AN EXPERIMENTER’S HIGHLIGHTS

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This selection concentrates more on $\gamma\gamma$ results, with some reference to the related HERA photoproduction data. Progress has been made on a wide range of topics, from $F_2^\gamma$ to the “stickiness” of glueball candidates, but many channels still need better statistics and/or a real photon target before they can match the comparable $ep$ studies.

1 Introduction

The HERA photoproduction data are the main experimental component in Forshaw’s “Theorist’s Highlights”[1], so this talk gives more stress to photon-photon collisions, with some mention of related HERA results. There are five sections; $F_2^\gamma$ hadronic; Other Photon Structure Functions; Inclusive Processes; Exclusive Processes; and Dreams - possible future developments. Many important contributions have had to be left out for lack of time and space.

2 $F_2^\gamma$, hadronic

New results on $F_2^\gamma(x,Q^2)$ from singly tagged events have been presented by three LEP experiments, DELPHI[2], ALEPH[3], and OPAL[4].

Figure 1 is the Feynman graph for a $\gamma\gamma$ scattering event at an $e^+e^-$ collider. For singly tagged events one of the scattered electrons is detected, giving a good measurement of $Q^2 = 2E_0E_{tag}(1 - \cos\theta_{tag})$ for the probing photon. The other lepton is required not to be seen, which keeps the value of $P^2$ for the target photon close to zero. The invariant mass of the hadronic system is $W_{\gamma\gamma}$, which is underestimated because some of the hadronic energy is poorly measured in the forward regions of the detectors[6]. This means that the value of $x = Q^2/(Q^2 + W_{\gamma\gamma}^2)$ is overestimated. The experiments use unfolding packages[8] to correct for this. (Things are much easier at HERA for the measurement of the proton structure function. There the target proton has a unique

[1] Invited review talk given at Photon’97, Egmond aan Zee, the Netherlands, 10–15 May 1997
high momentum instead of the soft distribution of virtual target gammas radiated from the electron beams at LEP, the $ep$ event rate at large values of $W$ is much higher than in $e\gamma$, and $x$ is well determined.)

OPAL has new $F_2^\gamma(x, Q^2)$ data for two bins with average $Q^2$ values of 1.86 and 3.76 GeV$^2$, the first measurements in this low $Q^2$ region since TASSO and TPC/2$\gamma$. Electrons were tagged in the OPAL Silicon-Tungsten luminometer at angles down to 27 mrad from the beam, with the LEP $e^+e^-$ energy close to the peak of the $Z^0$. Since LEP has now moved on past the $WW$ threshold these may be the last measurements in this $Q^2$ range for a long time.

The unfolded $F_2^\gamma$ distributions at low $Q^2$ show the following characteristics:

- There is no sudden change of the shape of $F_2^\gamma(x)$ when $Q^2$ drops below 5 GeV$^2$ (compare shape in ref. with ref. and ref. This is in contrast with the previous measurement from $TPC/2\gamma$.

- The absolute value of $F_2^\gamma$ (ref. Fig. 2) is higher than either the GRV or the SaS-1D predictions. The GRV-HO curve comes closest.
• A rise at $x < 0.01$, as seen in the proton structure at HERA, is allowed but not established, largely because –

• The systematic errors after unfolding are much larger than the statistical errors (true for all LEP $F_2^\gamma$ measurements, see discussion in next few paragraphs).

The values of $F_2^\gamma$ in the medium to large $Q^2$ range ($5 < Q^2 < 120 \text{ GeV}^2$) from the three LEP experiments are in good agreement (see Figure 3 in 4). All of them are consistent with the expected $\ln Q^2$ rise from QCD. The DELPHI error bars are less than those from ALEPH and OPAL, for comparable statistics, because DELPHI has a different approach to calculating the systematic errors from unfolding; what Lauber calls “the problem”.

The problem was posed – in exaggerated form, we now know – by Forshaw (reporting an exercise of Seymour, corroborated by Lönnblad) at Photon95. Events from the HERWIG Monte Carlo program were passed through a simple detector simulation which modelled the way the experimental analyses had previously been done by suppressing all hadron reconstruction in the endcap regions ($\theta < 200\text{ mr}$). In this HERWIG exercise, for generated values of $W_{\gamma\gamma} > 15 \text{ GeV}$ almost all correlation was lost between the visible reconstructed value $W_{\text{vis}}$ and the generated value – see the open circles in Figure 2. Studies with PYTHIA and ARIADNE showed a similar effect. If this were representative of what is really happening in experiments it must mean that, for large $W_{\gamma\gamma}$ and hence for small $x$, unfolding results would be unreliable – as experimenters already feared. An immediate partial remedy was clear to the experimenters; use the sampled hadron energy from the forward electromagnetic calorimeters. Figure 3 shows that approximately one third of this energy is actually measured by OPAL. ALEPH and DELPHI are similar. The result is shown as the solid circles in Figure 3(a). Some correlation is already restored.

But study of the data has led all three LEP experiments to doubt the completeness of the modelling in HERWIG and PYTHIA. The measured hadronic
energy flows in OPAL and ALEPH, as reported here,1-3 show less energy in the partially sampled forward region than predicted by these two Monte Carlo models, and more energy goes into parts of the well-measured central region. In OPAL the shape of the observed energy flow is closer to that from the simple F2GEN model where the outgoing hadronic system is generated as the pointlike production of a quark-antiquark pair, though this must be an incomplete model of the QCD process. Figure 2(b) shows how much better the correlation is between $W_{\text{vis}}$ and the true value for events generated with this pointlike F2GEN model, both with and without the sampled hadronic energy from the forward region. The distribution of hadronic transverse energy $E_{t,\text{out}}$, perpendicular to the beam-tag plane, is also very different between data and HERWIG or PYTHIA, especially at low $x$. And Rooke has shown that the number of events with 2 high transverse energy jets is much lower in HERWIG and PYTHIA than in the data. In both of these cases the pointlike F2GEN sample lies on the other side of the data points from HERWIG and PYTHIA. Butterworth (private communication) has speculated that HERWIG and PYTHIA may be underestimating the contribution from one or more hard-parton processes; photon-gluon fusion, for instance (Figure 4(b)).

The way the game is now being played is shown in Figure 5 as a flowchart. Lauber described an exercise with Seymour and Lönblad which is represented by the nearly vertical dotted arrow from item F to item B on the flowchart, using the energy flow and $E_{t,\text{out}}$ histograms from experiment, item F, to tune the parameters of the parton shower generators, item B, in HERWIG and PYTHIA. Tyapkin reported a similar exercise with the DELPHI generator TWOGAM which has an explicit singly resolved photon component, including photon-gluon fusion. The nearly horizontal dotted arrow, from INPUT to item B on the flowchart, represents a feature of both HERWIG and PYTHIA which use the input set of theoretical parton density functions in their parton shower generators as well as in the cross section generator. The large systematic errors on the OPAL and
ALEPH unfoldings come from assuming a set of Monte Carlo models which cover the whole range of variations in the histogrammed quantities. The DELPHI errors are smaller because they only use the tuned TWOGAM Monte Carlo for unfolding.

There is a serious dilemma here. If we tune the generators perfectly, to match all of the observed histograms, then it will not matter what input parametrisation of \( F_2^\gamma (x, Q^2) \) we have used; the unfolding package, item E, will automatically give us back the input \( F_2^\gamma (x, Q^2) \) as our measured output. What is needed is a set of Monte Carlo models whose parameters are all tied down, either by QCD theory or by fits to other data – hadronic scattering, HERA photoproduction, etc. We must use them to unfold \( F_2^\gamma (x, Q^2) \) from the visible \( x \) distribution, but we must also check that they give good energy flows, jet numbers and \( E_{t,\text{out}} \) distributions. If they do not there must be something missing from them which will have to be added in a well motivated way, or we have to look for better models. It is intriguing that the PHOJET Monte Carlo model\(^{26}\) fits some features of the untagged \( \gamma\gamma \) data as well as PYTHIA does\(^{27}\). A version of PHOJET with off-shell photons is eagerly awaited, as are re-engineered versions of HERWIG and PYTHIA.

The last three or four years of LEP running will double or triple the statistics available for photon structure function analysis. If the Monte Carlo tools can be refined to match there is every prospect of clear answers to two questions; can we measure \( \Lambda_{QCD} \) from the high \( Q^2 \) evolution, and is there a rise of \( F_2^\gamma (x, Q^2) \) at low \( x \)? Of course, we would also like to measure the gluon density in the photon – but that is only accessible directly through inclusive processes, see below.

### 3 Other Photon Structure Functions

There is no reason to expect surprises from measurements of the QED structure functions of the photon. A large part of our motive for studying them is to use them as a testbed for the techniques used to extract the hadronic structure functions. The longitudinal hadronic structure function \( F_L^\gamma \) is particularly interesting because it should have different QCD scaling behaviour from \( F_2^\gamma \). But it had been shown before LEP started up\(^{28}\) that \( F_L^\gamma \) would be hard to measure there because of poor statistics for events with the highest sensitivity to \( F_L^\gamma \), events with low tagged electron energies. The difficulties are now known to be even greater due to background from fake-tags by off-momentum electrons in the beam halo (e.g.\(^{29}\)). More recently Field and others\(^{30,31}\) have pointed out that there are other structure functions which are akin to \( F_L^\gamma \), but which can be measured from the main sample of tagged data.
ALEPH\textsuperscript{32} and OPAL\textsuperscript{33} both reported results from singly tagged $\gamma\gamma \rightarrow \mu^+\mu^-$ samples. The new structure functions govern the distribution of the azimuthal angle $\chi$ between plane of the outgoing muons and the plane of the beam and the tagged electron in the $\gamma\gamma$ C. of M. Both saw significant values for $F_{\gamma,QED}^B$, in agreement with the QED prediction. ALEPH also presented the first measurement of $F_{\gamma,QED}^A$. $F_{\gamma,QED}^B$ multiplies the $\cos^2\chi$ term in the angular distribution and $F_{\gamma,QED}^A$ multiplies the $\cos\chi$ term. Since the two experiments used different sign conventions for the definition of $\chi$ it may well be that OPAL “folded away” their sensitivity to $F_{\gamma,QED}^A$. Successful measurement of $F_{\gamma,QED}^B$ is particularly encouraging because its hadronic form has the same parton content as $F_{\gamma,L}^L$, in the limit of massless quarks, though it comes from a different set of helicity amplitudes.

The task now is to try and use the outgoing jets in hadronic events in the same way as the outgoing muons to define a $\chi$ angle. There will be problems. Whereas the tagged $\mu^+\mu^-$ events have a constrained fit which gives a precisely defined final state $\gamma\gamma$ energy, the hadronic events are very poorly defined because of the incomplete sampling of hadron energies in the forward regions. And only a sub-set of hadronic events has a clear two-jet axis. Telnov suggested that the statistics may be increased by including untagged events in which the electron recoil plane is implicitly defined by the overall transverse momentum of the hadronic system, but it is not clear that this will work. New ideas are still needed. If we are lucky Photon ’99 may see the first analyses for the hadronic $F_{\gamma}^B$ and its evolution with $Q^2$.

4 Inclusive processes

H1 continues to tease the $\gamma\gamma$ community by trying to extract photon structure from jets in photoproduction. The latest study\textsuperscript{34} uses an appropriate set of cuts to get a differential cross section which they say should be equal to the pointlike anomalous contribution to the photon interaction $\alpha^{-1}x_{\gamma}(q^2 + 4g)$. When this is plotted against the $p_T^2$ of the jets it has a logarithmic rise, as would be expected from the scale-breaking nature of the photon-quark coupling. In fact, the rise seems to be significantly steeper than either the GRV prediction or the observed logarithmic rise in $F_2^Z(Q^2)$. This may be a hint that the gluon contribution is doing something unexpected or – more likely I fear at this stage – that the H1 analysis could contain systematic effects which have not yet been understood. It is noticeable that H1 did not present an update at Photon ’97 of the Photon ’95 analysis\textsuperscript{35} that claimed to measure the gluonic structure of the photon, presumably because of systematic difficulties in separating the primary signal from underlying multiple parton interactions, as described at
Progress has been made in inclusive $\gamma\gamma$ analysis, thanks to two important factors: a) LEP has moved away from the $Z^0$ peak; b) the HERA experiments have developed analysis techniques which can be applied to $\gamma\gamma$ as well as to $\gamma p$. Even though the integrated LEP luminosity above the $Z^0$ is still only 10s of pb$^{-1}$ compared with over 100pb$^{-1}$ on peak, the rate for collecting untagged $\gamma\gamma \rightarrow \text{hadrons}$ is much greater than for tagged events – and the $Z^0$ background can be kept well below 10% of the sample with reasonable cuts.

DELPHI$^2$$^5$ presented a preliminary empirical survey of how the properties of events evolve with $\sqrt{s}_{e^+e^-}$. The observed cross section, after selection cuts, rises at about 10 pb/GeV from $\sqrt{s}_{e^+e^-} \approx 132$ GeV to $\sqrt{s}_{e^+e^-} \approx 172$ GeV, and it extrapolates back plausibly to just below the points at $\sqrt{s}_{e^+e^-} \approx 91$ GeV, under the background from the $Z^0$. The same TWOGAM Monte Carlo model that they use for unfolding $F_{\gamma\gamma}$ gives predicted distributions of final state quantities, including $W_{\gamma\gamma}$, energy flow as a function of pseudo-rapidity, transverse momentum of jets and number of jets. Most of them agree well; this home-made model seems to have a good combination of hard and soft components. But they draw attention to one disagreement between data and Monte Carlo at $\sqrt{s}_{e^+e^-} \approx 172$ GeV, where the energy flow in the forward region drops below the prediction in a way which is very reminiscent of the effect seen in the OPAL tagged data$^4$$^5$$^6$.

OPAL$^3$'s inclusive analysis goes further than DELPHI, and may be a prototype that other experiments could follow ($\gamma\gamma \rightarrow \text{hadrons}$ has long had as many different analysis techniques as experiments, which meant that no experiment could check another’s results). OPAL uses a development of the $x_\gamma$ variable from HERA as an estimator of the fraction of the target photon’s momentum carried by the hard parton which produces identified jets with high $E_T$.

$$x_\gamma^\pm = \frac{\sum_{jets} E_j \pm p_{z,j}}{\sum_{hadrons} E_i \pm p_{z,i}},$$

where $p_{z,i}$ is the momentum of a hadron projected along the LEP beam direction. The $\pm$ ambiguity arises because the initial state is intrinsically symmetric, unlike the situation at HERA, and either photon might be the target. Three main categories of events with high $E_T$ jets are expected: direct, singly resolved and doubly resolved (Figure $\gamma^5$). Using the PYTHIA Monte Carlo, OPAL shows that the direct sample should be very cleanly separated from the resolved samples by requiring both $x_\gamma^+$ and $x_\gamma^-$ to be greater than 0.8. They confirm this separation in the experimental data for two jet events with $E_T > 3$ GeV by computing an effective parton scattering angle $\theta^*$ in the dijet C. of M. and showing that the direct ($x_\gamma^\pm > 0.8$) sample has the expected
rather flat distribution, while the resolved samples ($x^+\gamma$ or $x^-\gamma$ less than 0.8) are much more forward-backward peaked, as predicted on a parton level by lowest order QCD (and as seen in a very similar analysis of photoproduction by ZEUS, quoted in Aurenche’s introduction to the inclusive session).

Given the evidence, at least in the two jet sample, for approximate jet-parton duality, OPAL has compared the $E_T$ distribution of jets with the parton level NLO matrix element predictions of Kleinwort and Kramer. The effects of measurement errors are removed by unfolding. The match between theory and experiment is good for $E_T > 5$ GeV and is consistent with the predicted domination by the direct matrix element for $E_T > 8$ GeV. Aurenche also showed how well these NLO curves matched $\gamma\gamma$ data from AMY and TOPAZ, as well as photoproduction from H1 and ZEUS.

Comparison of the OPAL inclusive two-jet cross sections with Monte Carlo predictions is tantalising. For direct events ($x^+\gamma > 0.8$) the PYTHIA and PHOJETS predictions agree with one another and with the data, regardless of the set of PDFs used. But for $x^+\gamma$ or $x^-\gamma$ less than 0.8, i.e. for the resolved samples, there are some disagreements between the two programs with the same PDFs, and large disagreements between different PDFs in the same program. The LAC1 PDFs, for instance, give much too high a cross section with both programs, surely because of too much gluon. Better statistics and further analysis may lead to an independent measurement of the gluon content of the photon.

The total cross section $\sigma_{\gamma\gamma}$ has been one of the worst measured quantities in particle physics (but see “Dreams” below). It remains so for $W_{\gamma\gamma} < 5$ GeV, but L3 has presented first measurements from LEP with $5 < W_{\gamma\gamma} < 70$ GeV which are much more coherent than anything at lower energies. They show a significant rise over this range, consistent with the logarithmic rise seen in hadron-hadron and $\gamma p$ cross sections. The problem with this measurement is an intensified version of the problem discussed above for $F_2^\gamma$, how to correct for the lost hadronic energy in the forward region. In the tagged events used for the structure function some transverse momentum is required in the hadronic system to balance the tagged electron. But the bulk of the events in the total cross section have no tag, and at high $W_{\gamma\gamma}$ there must be a large fraction of diffractive events in which the hadrons hardly have enough transverse momentum to enter the forward luminosity detectors. Most of these events give no trigger and the only way of allowing for them is to use a Monte Carlo program to correct for their loss. Rather surprisingly the PHOJETS and PYTHIA Monte Carlo models give very similar distributions for the $W_{\text{visible}}$ distribution, including the barrel region and the forward detectors, so the total cross section values do not change much when unfolded with either PYTHIA or PHOJETS. But a plot was shown of cluster energies in the forward luminosity detectors.
alone in which there was a marked divergence at high energies between, on
the one hand, the data and the PHOJETS prediction, which both levelled off
and agreed with one another, and on the other hand, the PYTHIA prediction
which fell away much more sharply. This is all we know about the region where
many events must be totally unseen, so it is hard to be completely confident in
the measurement until one or more of DELPHI, ALEPH and OPAL have done
a similar analysis, hopefully with a larger selection of Monte Carlo models.

Charm production in $\gamma\gamma$ remains intractable. The new L3 result for the
inclusive charm cross section agrees with the QCD model, but it is only
based on 43 events at LEP1 in 80pb$^{-1}$ and 29 events at LEP2 in 20pb$^{-1}$, both
tagged with muons from charm decay. It is frustrating to know that there
are thousands of unresolved charm events there, boosted forward by the $\gamma\gamma$
kinematics so that they cannot be identified in the microvertex detectors. A
few more tagging channels can be added, however, and the eventual LEP2
luminosity should give a factor of $\simeq \times 20$, so a worthwhile test of the theory
should come by Photon '01.

A potentially important $\gamma^*\gamma^*$ study has been suggested by Hautmann and
others who make predictions from the high energy limit of QCD (using
the BFKL pomeron) which give a significant doubly-tagged rate for $e^+e^- \rightarrow
\gamma\gamma$ (approximately 1 event per pb$^{-1}$ at LEP2 with $Q^2 \simeq 10$ GeV$^2$).
There was some surprise that the effect has not yet been noticed in LEP1 data,
if it is there. A few dozen doubly tagged events have been seen. They are
routinely rejected from the singly tagged samples of thousands of events which
are used for structure function studies. There may just be enough of them,
after inefficiencies have been allowed for, to accommodate the new prediction.
As ever, a Monte Carlo study of the hadronic acceptance will be needed to find
out if a significant part of the signal is being lost. This will surely be settled
by Photon '99. Come to Freiburg to see if BFKL survives!

5 Exclusive processes

There is no shortage of data, but there is a serious shortage of people to work
on it. Cleo II now has over 3fb$^{-1}$ of integrated luminosity, and we can expect
even more from the specialised beauty factory experiments, Belle in Japan and
BaBar at Stanford. For higher mass $\gamma\gamma$ systems LEP is accumulating worth-
while samples. And there is no shortage of problems to be solved, both from
QCD and in resonance physics where predictions proliferate for glueballs,
hybrids, molecules, 4-quark states and recurrences. I concentrate on two beau-
tiful results from Cleo II, supplemented by L3, and mention a first survey from
H1.
Cleo II has sufficient integrated luminosity to do a precision study on tagged samples of $\gamma^*\gamma \rightarrow \pi^0, \eta$ and $\eta'$. They have recalibrated the inner edge of their tagging detector so that they can use incompletely contained electron showers to go down to a lower limit of $Q^2 = 1.5 \text{ GeV}^2$, joining on well for the $\pi^0$ with lower $Q^2$ data from CELLO. There is a clear difference between the $Q^2$ behaviour of $\eta'$ and the behaviour of $\pi^0$ and $\eta$. Both $\pi^0$ and $\eta$ form factors appear to obey the perturbative QCD prediction of Brodsky and Lepage:

$$\lim_{Q^2 \rightarrow \infty} |F_{\gamma^*\gamma m}(Q^2)| = 2f_m,$$

where $m$ is the particular pseudoscalar meson, and they have consistent values ($\Lambda_{\pi^0} \simeq 776 \pm 20 \text{ MeV}, \Lambda_{\eta} \simeq 774 \pm 30 \text{ MeV}$) for the $\pi^0$ and $\eta$ mass parameters in the monopole formula:

$$F(Q^2) = F(0) \frac{1}{1 + Q^2/\Lambda^2_m}.$$ 

But the $\eta'$ form factor rises to approximately twice the pQCD prediction at $Q^2 \simeq 15 \text{ GeV}^2$, and it has a higher monopole mass ($\Lambda_{\eta'} \simeq 859 \pm 25 \text{ MeV}$; L3 is consistent but with bigger errors). Brodsky and Ruskov – in their talks and over breakfast this morning – agree that these results mean that the $\pi^0$ and $\eta$ are behaving as if their wavefunctions are already close to asymptotic whereas the $\eta'$ is a much more complicated mixed object.

Cleo II’s other beautiful result was totally negative but very clear. This was a search for $\gamma\gamma$ production of the glueball candidate $f_J(2220)$ and its decay to $K_sK_s$. Cleo II sees many other resonances in this analysis, so there is no question about their sensitivity, but they do not see even a hint of the $f_J(2220)$. They therefore put the highest ever lower limit (> 82 at 95% confidence) on the “stickiness” of a meson, the normalised ratio of its $\gamma\gamma$ width to its radiative branching ratio from $J/\psi$. Both BES and Mk II have clear signals for $J/\psi$ decays to the $f_J(2220)$. This object must now be one of the strongest of all glueball candidates. Two other experiments, L3 and ARGUS reported $\gamma\gamma$ resonance studies. The L3 results are promising and should soon have a physics impact. They demonstrate a good acceptance and resolution for many states with masses from 1200 to 1750 GeV/$c^2$ and the statistics will triple or quadruple before Photon ’01.

There was an encouraging first look at exclusive resonance production at HERA from H1, making particular use of the new SPACAL calorimeter to measure multi photon final states boosted in the backward direction. Clear $\pi^0$, $\omega$ and $\eta$ signals were seen, but no $\eta'$. There was also a suggestion of an $a_0(980)$ peak. As well as conventional $\gamma\gamma$ or $\gamma$-pomeron processes, some
of these channels should be sensitive to more exotic exchanges, such as the “odderon”. With rising HERA luminosity this could become very interesting.

6 Dreams; possible future developments

A recurrent good dream seems closer to the real world after Romanov’s talk. This is the hope for precise measurement of the total cross section \( \sigma_{\gamma\gamma} \) in the resonance region by using double tagging at around zero scattering angle in an \( e^+e^- \) collider. The KEDR detector at the VEPP-4M collider in Novosibirsk has focusing spectrometers built into it which measure the outgoing electron and positron to very high precision (we saw results from a setting-up experiment on photon splitting using one of the two spectrometers). The collider will run with \( \sqrt{s} \simeq 1 \text{ GeV} \) soon, but should then go up to around 12 GeV. The resolution on the mass of the system recoiling against the two tags will be better than 20 MeV/c\(^2\) over a range of masses from \( \simeq 0.5 \) to 3.5 GeV/c\(^2\), with a tagging efficiency of better than 15%. The main KEDR detector will have good tracking and calorimetry to measure the properties of the hadronic final state, so this experiment could make a substantial contribution to resonance studies. A daydream which some of us indulge in is to imagine the same kind of zero angle tagging system installed in one of the spare LEP straight sections, together with good luminosity monitors and forward tracking, with a simple barrel detector to trigger on hadronic systems. A well designed specialised experiment could push the \( \sigma_{\gamma\gamma} \) measurement up to \( \sqrt{s} \simeq 70 \text{ GeV} \) or more, could solve the big problem of measuring \( W_{\gamma\gamma} \) in the study of \( F_2 \), could see the BFKL effects predicted by Hautmann et al. and would be much more sensitive than the present LEP experiments to such diffractive processes as \( \gamma\gamma \to pp, J/\psi\rho \) etc. But I hear there is to be a new user for the LEP tunnel after 2001.

In this morning’s talks on the high energy photon linear collider Telnov reported on the steady progress being made in solving the fundamental problems of realising the full potential luminosity of such a machine and Jikia. Ginzburg and Takahashi updated some of the feasibility studies on physics, including measuring the couplings of Higgs bosons to \( \gamma\gamma \). Because this coupling could be sensitive to the existence of very heavy fermions and bosons – well beyond anything reachable at planned machines – it remains one of the most important of all the numbers to be determined once a Higgs boson is found. Nothing has been said here to undermine the conclusion presented at the LCWS in Morioka that, if a Higgs boson is found with a mass of less than 350 GeV, then a high energy \( \gamma\gamma \) collider must be built to study it. Such a machine in \( e^-\gamma \) mode will also give the definitive measurement of the high
$Q^2$ evolution of $F_2^\gamma$, avoiding the big problem of measuring $W_{\gamma\gamma}$ by using a narrow band beam of real photons as the target. Brodsky says that he believes the study of $e^-\gamma \rightarrow W\nu$ will give the best possible measurement of the $\gamma WW$ couplings. Telnov reminded us that if a high energy linear $e^+e^-$ collider is built there must be provision for a second interaction region with a finite beam crossing angle to be built at a later date for real $\gamma\gamma$ and $\gamma e^-$ physics.

The idea of a lower energy photon linear collider was mentioned in passing. It could be a superb tool for studying resonances in the 1 to 4 GeV/$c^2$ mass range. If it were done as part of an upgrade of the SLC at Stanford it might even reach the $e^-\gamma \rightarrow W\nu$ threshold.

7 Summary and Conclusions

In measuring $F_2^\gamma$ the LEP experiments agree with one another that the shape and evolution are consistent with QCD. But the problem of modelling the parton shower must be solved before the two important questions can be settled: is the hadronic part of the photon so like the proton that at low $x$ it has the same kind of rising structure function; and can a precise measurement of the QCD scale be made from the evolution at high $Q^2$? The influence of HERA photoproduction on untagged $\gamma\gamma$ studies is very important. It will be intriguing to see whether LEP or HERA gets the best eventual measurement of the gluon density in the photon; each has its own systematics and intrinsic background problems. Resonance studies continue to be frustrated by lack of effort; the work is intricate and time consuming, and it can be unrewarding if the results are not clear cut. Here Cleo II used its large statistics to report two convincingly clear results. L3 should be able to follow suit with its excellent neutral particle reconstruction.

The connections between photoproduction and $\gamma\gamma$ physics grow closer. Many of the “dreams” of $e\gamma$ and $\gamma\gamma$ physicists, from the previous section, involve achieving comparable statistics and precision to what HERA can already do in $e p$ or $\gamma p$. This may only be possible at a linear collider.

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