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PHOTON-PHOTON COLLISIONS*

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ABSTRACT

Highlights of the VIIIth International Workshop on Photon-Photon Collisions are reviewed. New experimental and theoretical results were reported in virtually every area of $\gamma\gamma$ physics, particularly in exotic resonance production and tests of quantum chromodynamics where asymptotic freedom and factorization theorems provide predictions for both inclusive and exclusive $\gamma\gamma$ reactions at high momentum transfer.

1. INTRODUCTION

The field of photon-photon collisions[1] now plays a central role in hadron physics, especially as a testing ground for quantum chromodynamics.[2] Two-photon reactions have a number of unique features which are especially important for testing QCD:

1. Any even charge conjugation hadronic state can be created in the annihilation of two photons—an initial state of minimum complexity. Because $\gamma\gamma$ annihilation is complete, there are no spectator hadrons to confuse resonance analyses. Thus, one has a clean environment for identifying the exotic color-singlet even C composites of quarks and gluons $|q\bar{q}>$, $|gg>$, $|ggg>$, $|q\bar{q}g>$, $|qq\bar{q}\bar{q}>$,... which are expected to be present in the few GeV mass range. (Because of mixing, the actual mass eigenstates of QCD may be complicated admixtures of the various Fock components.)
2. The mass and polarization of each of the incident virtual photons can be continuously varied, allowing highly detailed tests of theory. Because a spin-one state cannot couple to two on-shell photons, a $J = 1$ resonance can be uniquely identified by the onset of its production with increasing photon mass.[3]

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3. Two-photon physics plays an especially important role in probing dynamical mechanisms. In the low momentum transfer domain, $\gamma\gamma$ reactions such as the total annihilation cross section and exclusive vector meson pair production can give important insights into the nature of diffractive reactions in QCD. Photons in QCD couple directly to the quark currents at any resolution scale. (See Fig. 1.) Predictions for high momentum transfer $\gamma\gamma$ reactions, including the photon structure functions, $F_2^\gamma(x,Q^2)$ and $F_L^\gamma(x,Q^2)$, high p_T jet production, and exclusive channels are thus much more specific than corresponding hadron-induced reactions. The pointlike coupling of the annihilating photons leads to a host of special features which differ markedly with predictions based on vector meson dominance models.

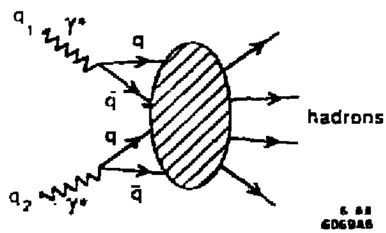

Fig. 1. Photon-photon annihilation in QCD. The photons couple directly to one or two quark currents.

4. Exclusive $\gamma\gamma$ processes provide a window for viewing the wavefunctions of hadrons in terms of their quark and gluon degrees of freedom. In the case of $\gamma\gamma$ annihilation into hadron pairs, the angular distribution of the production cross section directly reflects the shape of the distribution amplitude (valence wavefunction) of each hadron.

Nearly 100 experimental and theoretical physicists gathered in the Jerusalem Hills to assess the progress in photon-photon physics as of 1988. New experimental results were reported in virtually every area of $\gamma\gamma$ physics, including:

1. High $Q^2 \sim 60$ GeV^2 measurements of the photon structure function from the AMY group—the first $\gamma\gamma$ results reported from TRISTAN.[4] (See Fig. 2.) The logarithmic rise of $F_2^\gamma(x,Q^2)$ in Q^2 at fixed x is a crucial test of QCD, reflecting both the pointlike coupling of the on-shell target photon to the quark current and the asymptotic freedom property of the effective coupling constant $\alpha_s(Q^2)$.

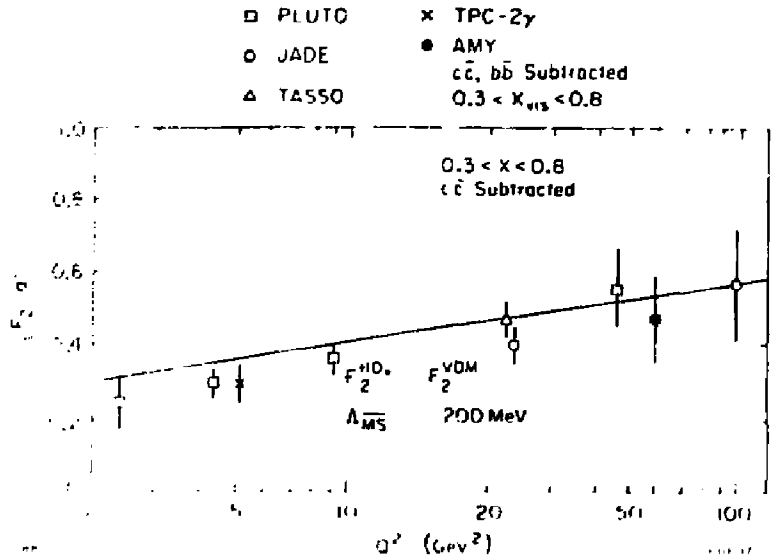

Fig. 2. Data for the photon structure function structure function $F_2^\gamma(x, Q^2)$ as a function of *log* Q^2, including a new point from the AMY collaboration at TRISTAN.[4] The solid line represents the QCD prediction.

2. New measurements of exclusive hadronic channels, resonances, and baryon pairs from ARGUS at DORIS.[6]

3. High precision measurements of the $\gamma\gamma$ width of the η and η' states, including the first $\gamma\gamma$ results from the ASP group at PEP.[8]

4. Measurements of pair production of vector mesons, resonance production [π_0, $\eta'(958)$, $f_1(1285)$] with virtual tagged photons, and the photon structure function by CELLO at PETRA.[7]

5. Measurements of resonance production and a search for D^* production in tagged $\gamma\gamma$ reactions at JADE.[8]

6. Measurements by the Crystal Ball experiment at DORIS[9] of the $\gamma\gamma \to \pi^0\pi^0$ cross section and the first observations of the state $\pi_2(1680)$ decaying through the $f_2(1270)$ π^0 to six photons.

7. Measurements of Bose-Einstein correlations in inclusive $\gamma\gamma$ reactions, detailed results for $\gamma\gamma \to \pi^+\pi^-$ in the $f_2(1270)$ and $f_0(975)$ region, and studies of inclusive distributions of large transverse momentum hadrons in tagged $\gamma\gamma$ events by the Mark II group at PEP.[10]

8. Observation of tagged $\rho^0\rho^0$ events and the $\gamma\gamma$ coupling to η_c by the TASSO group at PETRA.[11]

9. A number of new contributions from the TPC/$\gamma\gamma$ group at PEP[12] including measurements of inclusive charmed hadron (D^*) production, the $\gamma\gamma$ production of the η_c, η, and η', tagged vector meson production, charged particle fractions in inclusive $\gamma\gamma$ annihilation, studies of hadron-hadron correlations which reflect the size of the production source, and measurements of $\gamma\gamma \to \rho\rho$ with tagged virtual photons

Data related to $\gamma\gamma$ physics now come from virtually every active e^+e^- storage ring. Data from DASP (particle fractions), DM-2 (resonances), PLUTO (jets, resonances), and Mark III (radiative J/ψ decays)[13] were also reviewed at the meeting. New $\gamma\gamma$ physics results are expected in the future from CESR at Cornell, VEPP-IV in Novosibirsk, BEPC in Beijing, the upcoming high luminosity run at PEP with the TPC/$\gamma\gamma$ detector, as well as the SLC and LEP

Excellent reviews of the latest $\gamma\gamma$ experimental results were given in the meeting in the reports by Maxwell (studies of inclusive hadron production and jet physics), Gidal (production of narrow resonances and meson pairs), Nilsson (exotic resonance candidates and $\gamma\gamma$ exclusive channels), and Augustin (radiative J/ψ decay and other processes related to $\gamma\gamma$ annihilation).

The theory talks also set high standards for the analysis of $\gamma\gamma$ reactions Chanowitz discussed the evidence and interpretation of the array of C 1 states which are possible candidates for the exotic spectrum predicted by QCD Pennington discussed the care needed to reliably extract resonance parameters in $\gamma\gamma$ physics.[14] The unique features of jet production predicted by perturbative QCD and the special advantages for studies of jets at HERA were discussed by Kunzst. Field presented a detailed review of the virtual photoabsorption cross section $\sigma_{\gamma\gamma^*}(s, Q^2)$ and the photon structure function in the large Q^2 domain The provocative situation concerning vector meson pair production, and the competing interpretations of these exclusive reactions in terms of exotic $qq\bar{q}\bar{q}$ states versus models based on diffraction and factorization were discussed by Maor

Isgur presented a critique of perturbative QCD predictions for exclusive reactions, based on possible corrections from the nonperturbative domain The questions raised by Isgur and Llewellyn Smith highlight the importance of $\gamma\gamma$

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exclusive reactions as a test of basic principles in QCD. I will comment further on these issues in Sections 3 and 4.

The $\gamma\gamma$ data reported at this meeting show that the photon-photon channel provides a window to an *extraordinarily rich* spectrum of relatively narrow C + states in the 1 to 2 GeV mass range. At this point definitive identification of QCD exotic candidates cannot be claimed, but positive evidence is mounting. Gluonium $|gg>$ candidates are expected to be produced more copiously in the gluon-rich radiative J/ψ decays than in $\gamma\gamma$ annihilation.[15] This expectation is quantified by the "stickiness" ratio suggested by Chanowitz.[16] States with $J = 1$ states can be uniquely identified by their appearance in virtual $\gamma^*\gamma$ rather than real $\gamma\gamma$ reactions, a technique pioneered by the TPC/$\gamma\gamma$ group. One thus has strong evidence that the $f_1(1420)$ state [the $E(1420)$] is indeed a spin-one state. Whether this state is a an exotic "meikton" ($q\bar{q}g$ hybrid state) as advocated by Chanowitz, or a four-quark composite, as advocated by Caldwell,[17] will require more data and analysis.

The situation is even more perplexing in the case of $\gamma\gamma$ annihilation into vector meson pairs and diffractive exclusive channels. As discussed at this meeting by Maor and Nillson, the TPC/$\gamma\gamma$ data for $\gamma\gamma \to \omega\pi^+\pi^-$ seems more characteristic of a $qq\bar{q}\bar{q}$ resonance near 1.8 GeV rather than a threshold characteristic of the t-channel factorization model of Alexander et al.[18] On the other hand, the four-quark resonance predictions of Li and Liu[19] and Achasov et al.,[20] do not give a good description of the $\gamma\gamma \to \rho^+\rho^-$ data.

Two-photon physics is an important source of information on the $\gamma\gamma$ couplings of charmonium states. The theory of such couplings and the relation of the wavefunctions at the origin to hyperfine splittings was discussed by Lipkin.

An excellent summary of the future physics of $\gamma\gamma$ collisions, especially at the new colliders, was given by Zerwas in his talk. The topics include detailed tests of QCD reactions at LEP-200 energies,[21] plus studies of the standard model in $\gamma\gamma \to W^+W^-$ and its sensitivity to the W anomalous magnetic moment, searches for supersymmetric particles, excited leptons, etc. He also reviewed the exciting potential that beamsstrahlung induced by the e^+ and e^- passing through the charge density of the other beam in a TeV *linear collider can be maximized* to produce useful photon beams for high energy $\gamma\gamma$ collisions. Work by Jacob and Wu[22] and by Blankenbecler and Drell[23] shows that the beamsstrahlung spectrum has a peak at large x_γ; i.e., the photon can take a large fraction of the lepton energy.

Sens and Dorfan both emphasized in their talks the potential for a "SLAC laser collider." In this scheme one utilizes laser light, back-scattered on the SLC colliding beams, to convert the energy of virtually every electron and positron into high energy colliding photons. Early discussions of this idea were given by Spencer,[24] Akerlof,[25] and Ginzburg et al.[26] More recently, Spencer and I[27] discussed the possibility of replacing the laser source with the beam of low energy photons produced by "wigglers," the insertion devices used to produce synchrotron beams in storage rings.

The conventional source of $\gamma\gamma$ collisions is the the reaction $e^+e^- \to e^+e^- X$. As discussed at this meeting by Kunszt, HERA will also provide a source of $\gamma\gamma$ reactions from the process $pe \to pe X$. The factorization formula derived from the double equivalent photon approximation for π^0 production[28] and extended in Ref. 1 to general $\gamma\gamma$ reactions was the forerunner of the factorization form for the $\gamma\gamma$ "fusion" processes currently used in QCD for heavy particle production. Conversely, the QCD factorization formulae can be used as a basis for calculating QED radiative corrections to e^+e^- reactions.

The concept of colliding photons has been elegantly generalized by Cahn and Dawson[29] to the domain of virtual gauge boson collisions, including Higgs production. The scattering and annihilation of the W and Z gauge bosons with photons, electrons, or other gauge bosons test essential features of the $SU(2)_L \times U(1)$ standard model. The consequences for these reactions for various alternatives to the standard Higgs model were reviewed in Cahn's talk. The contributions of Nir[30] and Schildknecht[31] to this conference demonstrated the possible structure of gauge boson scattering and annihilation reactions and how they are already significantly constrained by low energy phenomena and general principles.

2. HIGH MOMENTUM TRANSFER $\gamma\gamma$ REACTIONS

The asymptotic freedom property of QCD plus its factorization theorems allow the use of perturbation theory to predict detailed features of both exclusive and inclusive $\gamma\gamma$ reactions at high momentum transfer.

A basic prediction of QCD is the existence of two-jet reactions[32] $\gamma\gamma \to q\bar{q}$ with a rate $R_{\gamma\gamma} = 3\sum e_q^4 [1 + O(\alpha_s(p_T^2)/\pi)]$ times the corresponding $\gamma\gamma \to \mu^+\mu^-$ rate. From the standpoint of vector meson dominance models, the existence of a reaction in which all of the photon energy goes into a transverse jet is remarkable. There is, however, some question whether the QCD perturbation series in $\alpha_s(p_T^2)$ is convergent. A very large 3-loop coefficient was reported recently for the corresponding calculation of $R_{e^+e^-}$ by Gorichny, Kateev, and Larin.[33] Recent measurements from the Mark II and earlier TASSO data on tagged $\gamma\gamma$ large transverse momentum single-charged hadron inclusive events appear to give event rates considerably larger than the PQCD predictions of Aurenche et al.[34] These theoretical predictions do not include either higher twist contributions which are enhanced by the single hadron trigger bias, nor the multi-jet contributions related to the diagrams which contribute to the photon-structure function.[35] The latter processes leave spectator jets in the photon beam directions and have the same dependence in *log* Q^2 as the two-jet reactions.[35] [The extra powers of $\alpha_s(p_T^2)$ from the hard-scattering subprocess cross section cancel against the logarithmically-rising photon structure function.] However, these reactions are relatively suppressed at large p_t^2/s so it seems unlikely they can cure the discrepancy between experiment and theory.

The photon structure functions[36] $F_2(x,Q^2)$ and $F_L(x,Q^2)$, measured where the target photon is nearly real, provide a critical testing ground for QCD. As first discussed by Witten,[37] the large Q^2 behavior $F_2(x,Q^2) \sim ln(Q^2)f(x)$ is due to the direct photon coupling to quarks corresponding to an inhomogeneous driving term in the QCD evolution equations. Both the logarithmic rise (see Fig. 1) and the broad shape of $f(x)$ predicted to leading order in $\alpha_s(Q^2)$ are consistent with the available data. However, as emphasized by Zerwas in his talk, present data do not rule out theories with fixed-point behavior in the coupling constant. Measurements beyond Q^2 100 GeV^2 will be necessary in order to discrimate between theories with asymptotic freedom versus fixed-point behavior.

Some of the diagrams which contribute to the photon structure for nearly-real photon targets necessarily involve soft integration regions, and thus they are similar to diagrams which contribute to the structure functions of vector mesons. The analysis of QCD evolution from low to high Q^2 requires a consistent interweaving of both the hadronic and pointlike contributions.[38] The nonperturbative aspects may be isolated by introducing a partition in transverse momentum[39] or an equivalent parameter,[40] but at the expense of removing the sensitivity of the analysis to the QCD scale Λ_{QCD}. A detailed discussion of this problem is given in Field's report to this meeting and the review by Kolanoski and Zerwas, Ref. 2.

In a provocative contribution to this meeting, Glück and Reya[41] have shown that one can minimize the uncertainties associated with the nonpoint-like terms and obtain a quite good phenomenological representation of the data over the complete range $0.5 \cdot Q^2 \cdot 100\ \mathrm{GeV}^2$ by starting the evolution at $Q_0 \sim 250$ MeV, very close to the assumed scale value Λ_{QCD} 200 GeV. (See Fig. 3.) consistent with their analysis of hadronic structure functions. The Glück-Reya analysis is somewhat controversial since one normally would not expect perturbative evolution to be valid at such low momentum scales Q_0. The parameterization $\sim x^{1\ 2}(1 \ x)$ assumed for the hadronic component of the structure function at Q introduces some model dependence. For example, it is not clear how the Regge ansatz of fixed $x^{1\ \alpha}$ power behavior at low x can be consistent with

QCD evolution. Nevertheless, the Glück-Reya analysis may be pointing to further evidence of "precocious" scaling in QCD. As emphasized by Kolanoski and Zerwas,[12] the rapid evolution of the photon structure function seen in Fig. 3 at small $Q^2 \sim 1\ \mathrm{GeV}^2$ implies the presence of higher twist contributions.

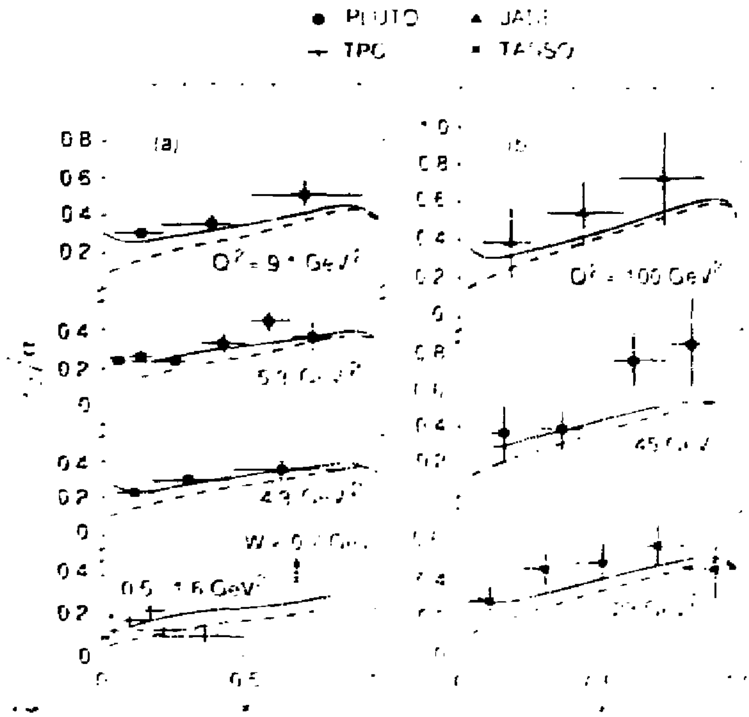

Fig. 3. Comparison of JADE, PLUTO, TASSO and TPC [illegible] data with the theoretical prediction by Glück and Reya for [illegible] assuming a low value for the starting point for QCD evolution. The dashed curve excludes the VDM contribution. See M. Glück, this meeting.

In the case of double-tagged reactions $\gamma^*(Q_1) + \gamma^*(Q_2) \to X$ with $Q_1^2, Q_2^2 \gg \Lambda^2_{QCD}$, the structure function of the virtual photon is dominated to leading order in α_s by the Born diagram for $\gamma\gamma \to q\bar{q}$ and thus it is completely determined. One also would like to verify experimentally the predicted scaling and x-dependence of the charm contributions to the photon structure function including low values of Q^2. As discussed in the workshop by Cordier and Zerwas, such experiments should be quite feasible at LEP 200. Cordier also discussed the advantages of using $\gamma\gamma$ reactions as a luminosity calibration at high energy colliders.

3. EXCLUSIVE $\gamma\gamma$ REACTIONS

Perturbative QCD predictions for $\gamma\gamma$ exclusive processes at high momentum transfer and high invariant pair mass provide some of the most severe tests of the theory.[42] A simple, but still very important example[43] is the Q^2-dependence of the reaction $\gamma^*\gamma \to M$ where M is a pseudoscalar meson such as the η. The invariant amplitude contains only one form factor:

$$M_{\mu\nu} = \epsilon_{\mu\nu\sigma\tau} p_\eta^\sigma q^\tau F_{\gamma\eta}(Q^2) \ .$$

It is easy to see from power counting at large Q^2 that the dominant amplitude (in light-cone gauge) gives $F_{\gamma\eta}(Q^2) \sim 1/Q^2$ and arises from diagrams (see Fig. 4) which have the minimum path carrying Q^2; i.e., diagrams in which there is only a single quark propagator between the two photons. The coefficient of $1/Q^2$ involves only the two-particle $q\bar{q}$ Fock component of the meson wavefunction. More precisely the wavefunction is the distribution amplitude $\phi(x,Q)$, defined below, which evolves logarithmically on Q. Higher particle number Fock states give higher power-law falloff contributions to the exclusive amplitude.

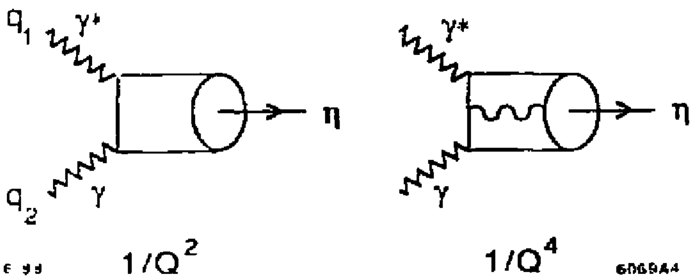

Fig. 4. Calculation of the γ - η transition form factor in QCD from the valence $q\bar{q}$ and $q\bar{q}g$ Fock states.

The TPC/$\gamma\gamma$ data[44] shown in Fig. 5 are in striking agreement with the predicted QCD power: a fit to the data gives $F_{\gamma\eta}(Q^2) \sim (1/Q^2)^n$ with $n = 1.05 \pm 0.15$. Data for the η' from Pluto and the TPC/$\gamma\gamma$ experiments give similar results, consistent with scale-free behavior of the QCD quark propagator and the point coupling to the quark current for both the real and virtual photons. In the case of deep inelastic lepton scattering, the observation of Bjorken scaling tests these properties when both photons are virtual.

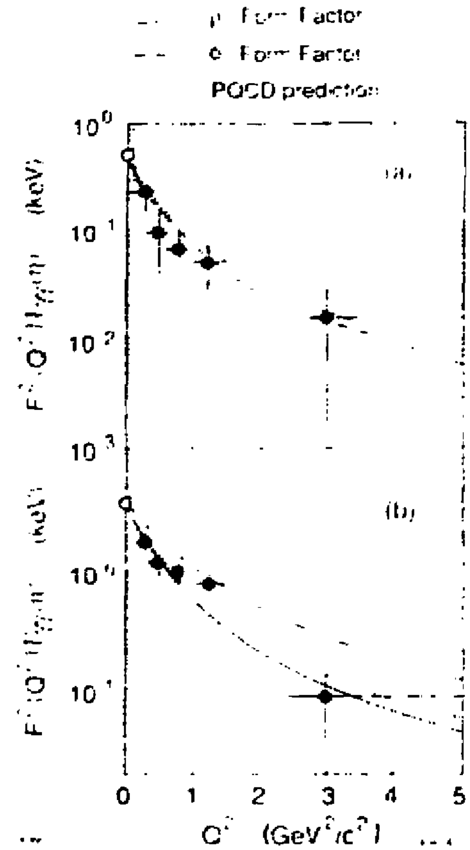

Fig. 5. Comparison of TPC/γγ data[**] for the γ η and γ η′ transition form factors with the QCD leading twist prediction of Ref. 42. The VMD predictions are also shown. See S. Yellin, this meeting.

The QCD power law prediction, $F_{\gamma\eta}(Q^2) \sim 1/Q^2$, is consistent with dimensional counting[45] and also emerges from current algebra arguments (when both photons are very virtual).[46] On the other hand, the $1/Q^2$ falloff is also expected in vector meson dominance models The QCD and VDM predictions can be readily discriminated by studying $\gamma^*\gamma^* \to \eta$. In VMD one expects a product of form factors; in QCD the falloff of the amplitude is still $1/Q^2$ where Q^2 is a linear combination of Q_1^2 and Q_2^2. It is clearly very important to test this important feature of QCD.

The analysis of $\gamma^*\gamma \to \eta$ given here is the prototype of the general QCD analysis of exclusive amplitudes at high momentum transfer.[47] At large p_T the power behavior of the amplitude is controlled by the minimum tree diagram connecting the valence quarks in the initial and final state—this is the hard scattering amplitude T_H which shrinks to a local operator at asympotic momentum transfer—effectively the quarks interact when they are all at relative impact separation $b_T \sim 1/p_T$. One then convolutes T_H with the distribution amplitudes $\phi(x_i, Q)$ of the hadrons—analogs of the "wavefunction at the origin" in nonrelativistic quantum mechanics—to construct the hadronic amplitude. This convolution is the basis of the factorization theorem for QCD exclusive reactions: to leading order in $1/p_T$, the nonperturbative dynamics associated with the hadronic bound states is isolated in universal, process-independent distribution amplitudes.[47] In cases such as $\gamma\gamma$ annihilation into meson pairs and meson form factors, the analysis is completely rigorous in the sense that it can be carried out systematically to all orders in perturbation theory.

A striking feature of the QCD description of exclusive processes is "color transparency."[48] The only part of the hadronic wavefunction that scatters at large momentum transfer is its valence Fock state where the quarks are at small relative impact separation. Such a fluctuation has a small color-dipole moment and thus has negligible interactions with other hadrons. Since such a state stays small over a distance proportional to its energy, this implies that quasi-elastic hadron-nucleon scattering at large momentum transfer as illustrated in Fig. 6 can occur additively on all of the nucleons in a nucleus with minimal attenuation due to elastic or inelastic final state interactions in the nucleus, i.e., the nucleus becomes "transparent." By contrast, in conventional Glauber scattering, one predicts strong, nearly energy-independent initial and final state attenuation.

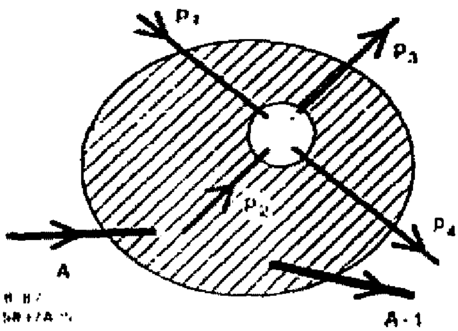

Fig. 6. Quasi-elastic pp scattering inside a nuclear target. Normally one expects such processes to be attenuated by elastic and inelastic interactions of the incident proton and the final state interaction of the scattered proton. Perturbative QCD predicts minimal attenuation; i.e., "color transparency," at large momentum transfer.

A recent experiment[49] at BNL measuring *quasi-elastic* $pp \to pp$ scattering at $\theta_{cm} = 90°$ in various nuclei appears to confirm the color transparency prediction—at least for p_{lab} up to 10 GeV/c. (See Fig. 7.) Descriptions of elastic scattering which involve soft hadronic wavefunctions cannot account for the data. However, at higher energies, $p_{lab} \sim 12$ GeV/c, normal attenuation is observed in the BNL experiment. This is the same kinematical region $E_{cm} \sim 5$ GeV where the large spin correlation in A_{NN} are observed.[50] Both features may be signaling new s-channel physics associated with the onset of charmed hadron production[51] or interference with Landshoff pinch singularity diagrams.[52] Much more testing of the color transparency phenomena is required, particularly in quasi-elastic lepton-proton scattering, Compton scattering, antiproton-proton scattering, etc.

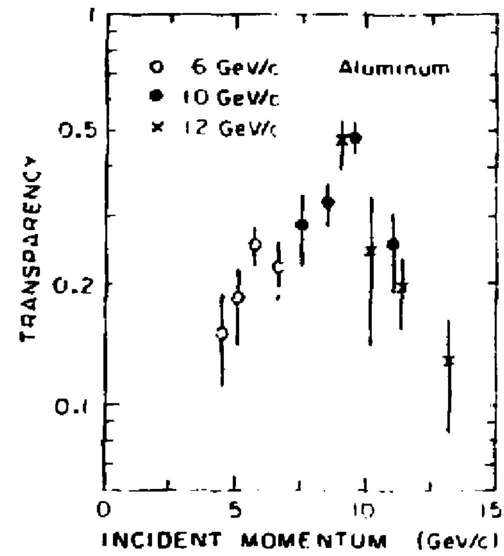

Fig. 7. Measurements of the transparency ratio

$$T = \frac{Z_{eff}}{Z} = \frac{d\sigma}{dt}(pA \to p(A-1)) \Big/ \frac{d\sigma}{dt}(pA \to pp)$$

near 90° on Aluminum (from Ref. 49). Conventional theory predicts that T should be small and roughly constant in energy. Perturbative QCD[48] predicts a monotonic rise to $T \to 1$.

The essential nonperturbative input for exclusive reactions at high momentum transfer is the hadron "distribution amplitude" $\phi(x,Q)$ which describe the longitudinal momentum distribution of the quarks in the valence, lowest-particle-number Fock state.[43] Hadron wavefunctions can be conveniently defined as coefficients on a Fock basis at fixed $\tau = t + z/c$ in the light-cone gauge. Then

$$\phi(x,Q) = \int d^2k_\perp \theta(Q^2 - k_\perp^2)\psi_V(x,k_\perp) \ ;$$

i.e., $\phi(x,Q)$ is the probability amplitude to find the quark and antiquark in the meson (or three quarks in a baryon) collinear up to the transverse momentum scale Q. Here $x = (k^0+k^z)/(p^0+p^z)$. More generally, the distribution amplitude can be defined as a gauge-invariant matrix-element product of quark fields evaluated between the QCD vacuum and the hadron state. At large Q^2 one can use an operator product expansion or an evolution equation to determine $\phi(x,Q)$ from an initial value $\phi(x,Q_0)$ determined by nonperturbative input. The distribution amplitude contains all of the bound-state dynamics and specifies the momentum distribution of the quarks in the hadron. The hard scattering amplitude can be calculated perturbatively as a function of $\alpha_s(Q^2)$. The analysis can be applied to form factors, exclusive photon-photon reactions, photoproduction, fixed-angle scattering, etc.

Exclusive two-body processes $\gamma\gamma \to H\overline{H}$ at large $s = W_{\gamma\gamma}^2 = (q_1+q_2)^2$ and fixed $\theta_{\rm cm}$ provide a particularly important laboratory for testing QCD, since the large momentum transfer behavior, helicity structure, and often even the absolute normalization can be rigorously predicted.[42,44]

As emphasized above, the angular dependence of some of the $\gamma\gamma \to H\overline{H}$ cross sections reflects the shape of the hadron distribution amplitudes $\phi_H(x_i,Q)$. The $\gamma_\lambda\gamma_{\lambda'} \to H\overline{H}$ amplitude can be written as a factorized form

$$\mathcal{M}_{\lambda\lambda'}(W_{\gamma\gamma},\theta_{\rm cm}) = \int_0^1 [dy_i]\, \phi_H^*(x_i,Q)\, \phi_{\overline{H}}^*(y_i,Q)\, T_{\lambda\lambda'}(x,y;W_{\gamma\gamma},\theta_{\rm cm})$$

where $T_{\lambda\lambda'}$ is the hard scattering helicity amplitude. To leading order $T \propto \alpha(\alpha_s/W_{\gamma\gamma}^2)^{1/2}$ and $d\sigma/dt \sim W_{\gamma\gamma}^{-4,-6} f(\theta_{\rm cm})$ for meson and baryon pairs, respectively.

Lowest order predictions for pseudo-scalar and vector-meson pairs for each helicity amplitude are given in Ref. 42. In each case, the helicities of the hadron pairs are equal and opposite to leading order in $1/W^2$. The normalization and angular dependence of the leading order predictions for $\gamma\gamma$ annihilation into charged meson pairs are almost model independent; i.e., they are insensitive to the precise form of the meson distribution amplitude. If the meson distribution amplitudes is symmetric in x and $(1-x)$, then the same quantity

$$\int_0^1 dx\, \frac{\phi_\pi(x,Q)}{(1-x)}$$

controls the x-integration for both $F_\pi(Q^2)$ and to high accuracy $M(\gamma\gamma \to \pi^+\pi^-)$. Thus for charged pion pairs Lepage and I found the relation:

$$\frac{\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)}{\frac{d\sigma}{dt}(\gamma\gamma \to \mu^+\mu^-)} \cong \frac{4|F_\pi(s)|^2}{1-\cos^4\theta_{cm}} .$$

Note that, in the case of charged kaon pairs, the asymmetry of the distribution amplitude may give a small correction to this relation.

The scaling behavior, angular behavior, and normalization of the $\gamma\gamma$ exclusive pair production reactions are nontrivial predictions of QCD. Recent Mark II meson pair data and PEP4/PEP9 data for separated $\pi^+\pi^-$ and K^+K^- production in the range $1.6 < W_{\gamma\gamma} < 3.2$ GeV near 90° are in satisfactory agreement with the normalization and energy dependence predicted by QCD. (See Fig. 8.) In the case of $\pi^0\pi^0$ production, the $\cos\theta_{cm}$ dependence of the cross section can be inverted to determine the x-dependence of the pion distribution amplitude. The one-loop corrections to the hard scattering amplitude for meson pairs have been calculated by Nizic.[53] The QCD predictions for mesons containing admixtures of the $|gg\rangle$ Fock state is given by Atkinson, Sucher, and Tsokos.[63]

The perturbative QCD analysis has been extended to baryon-pair production in comprehensive analyses by Farrar et al.[64] and by Gunion et al.[53] Predictions are given for the "sideways" Compton process $\gamma\gamma \to p\bar{p}$, $\Delta\bar{\Delta}$ pair production, and the entire decuplet set of baryon pair states. The arduous calculation of 280 $\gamma\gamma \to qqq\bar{q}\bar{q}\bar{q}$ diagrams in T_H required for calculating $\gamma\gamma \to B\bar{B}$ is greatly simplified by using two-component spinor techniques. The doubly charged Δ pair is predicted to have a fairly small normalization. Experimentally such resonance pairs may be difficult to identify under the continuum background.

The normalization and angular distribution of the QCD predictions for proton-antiproton production shown in Fig. 9 depend in detail on the form of the nucleon distribution amplitude, and thus provide severe tests of the model form derived by Chernyak, Ogloblin, and Zhitnitsky from QCD sum rules.[55]

A three-dimensional representation of the COZ model is shown in Fig. 10. The moments of the proton distribution amplitude computed by Chernyak et al. have now been confirmed in an independent analysis by Sachrajda and King.[66] In the case of the meson distribution amplitudes, there is good agreement of

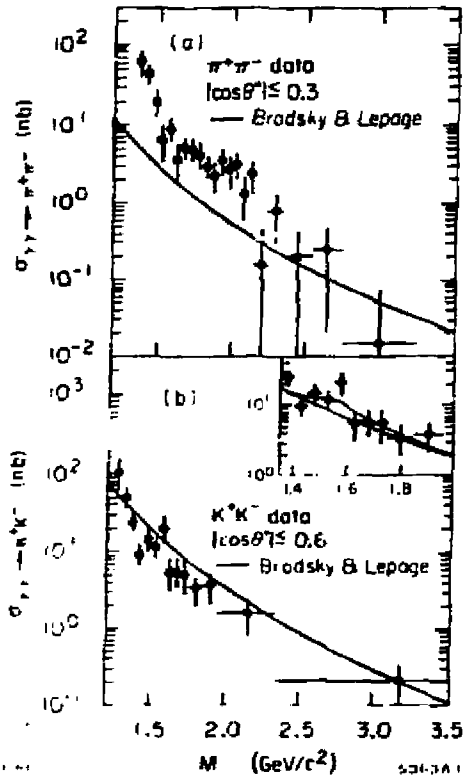

Fig. 8 Comparison of $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$ meson pair production data with the parameter-free perturbative QCD prediction of Ref. 42. The theory predicts the normalization and scaling of the cross sections. The data are from the TPC/$\gamma\gamma$ collaboration.

the lattice gauge theory computations of Martinelli and Sachrajda[87] with the QCD sum rule results. These checks have greatly strengthened confidence in the reliability of the QCD sum rule method, although the shapes of the distribution amplitudes are unexpectedly structured: the pion distribution amplitude is broad and has a dip at $x = 1/2$; the u quark with helicity parallel to the proton helicity carries nearly 2/3 of the momentum in the three-quark valence Fock state of the proton. In fact, the QCD sum rule distributions, combined with the perturbative QCD factorization predictions, account well for the scaling, normalization of the pion form factor, and also the branching ratio for $J/\psi \to p\bar{p}$. In addition, as shown in a contribution by Maina to this workshop, data for large angle Compton scattering $\gamma p \to \gamma p$ is well described.

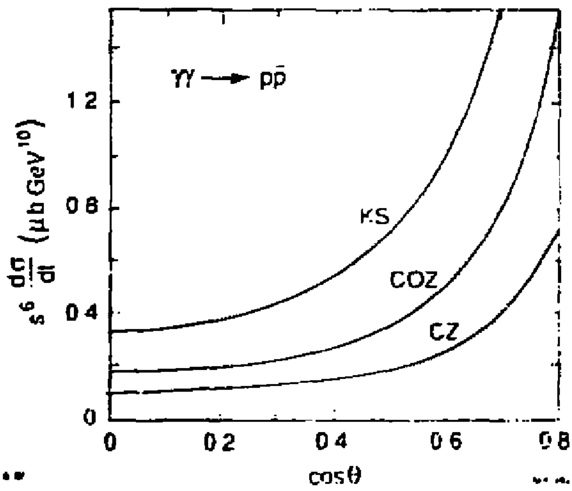

Fig. 9. Perturbative QCD predictions by Farrar and Zhang for the $\cos(\theta_{cm})$ dependence of the $\gamma\gamma \to p\bar{p}$ cross section assuming the King-Sachrajda (KS), Chernyak, Ogloblin, and Zhitnitsky (COZ), and original Chernyak and Zhitnitsky (CZ) forms for the proton distribution amplitude, $\phi_p(x_i, Q)$. See G. Farrar, this meeting.

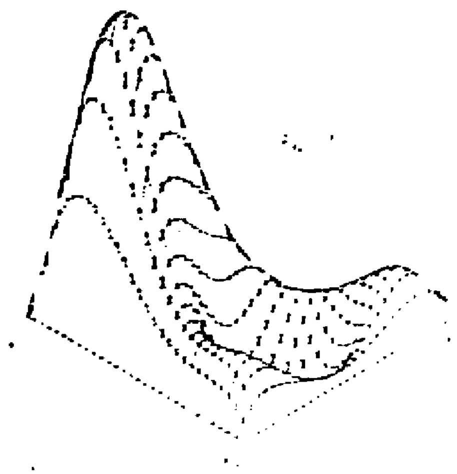

Fig. 10. The proton distribution amplitude $\phi_p(x_i, \mu)$ determined at the scale $\mu \sim 1$ GeV from QCD sum rules by Chernyak, Ogloblin, and Zhitnitski

An important check of the QCD predictions can be obtained by combining data from $\gamma\gamma \to p\bar{p}$ and the annihilation reaction, $p\bar{p} \to \gamma\gamma$, with large angle Compton scattering $\gamma p \to \gamma p$.[68]

This comparison checks in detail the angular dependence and crossing behavior expected from the theory. Furthermore, in $p\bar{p}$ collisions one can study timelike photon production into e^+e^- and examine the virtual photon mass dependence of the Compton amplitude. Predictions for the q^2 dependence of the $p\bar{p} \to \gamma\gamma^*$ amplitude can be obtained by crossing the results of Gunion and Millers.[63]

The region of applicability of the leading power-law predictions for $\gamma\gamma \to p\bar{p}$ requires that one be beyond resonance or threshold effects. It presumably is set by the scale where $Q^4 G_M(Q^2)$ is roughly constant, i.e., $Q^2 > 3$ GeV^2. Present measurements may thus be too close to threshold for meaningful tests.[69] It should be noted that, unlike the case for charged meson pair production, the QCD predictions for baryons are sensitive to the form of the running coupling constant and the endpoint behavior of the wavefunctions.

The QCD predictions for $\gamma\gamma \to H\overline{H}$ can be extended to the case of one or two virtual photons, for measurements in which one or both electrons are tagged. Because of the direct coupling of the photons to the quarks, the Q_1^2 and Q_2^2 dependence of the $\gamma\gamma \to H\overline{H}$ amplitude for transversely polarized photons is minimal at W^2 large and fixed θ_{cm}, since the off-shell quark and gluon propagators in T_H already transfer hard momenta; i.e., the 2γ coupling is effectively local for $Q_1^2,\ Q_2^2 \ll p_T^2$. The $\gamma^*\gamma^* \to \bar{B}B$ and $M\overline{M}$ amplitudes for off-shell photons have been calculated by Millers and Gunion.[63] New results on charged $\pi\rho$ pair production were also presented to this meeting by Kessler and Tamazouzt. In each case, the predictions show strong sensitivity to the form of the respective baryon and meson distribution amplitudes.

We also note that photon-photon collisions provide a way to measure the running coupling constant in an exclusive channel, independent of the form of hadronic distribution amplitudes. The photon-meson transition form factors $F_{\gamma\to M}(Q^2)$, $M = \pi^0, \eta^0, f$, etc., are measurable in tagged $e\gamma \to e'M$ reactions. QCD predicts

$$\alpha_s(Q^2) = \frac{1}{4\pi}\,\frac{F_\pi(Q^2)}{Q^2|F_{\pi\gamma}(Q^2)|^2}$$

where to leading order the pion distribution amplitude enters both numerator and denominator in the same manner.

4. APPLICABILITY OF PERTURBATIVE QCD TO EXCLUSIVE PROCESSES

Nathan Isgur's contribution to this conference was particularly provocative. In his recent work[80] with Llewellyn Smith, Isgur has challenged the application of perturbative QCD to exclusive reactions in the momentum transfer range presently accessible to experiment. The issues involved are very important for understanding the basis of virtually all perturbative QCD predictions. As might be expected, I disagree with the Isgur-Llewellyn Smith analysis and conclusions. Let me deal in turn with each of their points:

1. Isgur and Llewellyn Smith, and also Radyshkin,[81] argue that the normalization of the PQCD amplitude is of order $(\alpha_s/\pi)^n(\lambda^2/Q^2)^n$ where λ is a typical hadronic scale. If this were the correct estimate, the perturbative contributions would be too small to compete with the rapidly-falling "soft" nonperturbative contributions until very large momentum transfers Q.

In fact, the PQCD prediction for the pion form factor at large Q^2 is nominally of order $16\pi\alpha_s f_\pi^2$, a factor of order $16\pi^2$ times larger than the above estimate. The actual coefficient of the leading twist, leading power law term depends on the integral $\int_0^1 dx\, \frac{\phi_\pi(x,Q)}{(1-x)}$, and is thus only moderately sensitive to the shape of the meson distribution amplitude in the endpoint region.

The normalization and sign of the leading power law terms predicted by PQCD are in agreement with the measurements of the meson and baryon form factors as well as large invariant mass exclusive photon-photon meson pair production cross sections if one uses the hadron distribution amplitudes predicted by Chernyak et al.[58] and Sachrajda and King[66] from QCD sum rules. As discussed in Section 3 the recent lattice gauge theory analysis of the moments of the meson distribution amplitude by Martinelli and Sachrajda[67] give results consistent with those of Chernyak and Zhitnitsky.

It might also be noted that in QED, the "soft" contributions to the positronium form factor from Coulomb photon exchange are the *same* order in α as the "hard" contributions from transverse photon exchange. There are no extra powers of α in the hard amplitude! Once the electrons are relativistic, i.e., for $Q^2 \sim M^2$, the hard, perturbative contribution dominates.[82]

2. Isgur and Llewellyn Smith argue that the momentum transfer flowing through the gluon propagator in the hard scattering amplitude for an exclusive reaction is typically too small to trust the perturbative expansion. This seems to be of particular concern for the skewed, highly relativistic distribution amplitudes obtained from the QCD sum rule analysis of

Chernyak et al. since the integration region where x is large tends to be emphasized. In the case of the hard scattering T_H amplitude for the pion form factor (illustrated in Fig. 11), the struck quark is off-shell at order $(1-x)Q^2$ whereas the momentum transfer of the exchanged gluon is of order $(1-x)(1-y)Q^2$, which can be considerably smaller.

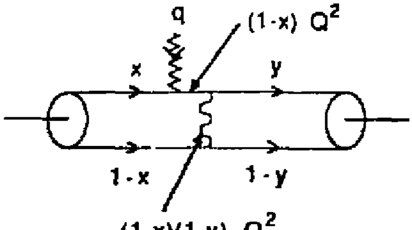

Fig. 11 Leading twist contribution to the meson form factor in QCD.

In fact, as shown by Lepage and myself,[43] the momentum transfer scale where one can analyze amplitudes perturbatively in QCD is controlled by the virtuality of the quark propagator not that of the exchanged gluon. [The range of the gluon virtuality is of course important in setting the scale of the effective coupling constant $\alpha_s(Q^2)$.] If the struck quark is sufficiently off-shell, $|k_q^2| > \Lambda^2_{QCD}$, one can easily show that multiple soft gluon exchange contributions are suppressed by powers of Q^2 relative to one-gluon exchange. The same considerations apply to the analysis of the evolution of deep inelastic structure functions: the critical scale is the off-shellness of the quark propagators—not the minimum virtuality of the gluons. Even though the radiated gluons have low virtuality, one can compute the form of QCD evolution with elementary vector gluon couplings provided that the struck quark is sufficiently off-shell. Similarily, in computations of quark jet evolution, the perturbative gluon coupling dominates even though the gluon can be radiated near its mass shell. Requiring the gluon to have a minimum virtual mass corresponds to multiple jet production.

How can one reconcile the PQCD analysis with the concept that at low momentum transfer the interaction between quarks is nonperturbative? The concept of a nonperturbative potential (and estimates of scales involving the glueball mass) can only be applicable to situations in which quarks are close to their mass shells and scatter at low relative velocity so that there is sufficient time to interact strongly. However, in the high momentum transfer form factor and deep inelastic scattering reactions, the struck quark is relatively far off its mass shell and interacts at high momentum relative to the spectator quarks. Thus its interactions may be computed perturbatively.

The above observations form the basis of the application of renormalization group equations and the operator product expansion to these reactions, and allow one to calculate the leading power behavior and the QCD logarithmic evolution of exclusive amplitudes for the pion form factor and $\gamma\gamma$ annihilation into meson pairs to all orders in perturbation theory.

The predictions[47] for the leading twist term in exclusive QCD hadronic amplitudes are thus unambiguous. Higher twist corrections to the quark and gluon propagator due to mass terms and intrinsic transverse momenta of a few hundred MeV give nominal corrections of higher order in $1/Q^2$. These finite mass corrections combine with the leading twist results to give a smooth approach to small Q^2. The PQCD scaling laws thus become valid at relatively low momentum transfer, the few GeV scale, consistent with what is observed in experiment, as in the results shown in Figs. 5 and 8.[63]

3. Independent of the underlying theory, the form factor of a hadron can be computed from the overlap of light-cone wavefunctions, summed over Fock states, as shown by Drell and Yan.[64] This is the starting point for all relativistic calculations including the PQCD analysis. Isgur and Llewellyn Smith, and also Radyshkin, argue that one can obtain reasonable agreement with the form factor data by parameterizing the three-point vertex amplitude using various models for the bound state wavefunctions.

However, phenomenological agreement with a parameterization of the vertex amplitude is not in contradiction with the PQCD analysis unless one can show that the QCD wavefunction with gluon exchange can be excluded in favor of purely nonperturbative forms. The analyses[65] of Dziembowski and Mankiewicz (which are consistent with QCD sum rules), Carlson and Gross, and Jacob and Kisslinger show that strictly soft wavefunctions, consistent with rotational invariance in the rest frame, and normalized correctly, cannot account for the pion or proton form factors in the power-law scaling regime.

Perhaps the most compelling evidence for the validity of the PQCD approach to exclusive processes is the observation[49] of color transparency in pp quasi-elastic scattering in nuclei, as discussed in Section 3. The BNL data exclude models in which the scattering is dominated by soft wavefunctions.

The perturbative QCD predictions for the leading twist power-law contributions are generally consistent with data for exclusive processes when the momentum transfer exceeds several GeV.[66] It is difficult to understand the claim that these data are explained by higher twist or soft nonperturbative contributions since such effects necessarily fall at least one power of Q^2 faster than the dimensional counting prediction.

5. $\gamma\gamma$ PHYSICS AND NONPERTURBATIVE QCD

Only a small fraction of the $\gamma\gamma$ physics considered at this meeting can be addressed by perturbative QCD analyses. Despite the simplicity of the initial state, the full complexity of hadron dynamics is involved in understanding resonance production, exclusive channels near threshold, jet hadronization, the hadronic contribution to the photon structure function, and the total $\gamma\gamma$ annihilation cross section. A primary question is whether we can ever hope to confront QCD directly in its nonperturbative domain.

As emphasized at this meeting by Rosner and Pennington, predictions can be made near threshold for the $\gamma\gamma \to \pi\pi$ channels from general principles: the low energy theorem, unitarity, and Watson's theorem. The successful analysis by Brown, Goble, and Rosner for $\pi^0\pi^0$ production at low invariant pair mass (see Fig. 12) is an important example of this type of analysis.

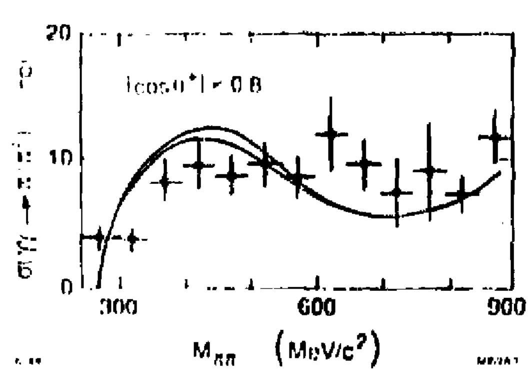

Fig. 12. Comparison of predictions by Goble and Rosner with Crystal Ball data for $\gamma\gamma \to \pi^0\pi^0$ at low energies. The upper and lower curves correspond to σ mass $M_0 = 755$ and 900 GeV/c^2, respectively. The data were presented to this conference by H. Marsiske et al. The analysis uses the method of Goble and Brown.[87] See J. Rosner, this meeting.

To go further and confront QCD directly in the nonperturbative domain is one of the most challenging tasks in particle physics. Lattice gauge theory and effective Lagrangian methods such as the Skyrme model offer some hope in understanding the low-lying hadron spectrum but dynamical computations relevant to $\gamma\gamma$ annihilation appear intractable. Considerable information[..] on the spectrum and the moments of hadron valence wavefunctions has been obtained using the ITEP QCD sum rule method, but the region of applicability of this method to dynamical problems appears limited.

Recently H. C. Pauli and I have developed a new method for analyzing QCD in the nonperturbative domain: discretized light-cone quantization (DLCQ).[88] Thus far the method has been successfully applied to gauge theories in one-space and one-time dimension, including QCD[1+1].[88] We are optimistic that it will be computationally viable when applied to QCD in 3+1 dimensions.

The basic idea of DLCQ is as follows: QCD dynamics takes a rather simple form when quantized at equal light-cone "time" $\tau = t + z/c$. In light-cone gauge $A^+ = A^0 + A^z = 0$, the QCD light-cone Hamiltonian

$$H_{QCD} = H_0 + gH_1 + g^2 H_2$$

contains the usual 3-point and 4-point interactions plus induced terms from instantaneous gluon exchange and instantaneous quark exchange diagrams. The perturbative vacuum is an eigenstate of H_{QCD} and serves as the lowest state in constructing a complete basis set of color singlet Fock states of H_0 in momentum space. Solving QCD is then equivalent to solving the eigenvalue problem:

$$H_{QCD}|\Psi\rangle = M^2|\Psi\rangle$$

as a matrix equation on the free Fock basis. The set of eigenvalues $\{M^2\}$ represents the spectrum of the color-singlet states in QCD. The Fock projections of the eigenfunction corresponding to each hadron eigenvalue gives the quark and gluon Fock state wavefunctions $\psi_n(x_i, k_{\perp i}, \lambda_i)$ required to compute structure functions, distribution amplitudes, decay amplitudes, etc. For example, as shown by Drell and Yan,[84] the form-factor of a hadron can be computed at any momentum transfer Q from an overlap integral of the ψ_n summed over particle number n. The e^+e^- annihilation cross section into a given $J = 1$ hadronic channel can be computed directly from its $\psi_{q\bar{q}}$ Fock state wavefunction.

The light-cone momentum space Fock basis becomes discrete and amenable to computer representation if one chooses (anti-)periodic boundary conditions for the quark and gluon fields along the $z^- = z - ct$ and $z_\perp$ directions. In the case of renormalizable theories, a covariant ultraviolet cutoff Λ is introduced which limits the maximum invariant mass of the particles in any Fock state. One thus obtains a finite matrix representation of $H_{QCD}^{(\Lambda)}$ which has a straightforward continuum limit. The entire analysis is frame independent, and fermions present no special difficulties.

DLCQ has been used to obtain the complete spectrum of neutral states in QED in one space and one time for any mass and coupling constant.[70] The results agree with the Schwinger solution at infinite coupling. Recently Hornbostel[71] has obtained the meson and baryon spectrum and their structure functions in QCD[1+1] for 2, 3, and 4 colors. Studies of QED in 3+1 dimensions are now underway.[74]

What are the *applications* to $\gamma\gamma$ physics? Assuming that DLCQ is indeed computationally viable for QCD in 3+1 dimensions, the spectrum of $C = +$ hadronic states could in principle be predicted. If electromagnetic interactions are included in the *light-cone* Hamiltonian, then the partial width $\Gamma_{\gamma\gamma}$ of each state could be computed from its $\gamma\gamma$ Fock component. The $\gamma\gamma$ annihilation cross section and photon structure functions could also be computed from sums over the Fock state *wavefunctions*. The τ evolution of states as they develop from the initial $\gamma\gamma$ state could be investigated.

Thus, one can envision a nonperturbative method which in principle could allow a quantitative confrontation of QCD with the $\gamma\gamma$ data even at low energies and momentum transfer. At this point only (computer) time will tell whether DLCQ will be viable for such problems.

6. FUTURE PROSPECTS FOR $\gamma\gamma$ PHYSICS

The field of photon-photon collisions has now become an essential and integral part of theoretical and experimental high energy physics.

The $\gamma\gamma$ physics issues presented at this workshop are exciting and fundamental, as was evidenced by many intense debates at the Shoresh meeting. The greatest strengths of $\gamma\gamma$ physics are clearly in unraveling the $C = +$ hadronic spectrum and testing hadron dynamics starting from an elegantly simple initial state. Two-photon physics is now a primary area for probing QCD at its perturbative-nonperturbative interface.

The energy domain thus far explored in $\gamma\gamma$ annihilation is still relatively low, but it is nevertheless a good match for testing predictions for exotic quark and gluon states, studying the production of hidden and open charmed hadrons, probing inclusive reactions at low and high p_T, and testing highly constrained predictions for exclusive channels both near threshold and at large invariant mass. The $\gamma\gamma$ measurements in this energy domain are also important as a testing ground for understanding jet hadronization, heavy quark production, and backgrounds to physics at high energy colliders.

Higher $\gamma\gamma$ luminosity and energy are essential in order to extend the reach and sensitivity of $\gamma\gamma$ physics — particularly for (a) the definitive identification of $C = +$

exotic states, (b) high sensitivity tests of perturbative QCD in meson and baryon pair production (reactions which give strong constraints on the hadron distribution amplitudes), (c) the measurement and separation of the photon structure functions, (d) the observation of the entire jet structure predicted by QCD, and (e) a detailed look at $\gamma\gamma$ annihilation into charmed hadrons.

Experiments have hardly begun to exploit the unique capability in $\gamma\gamma$ physics of varying the spacelike mass and polarization of the incident virtual photons. Such double-tagged experiments require both high acceptance and luminosity.

The upcoming run of the TPC/$\gamma\gamma$ detector at PEP will hopefully add a great deal to these studies. Much can be done at the CESR and TRISTAN rings even without tagging. Considerably higher $\gamma\gamma$ luminosity will come automatically with increased e^+e^- luminosity at LEP, and there is intense interest to explore $\gamma\gamma$ processes physics by subgroups at each of the four primary detectors.

The recently-published study of $\gamma\gamma$ physics at LEP-200 provides an excellent survey of physics possibilities at still higher energies and luminosity. Eventually the use of back scattered photons from lasers, wigglers, or controlled beamsstrahlung could lead to machines with photon energies and $\gamma\gamma$ luminosity rivaling that of the primary e^+e^- beams

The principles of $\gamma\gamma$ processes generalize to the domain of gauge-boson interactions in e^+e^-, hadron-hadron and lepton-hadron colliders. As discussed at this meeting by Cahn, Kunzst, Nir, and Schildknecht, these processes provide an important window to virtually all of the physics of the standard model.

We have also discussed at this meeting the relationship of $\gamma\gamma$ physics to closely related fields, such as Compton scattering, $\gamma p \to \gamma p$, and antiproton annihilation, $\bar{p}p \to \gamma\gamma$. Perhaps the most intriguing $\gamma\gamma$ reaction is the very narrow correlated $\gamma\gamma$ signal recently reported at $M_{\gamma\gamma} = 1.062 \pm 0.003$ MeV, in an experiment[75] at the LBL SuperHILAC studying uranium ion collisions on a thorium target at a laboratory kinetic energy of 5.95 MeV/nucleon. Assuming the signal is confirmed, a remarkable feature of this reaction is that the $\gamma\gamma$ system is apparently produced at close to zero rapidity in the center of mass. It is difficult to understand the origin of this state since its measured spread in total momentum $\Delta p_{c.m.} \sim 0.02 m_e$ corresponds to a length uncertainty exceeding 10,000 fm!

7. ACKNOWLEDGEMENTS

On behalf of the participants of the VIIIth International Workshop, I wish to thank Professor Uri Karshon and his colleagues for organizing an outstanding meeting and for their hospitality both at Shoresh and the Weizmann Institute. I thank P. M. Zerwas and G. P. Lepage for helpful suggestions. I also wish to acknowledge the support of the Alexander von Humboldt Foundation and the hospitality of the Max Planck Institute for Nuclear Physics, Heidelberg, where this summary was prepared.

8. DISCUSSION

G. Alexander: You stated in the beginning of your talk that the low $W_{\gamma\gamma}$ region of $\gamma\gamma \to$ hadrons is full of resonances. Does it then make sense to use this region as a testing ground for fundamental QCD and PQCD or should we move to a higher $W_{\gamma\gamma}$ region relatively free of resonances?

S. Brodsky: The applicability of PQCD to exclusive $\gamma\gamma$ reactions clearly requires that one should be in an energy range beyond the region of prominent resonances. On the other hand, the large number of resonances produced in photon-photon collisions in the 1 to 2 GeV energy range suggests that quark anti-quark states alone do not provide sufficient degrees of freedom to describe the observed spectrum. If one can show definitively that gluonic or other exotic states are present, then this regime of $\gamma\gamma$ physics would provide a fundamental testing ground for the bound-state spectrum of QCD.

M. Ronan: In your review, you mentioned the agreement between the TPC/$\gamma\gamma$ measurement of the $\rho^0\ \omega$ production and the four-quark model fit, and that there is no single model which can explain the various vector-vector measurements which have been made. I would like to add a few comments: First, the TPC/$\gamma\gamma$ measurement agrees with the ARGUS results within the 20–30% systematic errors the measurements as can be seen from a figure you have shown. The four-quark model has provided one possible explanation of the $\rho^0\ \rho^0$ enhancement. In an effort to begin to unravel the puzzle of the vector-vector production in photon-photon interactions, we have fit our $\rho^0\ \omega$ data with the four-quark model. We find that the mass of the four-quark resonance in the $\rho^0\omega$ channel would have to be about 1.8 GeV/c^2, and that the super-allowed decays dominate as might be expected. However, in the $\rho^0\rho^0$ channel, one finds an enhancement at about 1.5–1.65 GeV/c^2 and that half of the decays are not super-allowed. To pursue this model we must try to understand the dynamics of a four-quark state to explain the observed mass splitting between the $\rho^0\rho^0$ and $\rho^0\omega$ enhancements, as well as the possible differences in the decay channels or in final state interactions. Clearly, the ARGUS results on $\rho^+\rho^-$ production must also be addressed.

N. Isgur: I want to emphasize that we would gladly be willing to assume that the soft contributions are small if we could be convinced that QCD could legitimately explain the data. In the same spirit, let me say that I would prefer it if you were right about this issue, even though I think you are not. Anyway, you have to agree about one thing: I was correct in saying in my lecture that you would win the first round of this argument!

W. Frazer: You said Stan would have the last word, and so he will.

S. Brodsky: I am delighted to get the last word! Hopefully, I have made it clear in my talk that the predictions of PQCD for the leading power-law contribution to exclusive processes have a sound, rigorous basis. The issues raised by Isgur and Llewellyn Smith, and also by Radyshkin, on the range of applicability of the predictions, due to possible complications such as nonperturbative effects, highlight the importance of further experimental tests of exclusive photon-photon reactions, particularly hadron pair production and the virtual photon mass dependence of resonance production, using both single-tagged and double-tagged events.

The leading-twist PQCD predictions for exclusive processes such as the pion form factor and production of meson pairs in photon-photon collisions are derived to all orders in perturbation theory. These results have also been derived from the operator product expansion and renormalization group. Power-law corrections due to quark mass effects, intrinsic transverse momentum, etc., are in fact consistent with the corrections to the leading power behavior seen in experiment at low momentum transfer.

As I discussed in my talk, the sufficient condition for the validity of the perturbative QCD analysis is the off-shellness of the struck quark line, not the exchanged gluon momentum. Once the quark line is sufficiently off-shell, the perturbative structure of the exchanged gluons dominate. This point, which is critical to the PQCD analysis of exclusive processes, is also at the heart of the renormalization group derivation of the evolution of deep inelastic structure functions—in none of these cases is there a requirement that the radiated gluon, or the target photon in the photon structure function, have minimum virtuality. Such a requirement would significantly affect the predictions of PQCD in inclusive reactions such as the evolution of the deep inelastic structure functions, jet evolution, etc.

Finally, I want to emphasize that the recent test of "color transparency" at BNL in quasi-elastic pp scattering in nuclei gives strong support to the essential feature of the PQCD analysis that only the small, valence component of the hadron wavefunction participates in large momentum transfer exclusive reactions. The experimental observation of minimal attenuation of the incident and outgoing protons as predicted by PQCD excludes any model in which the full size of the hadron participates in the hard scattering reaction.

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