1 x 9 GeV)	*100,000*	*300*	*300*	*0.5*

For studies of resonance production, I normalized the generated rates by dynamical acceptance factors (typically 2-10%) taken from TPC/$\gamma\gamma$ analyses of the same or similar processes. This will likely cause an underestimate of event rates since newer detectors have larger acceptances, especially for neutrals. In the case of continuum production, where the physics interest is mostly at high W and the dynamical acceptance is probably large, I quote rates using the geometric acceptance only.

These Monte Carlo tools are likely to be able to predict overall event rates to within a factor of three or so and should be somewhat more accurate for comparing the capabilities of different facilities. Detailed detector simulations would be necessary to predict event rates with higher precision and also to predict kinematic distributions.

Table 2 shows the physics models used to compare the different experiments, and the additional normalization factors used to account for dynamical acceptance. For resonance production, I chose several known resonances of different masses and two-photon widths to illustrate the potential for understanding the standard $q\bar{q}$ nonets. In addition, to get an idea of rates for production of exotic hadrons, I simulated a glueball candidate (the $\iota(1440)$, with the small theoretical prediction[26] for $\Gamma_{\gamma\gamma}$) and a state of mass 2 GeV and parameters consistent with expectations either for ss states[13] or possible hybrid or 'molecule' states[27]. I studied one exclusive (non-resonant) process, $\gamma\gamma \rightarrow \pi^+\pi^-$ at high W, using the QCD prediction for the two-photon cross section in a range where it should apply (although there is likely still some resonant contribution in the 2 < W < 3 GeV range which would increase event rates there). Finally, I used a crude model of an inclusive process just to give a feeling for the Q^2 range of the experiments for structure function and cross section

measurements. The results from this model reproduce the measurements of TPC/$\gamma\gamma$ [28] and AMY[29] at low to moderate Q^2 with reasonable accuracy and carry the expected QCD logarithmic rise with Q^2.

Table 2 Physics models used to compare different experiments

Process simulated	*Physics Parameters Input*	*Normalization Factor Used*
$\gamma\gamma \to \eta\ (550) \to \pi^+\pi^-\pi^0$	$\Gamma = 0.88$ keV; $\Gamma\gamma = 0.4$ keV; BR=0.24 ρ form factor	2% (untagged) 4% (tagged)
$\gamma\gamma \to \eta'(960) \to \pi^+\pi^-\gamma$	$\Gamma = 0.21$ MeV; $\Gamma\gamma = 4$ keV; BR=0.30 ρ form factor	2% (untagged) 4% (tagged)
$\gamma\gamma \to \eta_c\ (2980) \to \pi^+\pi^-\pi^+\pi^-$	$\Gamma = 10.3$ MeV; $\Gamma\gamma = 6$ keV; BR=0.012 ψ form factor	15%
$\gamma\gamma \to \iota\ (1440) \to K^+K^0_S\pi^-$ (glueball candidate)	$\Gamma = 50$ MeV; $\Gamma\gamma = 23$ eV; BR=1 Form factor = 1	1%
$\gamma\gamma \to X\ (2000) \to \pi^+\pi^-\pi^0$ (ss, 4-quark, hybrid meson)	$\Gamma = 200$ MeV; $\Gamma\gamma = 0.1$ keV; BR=0.1 ϕ form factor	5% (untagged) 10% (tagged)
$\gamma\gamma \to 1^{++}\ (1420) \to K^+K^0_S\pi^-$ (spin-1 meson)	$\Gamma = 50$ MeV; $\Gamma\gamma = 1.3$ keV; BR=1 ρ form factor	2%
$\gamma\gamma \to \pi^+\pi^-$ continuum (QCD)	$2 < W < 9$ GeV; $\sigma_{\gamma\gamma} = (30\ nb) * W^{-6}$ ρ form factor (worst case)	None
$\gamma\gamma \to \pi^+\pi^-$ continuum (inclusive model)	$W > 2$ GeV; $\sigma_{\gamma\gamma} = 300$ nb flat in W GVDM* ln $Q^2/(1\ GeV^2)$ form factor	None

2.2. Inclusive studies at LEP, TRISTAN

The large beam energies at these storage rings carry both advantages and disadvantages for two-photon physics. The cross sections are somewhat larger than at lower energy machines and the two-photon fluxes extend to considerably larger W. Furthermore, there is a big separation in kinematics between annihilation and two-photon events. The down side is that the large difference between the e^+e^- c.m. energy and W causes the two-photon system to be severely boosted, making acceptances for final-state particles and, especially for tag detection, smaller. Together with the rather small integrated luminosities (compared to those at low-energy machines), this will make it very difficult to study low-mass resonances or exclusive hadron production.

Thus the focus at the high-energy colliders is likely to be on inclusive studies, and especially on measurement of jets and the photon structure function which we have already seen early results from at this workshop[4]. Fig. 1 shows the Q^2 distribution from the inclusive Monte Carlo model for the various experiments. Note that only LEP200 will have significant event rates at very high Q^2 (> 1000 GeV^2), although LEP and TRISTAN experiments should make substantial earlier contributions at more modest Q^2 values. CLEO-II may be able to improve on the TPC/$\gamma\gamma$ measurements[28] of the photon structure function in the low Q^2 transition region between vector dominance and QCD.

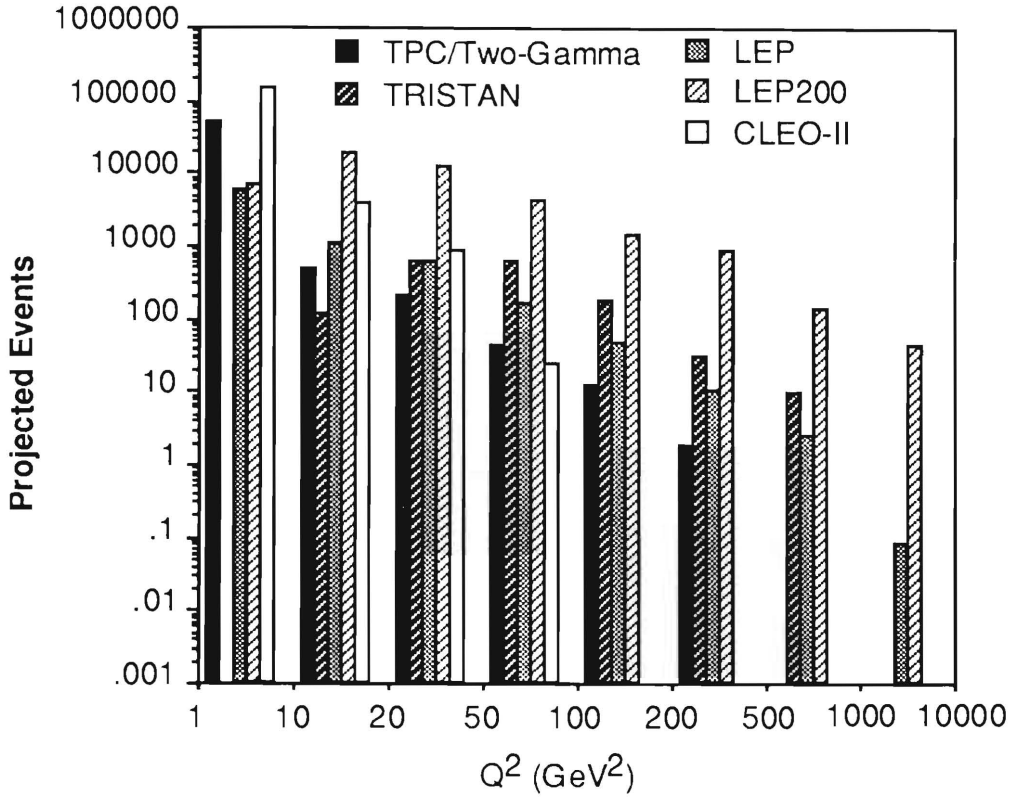

FIG. 1 Projected event rates vs. Q^2 from single-tagged two-photon inclusive production at present and future experiments.

2.3 Resonances and other exclusive processes at CLEO-II (and KEDR)

The principal advantages possessed by CLEO-II for two-photon physics are very high luminosity, coupled with an excellent detector for both charged and neutral particles. This is exactly what is needed to study exclusive hadron and resonance production. However, the low c.m. energy makes triggering more difficult, since the final-state momenta and energies are necessarily small and the backgrounds may be large. Also, the limited kinematic reach and nearness of annihilation backgrounds make it hard to do useful inclusive studies, except perhaps at low Q^2 and W.

Fig. 2 shows the untagged resonance event rates expected from the various experiments; clearly CLEO-II will dominate here for the next few years. Standard $q\bar{q}$ nonets with masses up to 2 GeV should be considerably better understood with such data and it is likely that $s\bar{s}$ mesons, radial excitations, and some exotic states will be identified. Our understanding of the charmonium sector should have improved as well, with real feedback given to the theoretical models. However, statistics for typical states expected in the 2-3 GeV

mass region will remain too low to do the detailed partial wave analyses needed to establish quantum numbers in most cases. In the single-tagged mode, shown in Fig. 3, only modest improvement is expected over present results from CLEO-II and none of the other experiments is likely to contribute. This is largely due to the relatively poor low angle coverage of the newer experiments (e.g. minimum Q^2 values for beam energy tags are TPC/$\gamma\gamma$ = 0.1, CLEO-II = 1.3, LEP = 1.9, LEP200 = 9.0 and TRISTAN = 56 GeV^2). It may be possible to establish the parity for low-mass mesons such as the X(1420), and thus determine whether they are hybrid states[30], but it is doubtful that more massive spin-1 particles will be detected.

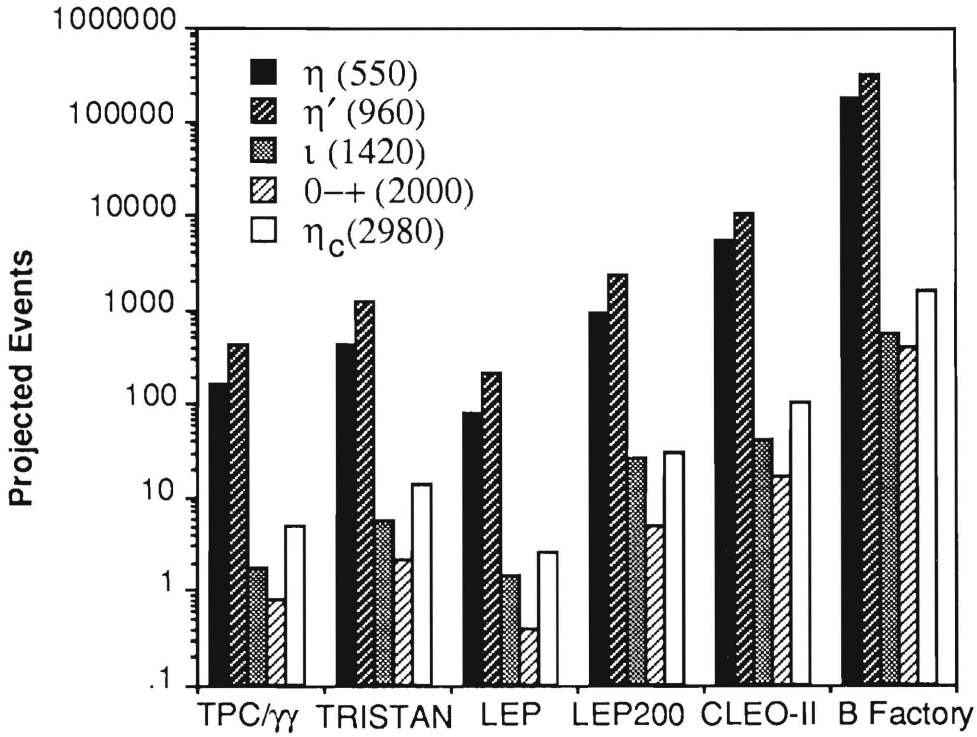

FIG. 2 Untagged two-photon resonance rates at various present and future experiments.

Finally, Fig. 4 and Fig. 5 show continuum (QCD) charged pion pair production rates as a function of W in untagged and single-tagged modes, respectively[31]. Clearly both CLEO-II and LEP200 will have some rate out to 4 GeV and should begin to test the QCD predictions for the W dependence of this and other processes. However, the single-tagged

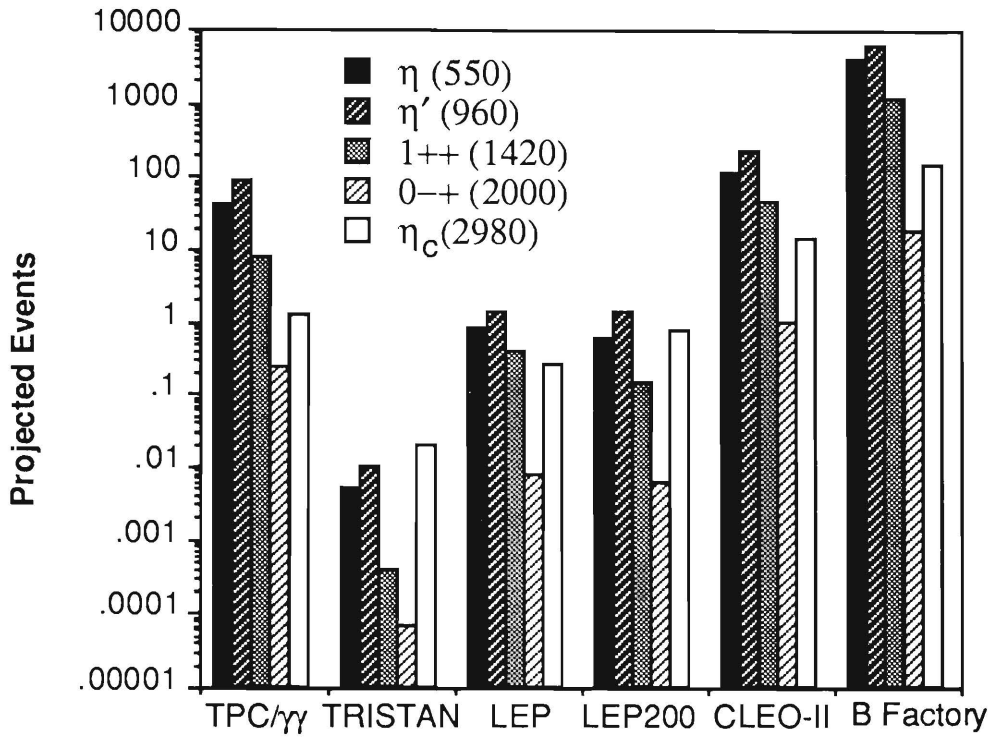

Fig. 3 Projected event rates from single-tagged two-photon resonance production at present and future experiments.

rates are probably too small to study the Q^2 dependence in any meaningful way. Note, however, that these event projections assumed a ρ form factor, which is probably too pessimistic at such high W. Employing a form factor of unity would increase untagged rates by factors like two and single-tagged rates by factors of ten (CLEO-II) to one hundred (LEP200) depending on the minimum detected Q^2. Even in this overly-optimistic scenario, however, the high-energy machines will have no significant single-tagged rate for this process for W > 3 GeV and CLEO-II will probe only up to about 3.5 GeV in mass.

3. The Factory Era

Thus, by the late 1990's, there will be much new data in all areas of two-photon physics. However, there will still be many issues which will not have been adequately addressed. For example, it is unlikely that any of the near-term experiments can contribute much to the study of low mass (< 1 GeV) ππ production due to the difficulties of detecting the necessarily small momenta and energies involved. Another area which may not be adequately studied is low Q^2 single-tagged studies (spin-1 production, structure function measurements) and double-tagged measurements of all sorts, because the near-term

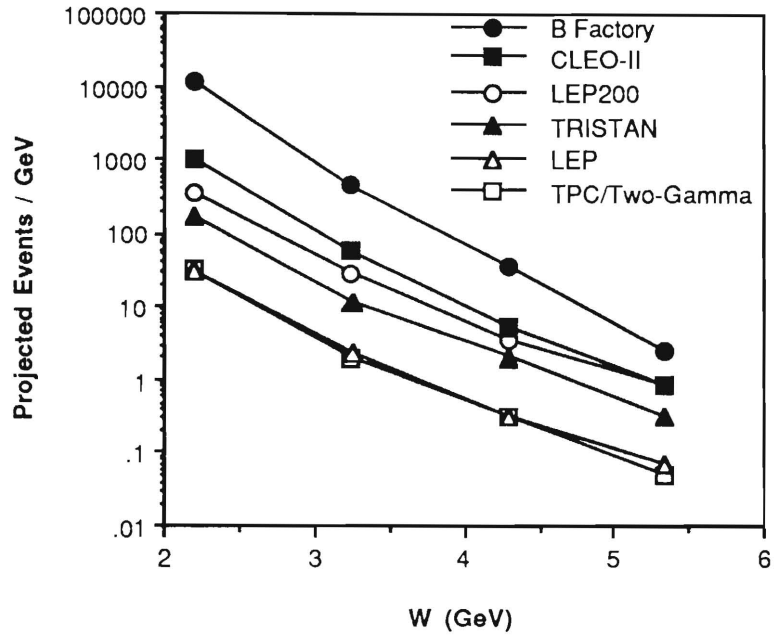

Fig. 4 Projected event rates vs. W for untagged two-photon continuum production of $\pi^+\pi^-$.

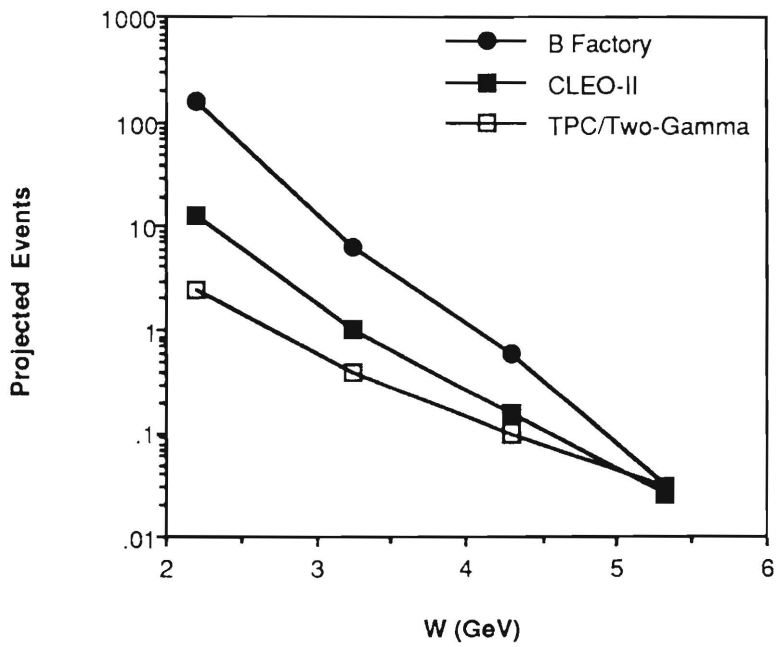

Fig. 5 Projected event rates vs. W for single-tagged two-photon production of continuum $\pi^+\pi^-$.

experiments do not in general have good low-angle coverage (KEDR will likely be the exception to this rule). However, the biggest unfilled need will be to extend the two-photon physics reach to higher W, where QCD predictions must apply. In all of these areas, the planned factory facilities should allow another quantum leap in progress for two-photon studies.

3.1. ϕ and τ/charm factories

Unquestionably these low energy facilities, especially the ϕ factories, will be the place to study low mass $\pi\pi$ production. The combination of relatively high luminosity with detectors optimized for detecting (and triggering on) low momenta and energies should allow very detailed measurements of both charged and neutral modes to be made from threshold up to nearly 1 GeV[32]. It is unlikely, however, that any other two-photon processes will be studied at these facilities due to their limited kinematic range.

3.2. B Factories

B factories[33] are very high luminosity storage rings, with the only really novel feature being the asymmetry in beam energies necessary to study CP violation. The designs call for a luminosity ten to forty times better than presently achieved at CESR, combined with a detector which has good solid-angle coverage, low energy thresholds, and a triggering scheme that should allow the efficient collection of two-photon events. Accumulation of data samples in the 100 fb^{-1} range should extend C=+1 resonance studies and exclusive hadron pair production measurements up through the charmonium sector to about 5 GeV, as shown in Figs. 2-5. Not only will the quark model nonets be much better understood with such large data samples, but the positive identification of exotic states, especially in the 2-3 GeV mass range, is very likely because partial wave analyses will become feasible. Furthermore, the expanded kinematic range will allow detailed comparisons with perturbative QCD predictions. In short, a B Factory will extend by at least an order of magnitude the two-photon physics reach which will be obtained at CLEO-II.

However, there are some important differences from present facilities caused by the asymmetry of the beam energies at a B Factory. As can be seen in Fig. 4, the untagged exclusive event rates drop faster with W at an asymmetric machine than at a symmetric one. This is because, at high mass, the resonance is produced with little motion in the lab frame in the symmetric case, but it is boosted forward, causing acceptance loss, in the asymmetric case. Only the very large integrated luminosity at the asymmetric B Factory will preserve useful rates out to W ~ 5 GeV. On the other hand, Fig. 5 shows that an asymmetric B Factory has a considerable advantage for low mass single-tagged resonance production, because the forward boost at an asymmetric machine tends to 'pull' the backward-going (low energy) tag out into the detector. This also skews the Q^2 distribution towards lower values at a B Factory than at CLEO-II. The effect fades at high mass because the corresponding tags already tend to have larger angles so as to balance the p_t of the hadrons.

Most of the high-mass (> 2 GeV) two-photon processes one would like to study will be relatively easy to obtain with the presently-envisioned B Factory detectors. Pipelined

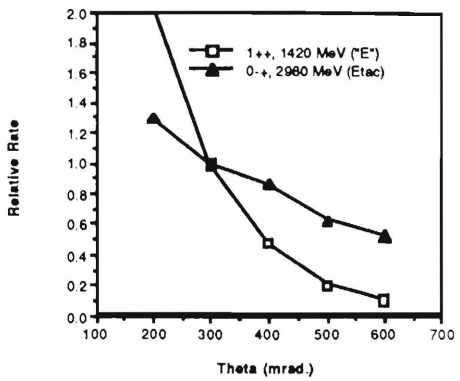

Fig. 6 Rate relative to that for θ=300 mrad. of single-tagged resonance production vs. θ.

triggers with sufficient energy range, segmentation, and flexibility for studying B decays will also be effective for capturing two-photon induced events. The ability to study both charged and neutral final states, which is a hallmark of CLEO-II, will be enhanced with the B Factory detectors, especially by better particle identification, with π/K separation up to 4 GeV in the barrel and forward endcap regions.

However, if one still wants to study the low-mass region (< 2 GeV), especially for low multiplicity final states, there would be considerably more impact on the detector. Triggering on two particles in the face of large cosmic ray (and possibly beam) backgrounds will certainly be difficult. Also of importance at low masses is the need to preserve endcap coverage to small polar angles, especially in the backwards direction for single-tagging purposes. Fig. 6 shows the dependence of the single-tagged rate for the production of a low-mass (X(1420) and high mass (η_c) resonance on this minimum polar angle. Clearly the rate for the low-mass state suffers dramatically if the endcap coverage is reduced. Furthermore, the ability to separate spin-1 mesons from even-spin mesons and to determine the parity of the spin-1 states relies heavily[30], for low-statistics samples, on having data in the range $0 < Q^2 < 0.5$ GeV^2, whereas the minimum Q^2 for a polar angle of 300 milliradians is about 0.5 GeV^2. Thus, for this physics, it might be necessary to add a low-angle tagging device in the backwards direction. Low angle detectors may also be needed as real-time luminosity monitors and for Bhabha calibration of the endcap calorimeters and might be achieved by instrumenting the final focus with scintillating fibers[34].

3.3. Heavy-Ion and Hadron Colliders

The Z^4 dependence of two-photon production from charged particles implies an enormous cross section in heavy ion interactions[35] (~ 8 μbarn for *Au x Au* at the η_c). However, the luminosities at heavy ion colliders are substantially less than at e^+e^- storage rings (~ 2 x 10^{26} cm^{-2} s^{-1} is planned for RHIC as compared to 2.5 x 10^{32} cm^{-2} s^{-1} at CESR). These two factors tend to balance out, leaving the rates for two-photon processes at RHIC generally lower than elsewhere. However, the real strength of heavy-ion colliders will be the ability to compare and contrast pomeron-pomeron interactions which are gluon rich, with photon-photon interactions, which are gluon poor, in the same experiment. This may allow better identification of hybrid and glueball states from their $q\bar{q}$ counterparts[36].

Although photon-photon interactions are not likely to be visible at the SSC (unless heavy ions are collided there), the extension to gauge boson collisions (WW, ZZ) and pomeron-pomeron scattering should be very fruitful there[37].

3.4. e^+e^- Linear Colliders

While two-photon physics at storage rings will continue to teach us a great deal about QCD, it will be very desirable to reach the heavier quark systems such as bottomonium, where non-relativistic theoretical predictions should be on very solid ground. There is no chance of doing this at any of the storage rings due to the rapid decline of virtual photon flux with energy. Reaching $\bar{b}b$ threshold will require a high energy, high luminosity, linear collider to provide a harder photon spectrum. A Monte Carlo calculation for a linear collider with beam energies of 250 GeV and with luminosity 10^{34} $cm^{-2}s^{-1}$ yielded about 400 events per year from the production of a C=+1, $\bar{b}b$ state with $\Gamma\gamma\gamma = 0.35$ keV, a branching ratio to detectable final states of 10%, and a detector efficiency of 10%. Unfortunately, the severe boost of the $\gamma\gamma$ system at these energies will make it very difficult to calibrate on lower-mass resonances or to do tagging.

There is an additional feature of linear colliders which can be exploited to study $\bar{b}b$ or even higher mass states; the small bunch sizes and large bunch populations lead to the emission of virtual photons by $e^{\pm}$ in the fields of the opposing bunch, a phenomenon called beamstrahlung. The resulting energy spectrum is considerably harder than that from virtual bremsstrahlung and results in large increases in $\gamma\gamma$ luminosity at high mass[38]. This technique might allow searches for resonances which couple to two photons up to masses of order 100 GeV, or it could provide an opportunity to study real $e\gamma$ scattering in a whole new kinematic region. However, beamstrahlung is undesirable for e^+e^- physics and will likely be minimized as much as possible.

None of the previous sources of photons can reach the energy scale associated with weak interactions, where high energy photon collisions may well be the cleanest technique for studying new particles such as the Higgs boson and toponium. However, Compton back scattering of a high-power, approximately optical wavelength laser beam with an intense, high-energy electron beam near the interaction point promises to produce a large flux of very high energy real photons at a linear collider[39]. This photon beam closely follows the original trajectory of the electron beam (typical scattering angles are a few μrad) and is therefore incident on the interaction point in a tight final focus. The original electrons are degraded substantially in energy, but also continue approximately on their original paths and thus must be deflected away. The high energy photon beam produced from one beam of a linear collider can be brought into collision with the other electron beam, resulting in $e\gamma$ collisions, or into collision with a similarly produced photon beam from the other electron beam, resulting in $\gamma\gamma$ collisions[40].

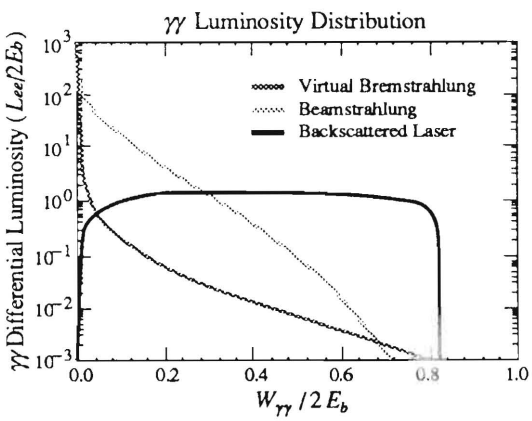

FIG. 7 A comparison of $\gamma\gamma$ luminosity distributions for virtual bremsstrahlung, beamstrahlung, and back scattered lasers.

It is useful to compare the back scattered laser scheme for creating photon beams with the two other methods already discussed: virtual

bremsstrahlung and beamstrahlung. Plotted in Fig. 7 is a comparison of the $\gamma\gamma$ luminosity distributions for a typical choice of machine parameters in each case[40]. It is obvious that 'low energy' photon collisions (< 10 GeV) remain the province of virtual bremsstrahlung, while 'moderate energies' (in the 10's of GeV) are more suited to the beamstrahlung spectrum; 'high energy' photon collisions will necessarily rely on Compton back scattering.

Two, more speculative, ideas for the study of two-photon interactions using linear collider beams have arisen from this workshop. The first is to employ the strong electric fields along certain crystal axes to channel high energy electrons. The large (x100) enhancement in bremsstrahlung leads to an intense photon beam emitted at relatively small angles (~ 200 μrad) from the incident electron direction. Two such beams, of energy a few GeV each, could be collided to achieve photon-photon interactions at masses of the same order as presently achieved. There are many questions about this idea, especially possible radiation damage to the crystals and backgrounds from photoproduction, but it deserves further study[41].

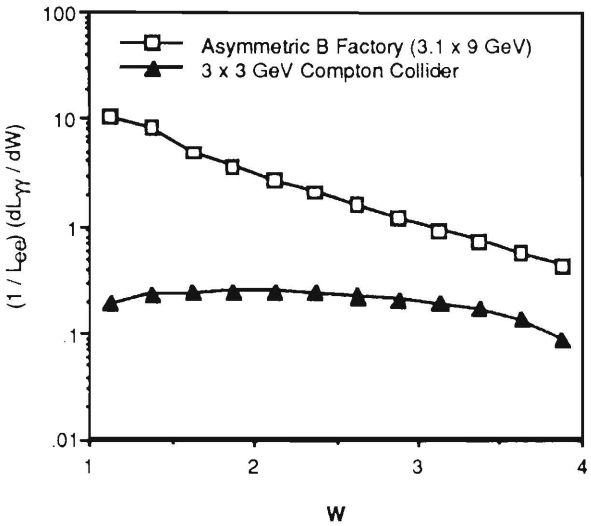

Fig. 8 Two-photon differential luminosity versus W for a B Factory and a low energy Compton Collider, normalized by the anticipated ratio of integrated luminosities (B Factory differential luminosity multiplied by 1000).

The second possibility for dedicated $\gamma\gamma$ and/or $e\gamma$ collisions at relatively low energy would use Compton back scattering of free electron laser beams from moderate energy linear collider electron beams. It appears[42] that such a facility could easily reach $\gamma\gamma$ luminosities of order 10^{31}, sufficient to produce tens of thousands of charmonium events per year. Unfortunately, due to their smaller $\gamma\gamma$ coupling and hadronic branching ratios, a luminosity approaching 10^{33} would be needed to produce useful bottomonium rates and this is not yet feasible at a low energy linear collider. Fig. 8 shows a comparison of the differential $\gamma\gamma$ luminosity, weighted by the expected integrated luminosities, at a B Factory versus such a low energy Compton collider. If it could be built soon, possibly making use of a prototype linear collider needed for R&D, such a machine would be very competitive, especially in the 3-4 GeV mass range. It would also supply unrivaled statistics for photon structure function measurements in the low Q^2 transition range from vector dominance to QCD. One of the best features of such a machine is that the $\gamma\gamma$ interactions would be nearly at rest in the lab frame, as opposed to the highly boosted system one normally must work with. This would likely allow much higher acceptances than at other machines.

4. Summary

The first decade of two-photon physics has shown that it is a viable tool for the exploration of hadron spectroscopy, QED and QCD. Over the next ten years or so, data from present and planned e^+e^- facilities should greatly extend the two-photon mass reach, with concomitant discoveries of conventional and exotic resonances and detailed challenges to perturbative QCD predictions. The advent of very high energy hadron and heavy-ion colliders will open up prospects for extending the field to interactions of pomerons and of gauge bosons.

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