IISc-CTS/9/03
hep-ph/0311188

Photon 2003: a theorist's summary and outlook

R.M. Godbole[1]

Centre for Theoretical Studies, Indian Institute of Science, Bangalore, 560 012, India.

ABSTRACT

In this talk I present a summary of some of the discussions at the conference on various topics in Photon physics, selected with a view to give a theorist's perspective, of the current status and future prospects, of the developments in the field. After discussing some of the recent theoretical developments in the subject of Photon Structure function, I will focus on what the photon has helped us learn about the spin structure of a proton, aspects of perturbative and nonperturbative QCD as well as forward and diffractive physics. I will discuss the challenges that the data on heavy flavour production in the two photon reactions and in photo production, seem to have presented to the theorists. Then I discuss the direction in which photon physics is likely to go in future and what we *need* the photons to still tell us. I will end by talking about the newer developments in prospects for photon studies at future colliders and opportunities that these will provide us to learn about the physics beyond the Standard Model.

Summary talk presented by R.M. Godbole at
PHOTON-2003, International Meeting on Structure and Interactions of the Photon
Frascati, Italy, April 7-11, 2003

---

[1] e-mail:rohini@cts.iisc.ernet.in

Photon 2003: a theorist's summary and outlook

Rohini. M. Godbole[a] †

[a]Centre for Theoretical Studies, Indian Institute of Science,Bangalore, 560 012, India.

In this talk I present a summary of some of the discussions at the conference on various topics in Photon physics, selected with a view to give a theorist's perspective, of the current status and future prospects, of the developments in the field. After discussing some of the recent theoretical developments in the subject of Photon Structure function, I will focus on what the photon has helped us learn about the spin structure of a proton, aspects of perturbative and nonperturbative QCD as well as forward and diffractive physics. I will discuss the challenges that the data on heavy flavour production in the two photon reactions and in photo production, seem to have presented to the theorists. Then I discuss the direction in which photon physics is likely to go in future and what we *need* the photons to still tell us. I will end by talking about the newer developments in prospects for photon studies at future colliders and opportunities that these will provide us to learn about the physics beyond the Standard Model.

1. Introduction

In 2005 we will be celebrating 100 years of the discovery of the photon as the quantum of electromagnetic field. During this period, photons have literally 'illuminated' the path of important developments in our knowledge of fundamental physics. The beginnings of the quantum theory were in realizing that radiation is quantized, photon being the quantum. It was the study of atomic spectra involving real photons that led us to a correct understanding of atomic structure. The study of interaction between photons and electrons ushered in the era of Quantum Gauge Field Theories which now form the paradigm for the description of all the interactions among the fundamental constituents of matter, the quarks and leptons. Probing the protons with virtual photons (DIS) led us to our understanding of the proton structure. Photons have the amazing 'self-analyzing' ability. As a result one has been able to study the structure of atoms, nuclei,proton and *photon* using photons. The last makes photon processes a particularly interesting laboratory to study QCD dynamics. The 'photon' conferences of which the current one is the 15^{th}, have had their own character and history. In the early years mainly the photo production and 2γ processes, the latter involving mainly spectroscopy, used to be the topic of discussion. Since the past ten years these have also included discussions of F_2^γ studies in 2γ processes at the e^+e^- colliders and study of 'resolved photon' processes [1] in hadronic interactions of high energy, real or 'quasi-real' photons. This means they have included, along with the discussion of physics at e^+e^- colliders TRISTAN and LEP, also a discussion of proton and photon structure as studied at the ep collider HERA. Thus these photon conferences have continued to reflect the use of photon physics as one big physics laboratory to study QED and QCD.

Highlights of what the community learned about the hadronic structure of the γ at this conference, have been described in the experimental summary[2]. I will include in the discussions below a theorist's perspective as to how this knowledge can (and has) improved our knowledge of γ interactions. I will essentially discuss what the photon has taught us. After discussing the new theoretical developments in the subject of 'real' photon Structure function, I will focus on what the photon has helped us learn about the spin structure of a proton, aspects of perturba-

---

†Author wishes to acknowledge the hospitality of the DESY-T division when part of this work was done

tive and nonperturbative QCD as well as diffractive physics. I will discuss the challenges that the data on heavy flavour production in two photon reactions and in photo production seem to have presented to the theorists. Then I will talk about the direction in which photon physics is likely to go in future and what we *need* photons to still tell us. I will end by talking about newer developments in the prospects at future colldiers for photon studies and opportunities these will provide us to learn about physics beyond the Standard Model. The choice of topics chosen reflects mainly a personal bias but also the theoretical developments and ideas concerning the topics covered in the experimental summary[2].

2. Structure function of the Photon and Proton: hard probes

In this section I discuss a new PDF for real photon that was presented at the conference, the issue of jet and heavy flavour production in photon induced processes, news from the proton structure function at high Q^2 as well as the interplay between forward physics in DIS and structure of the virtual photon. I end by discussing a prediction for beauty production in $\gamma\gamma$ collisions using lessons learned from a study of F_2^p at low-x and the information photons have provided on the spin structure of the proton

2.1. Structure of Real Photon: New theoretical developments

The basic terminology and concepts involved in the description of the 'hadronic' structure of the photon have already been introduced[2]. In spite of the experimental intricacies involved in extraction of F_2^γ from the 2γ processes in e^+e^- experiments at LEP, the data on F_2^γ have come of age, even if the precision is nowhere near the accuracies achieved in the F_2^p measurements[3]. The available data [4] now cover a rather large range of x and Q^2 and thus call for increasing theoretical sophistication in obtaining a parametrization of the parton densities in the photon, the ones normally in use being the ones from the Dortmund group[5,6].

A new LO analysis of the structure of a 'real', unpolarized γ was presented at this conference[7]. They have used[8] all the available high Q^2 data from LEP on F_2^γ in the fit. But more importantly they have given a refined treatment of the heavy flavour in the LO parametrization. The mismatch between the theoretical prediction and experimental observations for the $b\bar{b}$ production in $\gamma\gamma$ collisions [9] makes the case of looking into this issue more carefully, even stronger. A parton of heavy flavour h in any hadron, in this case the γ, can be treated in two different ways: one is the fixed flavour number scheme (FFNS) where the light quarks are the only massless partons along with the gluons. The heavy quarks in the hadron are produced in the Bethe Heitler process $G^\gamma\gamma^* \to h\bar{h}$. While this scheme is the correct one at scales $\sim 4m_h^2$, for higher scales a scheme which treats even the massive quarks to be 'massless' partons and includes them in the evolution equation, the zero mass variable flavour number scheme (ZVFNS), is the more appropriate, as it also resums the large logarithms. Of course results of the ZVFNS approach have to match smoothly with that of the FFNS one in the threshold region, $W \sim 2m_h$, where FFNS is the only correct description. Hence, schemes combining both the approaches, where the number of the 'active' flavours in the hadron changes with the scale, the variable flavour number schemes, (VFNS's) are the desired ones. The ACOT group[10] has suggested, and implemented for the case of the proton, a kinematic solution to handle the threshold matching problem, the so called $ACOT(\chi)$ scheme. This involves, introducing a scale μ which decides the number of 'active' flavours in the hadron, i.e., in the evolution equations and also a new variable $\chi_h \equiv x(1 + 4m_h^2/Q^2)$, where $-Q^2$ is the invariant mass of the probing photon.

The new LO analysis [8] has implemented the ACOT(χ) scheme for the γ. While treating the h quark as a constituent in the photon the contribution of the Bethe-Heitler diagram, where the t channel h quark is on shell, is already included and hence has to be subtracted to avoid double counting. This model is diagrammatically indicated in Fig. 1. They compare it with a FFNS$_{cjkl}$ fit obtained using FFNS. The χ^2 per degree of

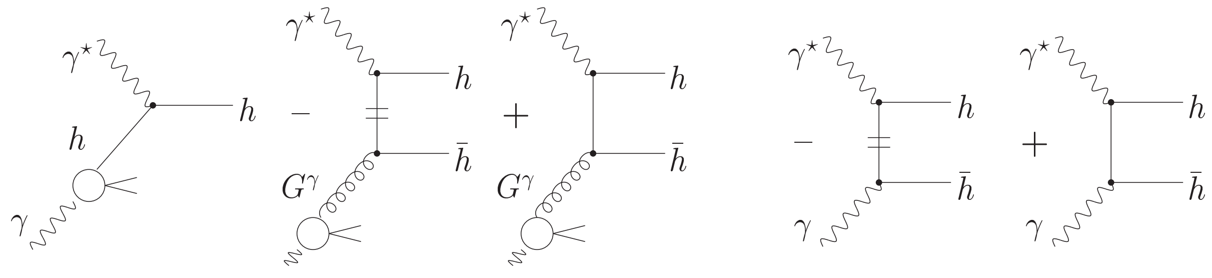


Figure 1. Direct and resolved contributions to F_2^γ in the ACOT (χ) model. The first diagram represents the ZVFNS contribution. The third (fifth) diagram shows the FFNS contribution of the resolved (direct) photon, while the second (fourth) diagram is the corresponding subtraction term[7].

freedom for the ACOT(χ) scheme fit obtained by the authors, is somewhat better and the description of the large Q^2 and large x OPAL data is also a little better than all the FFNS parameterizations including FFNS_{cjkl}. CJKL use the same philosophy, of generating the parton densities radiatively, as that used in the GRV/GRS scheme. However, for the initial conditions, they follow the more reasonable, original GRV ansatz and use an incoherent mixture of the vector meson state, as opposed to the coherent one used in the GRS parametrization. This changes the relative importance of the u quark densities to that of the d quark densities, due to the difference in the charge of the u versus d. As a result of this one has $(u/d)_{GRV} < (u/d)_{CJKL} < (u/d)_{GRS}$. This can indeed be tested at the future $e\gamma$ colliders in a study of both the charged current and neutral current processes $e + \gamma \to e + X$ and $e + \gamma \to \nu + X$, respectively, as pointed out in Photon-2001[11]. An NLO analysis of the PDF is in progress.

2.2. Jet Production in $\gamma\gamma$ collisions: a new NLO calculation

The discrepancy between the L3 data on jets in $\gamma\gamma$ processes and the theoretical predictions[12] has already been discussed[2]. Since the discrepancy exists only in case of L3 data and large p_T^{jet}, it is unlikely that this would be due to our ignorance of the structure of the 'quasi-real' γ. Since it occurs at the edge of the phase space region, it could be due to higher order corrections. The existing NLO calculation has been done by the slicing method. In a presentation at the conference[13] the same NLO calculation done using the subtraction method was reported. Very schematically, in the slicing and subtraction method the NLO result can be written as,

$$< F(x) > |^{NLO}_{slicing} = \int_0^{1-\delta} dx \frac{F(x)}{(1-x)} + F(1) Log(\delta) \qquad (1)$$

$$< F(x) > |^{NLO}_{subtraction} = \int_0^{1} \frac{F(x) - F(1)\theta(x-1+x_c)}{(1-x)} + F(1) log(x_c) \qquad (2)$$

In the slicing method, the phase space is divided into slices and in the part of the phase space where the kinematics is collinear, the contributions involving virtual and soft real quanta, are canceled numerically against each other. It is clear from the two terms involving δ on the right hand side of Eq. 1 that the cancellations are large as δ is small. Also this involves dropping terms of $\mathcal{O}(\delta)$. In the subtraction method, x_c is not necessarily small as the only condition on x_c is $0 < x_c < 1$. Hence the cancellation between the soft real term and the virtual term is done without any approximations and analytically. A finite remainder is then integrated numerically which does not involve large numerical cancellations.

The results of this calculation agree well with those done by the slicing method before[12].

Their results for inclusive distributions agree with OPAL data as well. The calculation also shows that even-though, in principle, the OPAL analysis of the dijet data with somewhat symmetric E_T cuts could have had IR problems, in practice the region chosen by OPAL is free of the possible IR problems. In short two different NLO calculations of inclusive jet cross-sections in $\gamma\gamma$ collisions, agree with the OPAL data but have trouble with the L3 data, thus deepening the mystery.

2.3. Charm content of the photon and heavy flavour production in real photon induced processes

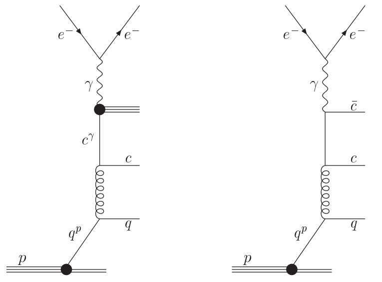
In general, definition of the heavy flavour content of any hadron has theoretical ambiguities (cf. discussion in section 2.1) and the issues are somewhat more complicated for γ due to the blurring of the boundary between the 'resolved' and 'direct' processes beyond the LO. It had been pointed out earlier[14] that inclusive photo production of the D^* could be used as a 'direct' probe of the charm content of the photon.

In the LO the 'resolved' contribution to the photo production of a D^* along with a jet, comes from diagram similar to that shown on the left in Fig. 2. This can be looked upon as 'excitation' of the charm in γ. This can also be seen as a part of the contribution of the 'fixed order' (FO) 2 → 3 processes, when the c quark in the t channel in the diagram shown in the right panel of the same figure is almost on mass shell. Actually a LO calculation in the former language might be better than just a simple FO calculation, as the former will sum up the leading large p_T logs. As a matter of fact, our calculation[14] had also demonstrated that one could enhance the 'excitation' contribution in the sample of the inclusive D^* events, by making cuts on the rapidity of the away side jet, to eliminate contribution coming from the 'direct' process $\gamma + G^p \rightarrow c + \bar{c}$.

A very nice analysis of the charm dijet photo production[15,16] presented at the conference, shows a clear evidence for events originating from the charm in the photon. For the dijets arising from $\gamma + G^p \rightarrow c + \bar{c}$, the hard subprocess involves exchange of a c quark in the t channel whereas for the dijets coming from the hard subprocess shown in Fig. 2 it is g which is exchanged in the t channel. The spin 0 and spin 1 character of the exchanged quanta would imply an angular distribution $\propto (1 - |cos\theta^*|)^{-1}$ and $\propto (1 - |cos\theta^*|)^{-2}$ respectively. The observable

$$x_\gamma^{OBS} = \frac{\sum_{jets} E_T e^{-\eta}}{2yE_e}$$

gives the fraction of the photon momentum entering the subprocess producing the dijet. Thus one expects $x_\gamma^{OBS} = 1$ for the direct process and $x_\gamma^{OBS} < 1$ for the resolved process. A cut of 0.75 on this variable thus separates the 'direct' and 'resolved' enriched part of the event sample. The upper and lower panels of Fig. 3, show the angular distributions for $x_\gamma^{OBS} < 0.75$ and $x_\gamma^{OBS} > 0.75$ respectively. It is clear that the 'resolved' and 'direct' samples are consistent with the g and q exchange respectively, thus showing clear evidence for the resolved photon charm excitation pointed out earlier [14]. The figure also shows that this conclusion is pretty robust and unaffected by the hadronisation model. About 40% contribution comes from the 'resolved' photons and hence mainly from the c in the γ.



Contribution of charm in photon

2 → 3 fixed order contribution

Figure 2. Diagrams showing 'resolved' contribution to inclusive production of D^* with a jet as charm excitation on the left or as contribution from a fixed order (FO) 2 → 3 process on the right.

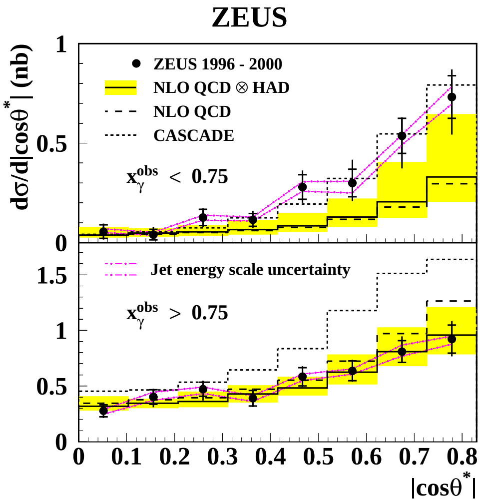


Figure 3. Charm dijet angular distribution in photo production, θ^* being the angle between the jet-jet axis and the beam axis in the dijet rest frame[15].

The observed distributions agree well in shape with a LO Monte Carlo. To understand the comparisons of the data with NLO calculations, one has to discuss different schemes that exist for doing these, the differences being due to two different ways of looking at heavy quark content of a hadron, mentioned already in section 2.1. The massive FO NLO calculation[17] contains, in principle, both the 'direct' and 'resolved' contributions, the scheme being valid only for $p_T, Q \sim m_c$. Further in FFNS ($m_c \neq 0$ and three active flavours in p and γ) the 'resolved' contribution is effectively treated only in the LO and hence has a large scale uncertainty. Further fragmentation function again is only perturbative and does not include evolution. This calculation, however, does include the m_c^2/p_T^2 terms correctly. For $p_T >> m_c$ large logs need to be resummed. Calculations can also be performed in ZVFNNS where the c is treated as an active flavour in the p, γ, the scheme being valid only at scales Q, p_T all much larger than m_c[18]. Of course in this case the $2 \rightarrow 3$ contribution needs to be subtracted, to avoid double counting, just as in the case of F_2^γ discussed in section 2.1. Further, one needs also to match the FO massive and massless calculations. In the matched FONLL calculation [19], m_c^2/p_T^2 mass effects are incorporated up to NLO and resummation of the p_T logs is done up to the NLL level. At this conference the massive variable flavour number scheme, massive-VFN, where one uses $m_c \neq 0$ and still c is an active flavour in the initial state, was discussed [20] in the context of charm production in $\gamma\gamma$ collisions. This scheme has the advantage that it includes both, the m_c^2/p_T^2 effects due to the nonzero mass of c and the $\log p_T^2/m_c^2$ effects in the evolution and the fragmentation function of the initial and final state charm, at large p_T^2, to NLO. At low p_T however, in the limit of $m_c = 0$, the massive VFN scheme does not reduce to FFNS. The two differ by finite terms, which have been calculated [20] for the direct and once resolved terms in $\gamma\gamma$ production of heavy flavour. The matching of the massive, resummed calculation to FFNS, at small p_T still needs work and is in progress.

To return to the data on the photo production of D^* with a jet, only NLO calculations available in the public domain are the FO, FFN[17] and FONLL[19] and have been used to make comparisons with the data. Comparison of the FO, FFNS calculation, including hadronisation effects, shown in Fig. 4 indicates that for $x_\gamma^{OBS} > 0.75$ the NLO calculation describes the data well. However, for the lower x_γ^{OBS} the NLO calculations fall short of the data in both the p and γ direction. CASCADE, a Monte Carlo which implements CCFM evolution, overestimates the $x_\gamma^{OBS} > 0.75$ contribution. The underestimation of the low x_γ^{OBS} tail of the data by the FO, NLO prediction is confirmed further by comparisons of more differential distributions, made possible by large data sample, in $\eta(D^*)$ for different bins of $p_T(D^*)$. The data are either close to or above the upper band of FO,FONLL predictions for medium $p_T(D^*)$ and forward $\eta(D^*)$.

Given the large size and precise nature of the data sample, a comparison of these data with a massive VFN calculation where the resolved con-

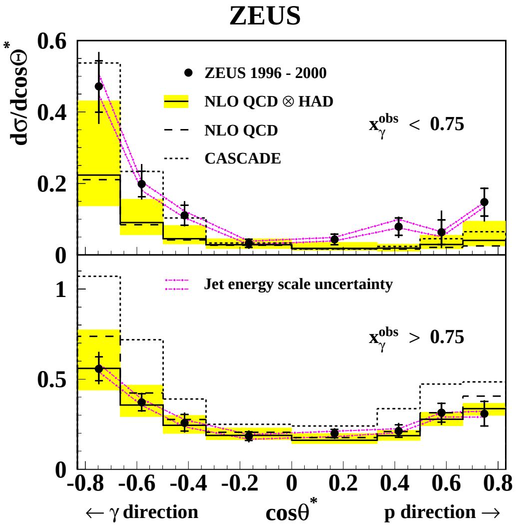


Figure 4. Comparison of the data with a FO NLO calculation with/out hadronisation effects as well as with CASCADE Monte Carlo, for the 'direct' and 'resolved' enriched sample with $x_\gamma^{OBS} > 0.75 (< 0.75)$[15].

tribution is also treated to NLO, is indeed the order of the day. These data provide a very nice laboratory to learn how to implement the heavy quark in the initial as well as in the final state. The fact that at LEP, data on D^* production in $\gamma\gamma$ processesfrom all the three LEP collaborations, ALEPH, OPAL and DELPHI, for $p_T(D^*) > 2$ GeV, is explained very nicely in terms of a massive, resummed NLO calculation[20], makes similar comparison for the photo production data quite imperative. Since the 'away' side jet will be a light quark jet for the 'resolved' contribution and will contain a D^* for the direct contribution, one could also use this for separating the two.

2.4. Proton Structure Function: news from large Q^2 region

In the six years of running, two experiments at HERA have collected an impressive amount of data on F_2^p over a wide range $1 < Q^2 < 4 \times 10^4 \mathrm{GeV}^2$ and $6.2 \times 10^{-5} < x < 0.65$, the coverage at low-$x$ being restricted to smaller Q^2 values and that at large x to $Q^2 \gtrsim 2.5 \mathrm{GeV}^2$ as reported at this conference[3]. The PDF's obtained using QCD fits to HERA data alone, show very nice consistency with those obtained from a global analysis. The errors on the $u(d)$ quark densities in the proton obtained from the HERA data are between 1–2% (3–10%) over the x range $0.01 < x < 0.4$, whereas the errors on the quark sea and gluon densities, which dominate the F_2^p at low-x, are $\sim$ 5%, and 10% for $x < 0.1$. Of course this is great news from the point of view of making more accurate predictions for the LHC possible.

More interesting from a theorist's point of view, is the fact that the errors in the reported values of F_3 from the measurements of cross-sections for the charged current process $e + p \to \nu + n$, σ_{CC}, which are statistics dominated, will reduce substantially after HERA-II running and hence can be used for some interesting tests of QCD. HERA-II low energy running has already yielded measurement of F_L. The reduced cross-sections $\tilde{\sigma}_{CC}$, where the factors involving Q^2, propagator and the coupling of the leptons to the W are removed, for incident e^- and e^+, can be simply written in terms of the Quark Parton Model expressions involving the known PDF's. Fig. 5 shows measurements of $\tilde{\sigma}_{CC}$, for $280 < Q^2 < 17,000$ GeV^2 covering two orders of magnitude in x, against the predictions given by PDF's extracted from the data on F_2^p. The consistency also indicates that there are no special surprises in the large Q^2 region covered up to now.

2.5. DIS and hadronic structure of virtual photon

HERA has provided interesting information on hadronic structure of the 'quasi' real photon as well as the virtual photon, via inclusive jet production and heavy flavour production. The new experimental results in this respect were covered in the experimental summary[2]. As far as the proton is concerned, low-x is the second frontier of interest and investigations at HERA. Some of the new results in the jet production in the 'forward region' in the DIS, where BFKL dynamics

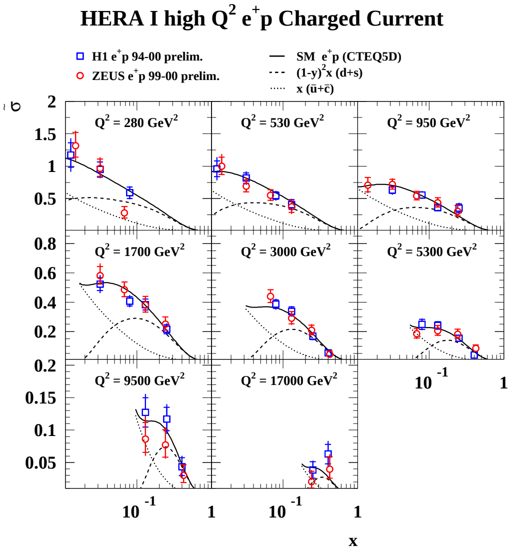


Figure 5. Data on $\tilde{\sigma}_{CC}$ at high Q^2 confronted with predictions from the PDF's obtained with the F_2 fits[3].

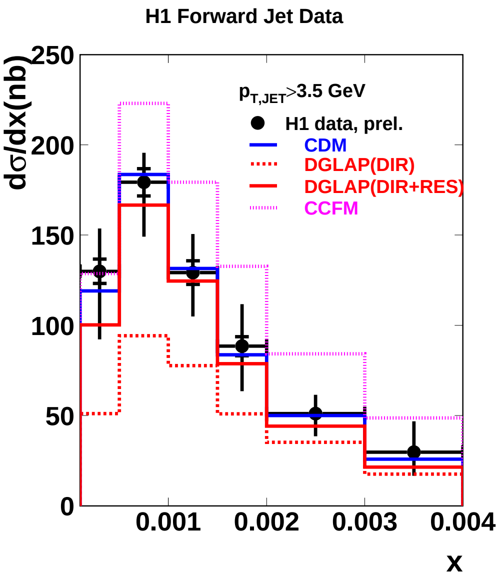


Figure 6. Comparison of the H1 forward jet data (1997) with DGLAP LO and CCFM predictions, for low x[21].

for the proton is likely to leave its imprint, indicate that the hadronic structure of the virtual photon might be playing an important role in the forward region. This also underscores the need to understand the structure of a virtual photon, if one wants to develop clean diagnostics to study the proton dynamics at low-x. Forward physics also holds the key to an understanding of the QCD dynamics of hadronisation. In this context the data on forward particle and jet production in DIS presented at this conference[21] have thrown open yet another challenge to the theorists.

Inclusive jet data in DIS were analyzed with a special focus on the forward jets in the H1 data, for $5 < Q^2 < 100$ GeV^2 and $0.2 < y < 0.6$. The description of the data by a DGLAP, NLO calculation slowly deteriorates as one goes from backward to forward direction[21]. The deviations are particularly large for small Q^2 and small transverse energy E_T. The comparison between the data on forward jets (with cuts to enrich the possible BFKL contribution) and calculations, shown in Fig. 6, makes it clear that the data can be understood in terms of a LO DGLAP calculation which includes both the 'direct' and 'resolved' contribution. However, one has to choose a scale $Q^2 + p_T^2$, for the structure of a virtual photon with virtuality Q^2; the p_T^2 values being $0.5 < p_T^2/Q^2 < 2$. An earlier theoretical analysis which treated the 'direct' contribution to NLO and included the virtual contribution as well[22], also needed to choose a similar scale. The CCFM model which should include effects of the BFKL dynamics at low x overshoots the data.

It is expected that features specific to BFKL dynamics might be washed out due to averaging if one looks at inclusive quantities at HERA. But study of exclusive variables chosen to maximize the effect of the BFKL dynamics whould offer a good probe. Thus forward particles are expected to be a better probe of the BFKL dynamics than forward jets. The analysis is more

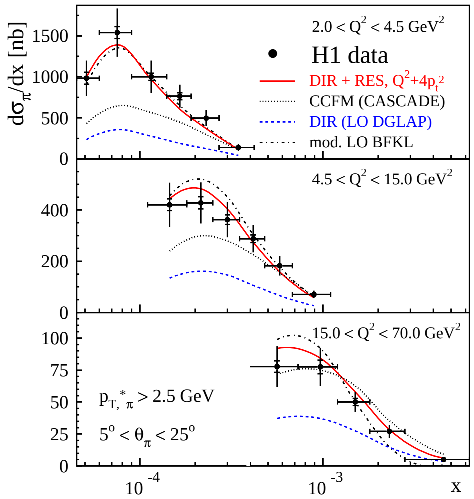


Figure 7. Comparison of the H1 forward particle data with DGLAP LO and CCFM predictions[21].

difficult but results are now available and were presented at the conference[21]. Comparison between the data and the DGLAP as well as CCFM calculations, shown in Fig. 7, indicates again that the *resolved* contribution *has* to be included for the best description of the data , but with $Q^2 + 4p_T^2$ as the scale for the PDF in γ. A modified BFKL calculation[23] seems to describe the data as well. Clearly a complete NLO calculation, for the resolved as well as the direct contributions to the forward particle production, in the usual DGLAP formulation is the order of the day. NLO calculation of the direct contribution are underway[24,25]. These seem to show trends similar to those seen in comparison of the data and FO,NLO calculation of forward jets, viz. the resolved contribution is a significant part of the FO, NLO corrections to the 'direct' process. A complete calculation should enable us to understand virtual photon structure better and also to address whether these data hold any indication of BFKL dynamics.

Recall also the indications that the ZEUS data on jet production in DIS[26] does not seem to be explained by just a FO, NLO calculation of the 'direct' process[27] in spite of the large Q^2 of the γ involved and one might need to inlcude the resolved contribution to the NLO[28], to explain the data in terms of a QCD calculation. Thus, the virtual photon has indeed thrown up some new challenges and these indicate more work for theorists.

2.6. Structure of the proton and heavy flavour production in $\gamma\gamma$ collisions

One of the important experimental presentations at the meeting was the fact that while data on charm production in $\gamma\gamma$ collisions from *all* the four LEP collaborations are in agreement with the NLO theoretical calculations *all* the LEP experiments find too much 'beauty' in $\gamma\gamma$ collisions [2,9,29] compared to the theoretical expectations. The observation is all the more puzzling since the theoretical uncertainties coming from the QCD higher order corrections and/or from the photonic parton densities are expected to be smaller for the $b\bar{b}$ than for $c\bar{c}$. Hence any new theoretical calculation of the former is of interest. One such attempt is described below.

It is possible that the collective phenomena like gluon recombination or saturation might play an important role because of the small values of x being explored at HERA. In that case CCFM evolution might be the more appropriate one to be used [30] for analyzing the data on F_2^p. The HERA data for $x < 5 \times 10^{-3}$ and $Q^2 > 4.5$ GeV^2, have been used[31] to determine the unintegrated gluon density in the proton, which is the correct one to use while calculating various quantities in the k_t factorization scheme rather than the usual collinear, DGLAP formulation.

In this approach the unintegrated gluon densities in a hadron are given in terms of the parton densities at a small scale Q_0 by the evolution equation governed by the CCFM splitting function. The scale Q_0 and the cutoff value of internal k_T, viz., k_T^{cut} below which nonperturbative region is entered, are the two parameters which are fitted to the data. Using the parameter values so determined[31], one can determine the unintegrated gluon densities in the case of a γ as well.

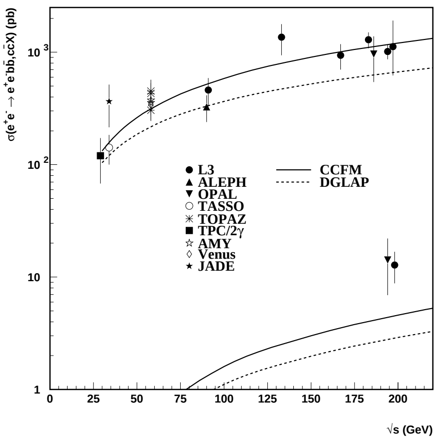


Figure 8. Predictions for the heavy flavour production in $\gamma\gamma$ collisions in the k_T factorization scheme[31].

In principle, these will include terms in higher order corrections beyond those included in the usual collinear approximation in the DGLAP formulation. Fig. 8 shows that while the charm production is reasonably well described. the beauty production, though somewhat higher than the one obtained in the collinear approximation at NLO, is still much below the data. This calculation thus shows that the discrepancy between the data and theoretical prediction are unlikely to be due to higher order effects neglected in the collinear, DGLAP calculation.

2.7. Spin Structure of proton

Most of the information on the spin structure of the proton normally has come from the polarized DIS. The measurements of polarization asymmetries of the inclusive DIS cross-sections can be used to extract the helicity distribution g_1 in a proton which is the longitudinal spin distribution of the quarks in a longitudinally polarized proton. The function $g_1(x)$ measures the difference between the quark density distributions (Δq) with its spin parallel and anti-parallel to the direction of spin for the longitudinally polarized photon, in the infinite momentum frame. Once one moves on to semi-inclusive DIS (SIDIS) and two hadrons are involved, then apart from the unpolarized structure function $f_1(x)$ and $g_1(x)$, the only other twist 2 distribution function characterizing the spin structure of the proton, is the transversity distribution, which measures the transverse spin distribution in a target polarized transversely to the virtual photon[32]. Since rotation and boost do not commute, $g_1(x)$ and $h_1(x)$, are two distinct functions. As a matter of fact the QCD evolution of the transversity and helicity distributions are different. Also the axial and the tensor charge of the nucleon i.e. the integral of the helicity and transversity distributions respectively are different from each other and their values as evaluated on the Lattice are 0.18 and 0.56[33] respectively. Here the axial charge is the integral of the isoscalar combinations of Δq.

Currently the focus of studies in the spin structure of the proton at Hermes and Compass, is the transversity distribution $h_1(x)$ in the SIDIS. Since it is a chiral odd function and all the gauge interactions preserve helicity, a measurement of $h_1(x)$ is possible only when combined with chirally odd fragmentation function. These will give rise to single-spin azimuthal asymmetries in SIDIS. There exist several different effects which could give rise to such chirally odd frgamentation and has been modelled theoretically. The analyzing power of the single-spin azimuthal asymmetry can get diluted to some extent due to the higher twist effects, in case of targets which are longitudinally polarized. It is clear that these studies are of immense theoretical interest.

An analysis of the single-spin azimuthal asymmetries $\mathcal{A}_{UL}(\phi)$ from Hermes, with unpolarized lepton but longitudinally polarized targets, was presented at the conference[34]. The data from the current run, show nonzero target-spin azimuthal asymmetry and these are consistent with predictions of models which are transversity related (at least for the pions). Measurements of the asymmetries with transversely polarized target, in Hermes-II, will provide much better information on the transversity distribution. Beam-spin azimuthal asymmetries as are being measured by the CLAs collaboration can probe the

Collins fragmentation function in combination with different distribution functions than one can do with polarized target. The results from Hermes-II and CLAs hold thus a great promise for spin physics.

3. Structure of p, γ: Soft and Diffractive Physics

A variety of theoretical and experimental discussions were presented at the conference on this subject. I choose to highlight the new results from HERA in diffraction which, along with the data from the Tevatron, have sparked a very intense theoretical activity in the area. These measurements have also implications for the energy dependence of the total cross-sections for the proton and photon induced processes and thus hold a lot of promise for us to learn about the dynamics of QCD in the nonpeturbative regime. The exclusive, diffractive production of vector mesons has seen developments in the theoretical models recently which will, however, not be discussed for reasons of stpace.

3.1. Diffraction

A summary of the vast amount of data on hard diffraction at HERA[35] as well as the information on diffraction from the Tevatron[36] was presented at the meeting. The cross-section for the reaction $ep \to epX$, can be written in terms of the diffractive structure function $F_2^{D(4)}(\beta, x_{\mathbb{P}}, t, Q^2)$. The earlier HERA data had supported the Regge factorization hypothesis according to which one has,

$$\begin{aligned} F_2^{D(4)}(\beta, x_{\mathbb{P}}, t, Q^2) &= f_{\mathbb{P}/p}(x_{\mathbb{P}}, t) F_2^{\mathbb{P}}(Q^2, \beta) \\ &= \frac{e^{bt}}{x_{\mathbb{P}}^{(2\alpha_{\mathbb{P}}(t)-1)}} F_2^{\mathbb{P}}(Q^2, \beta) \qquad (3) \end{aligned}$$

where $x_{\mathbb{P}}, \beta$ are related to Bjorken x by $x = x_{\mathbb{P}}\beta$. New results from H1 and ZEUS for diffractive jet production at HERA were presented at the conference and these covered a wide range of Q^2, β and $x_{\mathbb{P}}$. The selection of diffractive events was done in more than one ways. Q^2 evolution of $F_2^{\mathbb{P}}(Q^2, \beta)$ in Eq. 3 is given by the DGLAP equation. The data show scaling violation up to large values of β, which in turn means large gluon component in the colourless exchange which causes the diffractive scattering. This is indeed consistent with our QCD picture of this colourless exchange (i.e. the Pomeron) as a multigluon ladder. The data allow an extraction of the pomeron intercept $\alpha_{\mathbb{P}}(0)$ as a function of Q^2. Most interestingly the value of $\alpha_{\mathbb{P}}(0)$ is substantially higher than the 1.09 expected for the universal soft Pomeron, even-though the errors on $\alpha_{\mathbb{P}}(0)$ are quite large[35].

Further, H1 has been able to make an NLO QCD fit to the data on Diffractive structure function and they presented[35] a set of diffractive parton densities. The ideas of QCD factorization will imply that the diffractive cross-sections for different hard processes be given by convolution of the diffractive parton densities with the partonic subprocess cross-section. This seems to work between the diffractive jet and charm production at HERA. However, the factorization breaks down when one uses the same densities to calculate the diffractive jet cross-section measured at the Tevatron[36], where the diffractive events are selected by requiring rapidity gaps. This confirms the breakdown of factorization between the ep and $\bar{p}p$ case, noticed before. This strong violation of factorization can be understood in terms of the additional spectators present in the $\bar{p}p$ environment. However, a recent analysis [37] by H1, presented after the conference, of the diffractive charm production in resolved photon processes, puts some doubt on this understanding of violation of factorization. Therefore, hard diffraction is certainly an area to look to-wards when HERA-II data start coming out. Theory interest is not just due to the insight in the nonperturbative /semi-hard QCD dynamics that one expects these data to provide, but also from a very pragmatic point of view of being able to calculate cross-sections of different diffractive processes, at the Tevatron and the LHC, where these might give novel search channel for the Higgs.

3.2. Total cross-sections

In the Regge-Pomeron theory one expects the rise with energy of total cross-section to be given by $s^{\alpha_{\mathbb{P}}(0)-1}$. One possible implication of a value of $\alpha_{\mathbb{P}}(0)$ substantially larger than the universal soft pomeron value of 1.09 as reported above, albeit with large errors, is that the cross-sections might rise faster with energy than the expected universal $s^{0.09}$ behavior. The high energy behavior of the total cross-sections was a subject of much discussion at the conference. No new results were presented on the experimental side, though new analyses from H1 and OPAL are expected to yield new numbers for the total γp and $\gamma\gamma$ cross-section soon. The extraction of the total hadronic cross-sections involving photons from the measurements of the ep and e^+e^- processes, is beset with the same problems as in extraction of F_2^γ, explained in detail[2] in that context.

One of the analysis[38] presented studies all the cross-sections in a global picture and a fit is made in a QCD inspired model, using unitarity and factorization. An eikonal picture is used. Normally the eikonal is determined by the parton densities in the hadron and the QCD parton scattering cross-sections. In this model the coefficient of the subprocess cross-sections appearing in the eikonal are not the product of the parton densities but are free functions which are fitted using the proton data. Using these fitted functions and ideas of VDM and quark parton model, the γp and $\gamma\gamma$ cross-sections are obtained. The authors find a good description of γp and $\gamma\gamma$ data with these fitted parameters, if they use the L3, OPAL data obtained by using PHOJET for unfolding and *further renormalise both* the data downward by about 10%. The global fit is much worse and requires a downward normalization of the data by about 20% if the data obtained using PYTHIA for unfolding are used. The authors conclude from this that all the cross-sections rise universally. However, the L3 data, the only one data set to have points at higher energy, still systematically lies above their fit even after normalizing it downward as can be seen in Fig. 9.

The other sets of talk[39,40] on total cross-sections presented theoretical motivation of an unitarised eikonal model based on QCD where the eikonal is calculated in terms of minijet cross-sections which can be computed using perturbative QCD subprocess cross-sections $\sigma(p_1p_2 \to p_3p_4)$ and parton densities in the proton and photon as measured experimentally. In this formalism one has to make a model for the transverse overlap function of the two hadrons. One talk [39] outlined the basic idea of this model and the other one [40] discussed the results obtained in the model for $pp/p\bar{p}, \gamma p$ and $\gamma\gamma$ total cross-sections. The soft parameters of the model are fixed by fitting the $p\bar{p}$ and pp cross-sections. This model gives a nice description of the initial *fall* and the subsequent *rise*. Fig. 10 shows the comparison of the model predictions with data for the $\gamma\gamma$ case, with the soft parameters in the eikonal being taken to be average of those fitted in case of pp and $\bar{p}p$. The model gives a good description of the observed energy dependence of the γp cross-section as well, provided the soft part in the eikonal is taken from only the pp fits. Thus here one seems to have a breakdown of exact factorization. Also the BN form of the transverse overlap function of the two hadrons $A(b, s)$ is derived only in the LO and in Abelian approximation. Further, prediction for the elastic cross-section is off by about 10% in this approach.

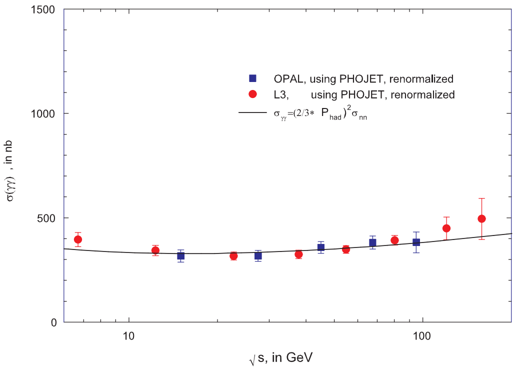


Figure 9. Renormalized OPAL and L3 data on $\gamma\gamma$ cross-sections, given using PHOJET for unfolding, compared with global fit of [38].

Clearly the situation needs clearing up. The work with global fits seems to indicate that using the PHOJET unfolding, the rate of rise with energy of the hadronic cross-section for $\gamma\gamma$ is the same as that for $pp, \bar{p}p$. But this is not quite con-

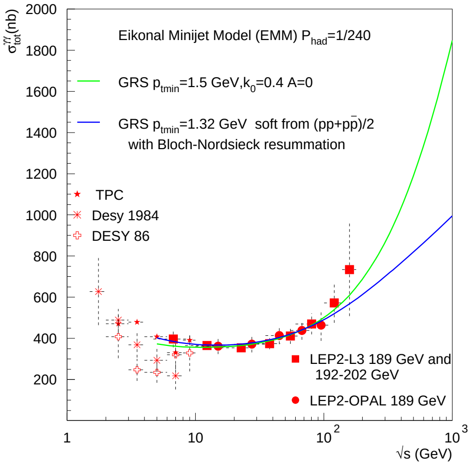


Figure 10. All the data on the hadronic $\gamma\gamma$ cross-sections, compared with predictions of the Eikonalized Minijet Model and the BN model[40].

sistent with the observation by the L3 collaboration that fits to their data of the form $As^{\epsilon} + Bs^{-\eta}$ gave them values of ϵ much higher than the 0.09 quoted for the $pp/p\bar{p}$. Secondly the global fit does require a renormalization of both the L3 and OPAL data. Further, this means that effectively one is using parton densities for the γ quite different than those experimentally measured. These, as we know, are quite different for the p and the γ. Since the γ 'owes' part of its hadronic structure to the 'hard' $q\bar{q}\gamma$ vertex, should we actually not expect a different behavior for the γ than for a proton? On the other hand, the EMM model predicts an uncomfortably fast rise with energy of $\sigma_{\gamma\gamma}^{tot}$ beyond the LEP energy range whereas the BN model requires a possible breakdown of factorization for a consistent description of *both* the normalization and energy rise of all the three, $pp/p\bar{p}, \gamma p$ and $\gamma\gamma$, cross-sections. Luckily newer measurements of $\sigma_{\gamma p}^{tot}$ and $\sigma_{\gamma\gamma}^{tot}$ are expected to be available from H1 and OPAL soon. We can only look forward to that.

4. Future Physics Studies of the Photons and with the Photons

The next generation e^+e^- and $e\gamma$ colliders will offer an excellent chance to study the structure of photon, both real and virtual, via the measurements of hard processes. There have been no new developments in that area since the discussions at the PHOTON-01[41]. Measurement of quantities such as total hadronic cross-sections in 2γ processes will offer possibilities for studying the nonperturbative QCD dynamics and model building for calculation of soft quantities such as cross-sections, as discussed partially in section 3.2. In the last two years a very complete study of the physics potentials of the Compton Collider option was made, using realistic energy and polarization spectra of photons expected at the Photon Linear Colliders (PLC) after inclusion of nonlinear effects as well as using realistic detector simulations. Various aspects of these studies at the future colliders were discussed at the conference [42]. I will mention some aspects of the Higgs and CP studies that photons make possible.

I also review the discussions at the conference of the use of the data from low-energy e^+e^- colliders to determine the all important hadronic contribution to $(g-2)_\mu$, role that $\gamma\gamma$ colliders can play in studying physics beyond the SM and a method, for helicity amplitude calculations, well suited for automation.

4.1. Higgs and CP studies at the future $\gamma\gamma$ colliders

The possibility of very accurate measurement of the $\gamma\gamma$ width of the SM Higgs boson, at a PLC, where it is produced as a s channel resonance, has been discussed at previous photon meetings[43]. Since these original studies, further investigations on accuracy of measurements of the $\Gamma(H \to \gamma\gamma)$ using the $b\bar{b}, WW$ and ZZ channel as well as getting information on the the phase of $\gamma\gamma H$ coupling using the decay of the Higgs in WW, ZZ channel, with realistic detector simulations and careful consideration of higher order corrections and backgrounds, for a Higgs with mass $180 < m_H < 350$ GeV at a PLC, have been performed recently[44]. These show that a PLC

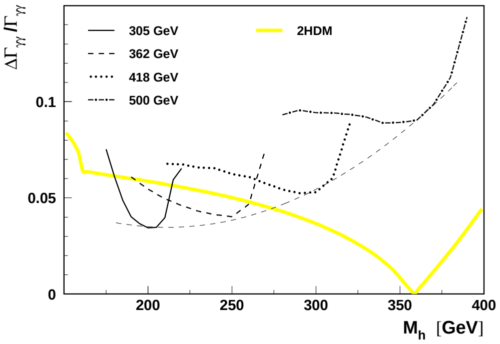


Figure 11. Statistical error on the measurement of the $\gamma\gamma$ width of a H as a function of Higgs mass at a PLC[42]

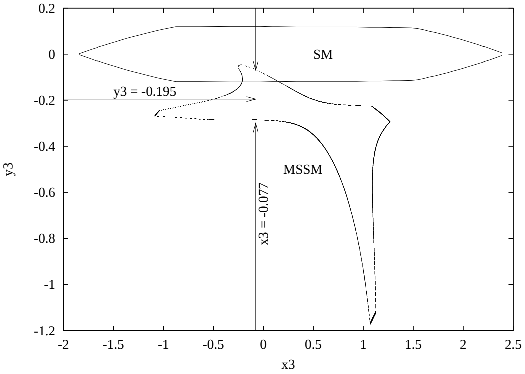


Figure 12. Sensitivity of a PLC for separating between a SM and MSSM Higgs using $\gamma\gamma \to H \to t\bar{t} \to lX$[45]

will offer possibilities for discrimination of an observed Higgs resonance from the SM case. Figure 11 shows expectations for a two Higgs Doublet Model (2HDM) along with the possible sensitivity of measurement. These analyses have also shown that $\Gamma(H \to \gamma\gamma)BR(H \to b\bar{b})$ can be measured to an accuracy varying between 1.8% to 6.8% as the mass of the Higgs varies from 120 GeV to 160 GeV, for a SM Higgs.

If the Higgs is heavy enough to decay in to a $t\bar{t}$ then the CP property of the Higgs can be determined by using the interference of the s channel resonance amplitude with the SM QCD production process. This gives rise to *mixed* asymmetries in the polarization of the initial laser beam which is backscattered and the charge of the lepton coming from the $t/\bar{t}$ decay. Fig. 12 shows the sensitivity to the CP violating couplings possible for a MSSM Heavy Higgs.

The interesting thing is that these asymmetries can be nonzero even for the SM contribution due to the $V - A$ nature of the tbW coupling. Existence of similar nonzero charge asymmetries which arise from the left handed nature of the W coupling to fermions was pointed out at the conference [46]. They studied reactions $\gamma\gamma \to \mu^+\mu^- + \nu\bar{\nu}$ and $\gamma\gamma \to W^\pm\mu^\mp + \nu(\bar{\nu})$ for $\sqrt{s} > 200$ GeV and showed that the differences in the distributions of positive (μ^+) and negative charged leptons (μ^-), give rise to observable *charge asymmetry* of muons which will have nothing to do with any new physics. In their calculations they take into account all the possible diagrams and *not* just the double resonant ones. They present the first results on the distributions

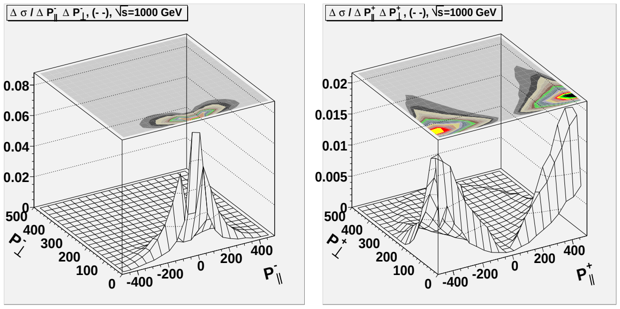


Figure 13. The distributions in the $(p_\parallel, p_\perp)$ plane for $(--)$ helicity of colliding photons: μ^- on the left, μ^+ on the right for $\sqrt{s} = 1000$ GeV and monochromatic beams[46].

of muons $\partial^2\sigma/(\partial p_{\|}\partial p_{\perp})$ (with $p_{\|}$ the component of $\vec{p}_{\mu^\pm}$ parallel to the collision axis (taken to be the z axis) and $p_{\perp} = \sqrt{p_x^2 + p_y^2}$ the transverse momentum). Fig. 13 shows such muon distributions in the $(p_{\|}, p_{\perp})$ plane for a $(--)$ initial photon polarization state with monochromatic photons. We see the difference in the distributions between the negative and positive muons.

4.2. Physics beyond the SM and photons

Many current investigations of Physics beyond the SM involve modification of the geometry of our space time; be it extra dimensions, warped or otherwise, or non-commutative geometry. In all these cases there are interesting effects on the photon interactions and hence PLC offers very many possibilities of testing/studying these ideas. Apart from a summary[42] of the reach of leptonic and photonic collider for Extra Dimensional theories, the conference also had an experimental presentation[47] of constraints on such theories placed by consideration of the LEP data. In one formulation of the non-commutative QED, the $ee\gamma$ vertex receives a kinematic phase which depends on the energy momentum tensor $\theta_{\mu\nu}$ as well as p_μ. Thus Lorentz invariance is violated and there is an unique direction in space. The modification of the $ee\gamma$ vertex, affects the behavior of all the high energy processes involving γ such as $e\gamma, e^+e^-$ and $\gamma\gamma$ scattering. The process which could be studied at LEP was $e^+e^- \to \gamma\gamma$, which can probe the scale of noncommutavity λ_{NC}, as these effects modify the polar angle and azimuthal angle distribution. Of course, since there is a unique direction in space the effects now will have a time dependence due to earth's motion. They studied three quantities: 1) $\frac{d\sigma}{d\cos\theta}$: ϕ integrated and time averaged, 2) $\frac{d\sigma}{d\phi}$: $\cos\theta$ integrated and time averaged and 3) $\sigma(t)$: ϕ integrated and $\cos\theta$ integrated. The effect on the θ distribution is almost independent of η, the polar angle of the unique direction, whereas the ϕ distribution, even after time averaging, has a weak dependence on it. As a result in the end the non-observation of any deviation from the SM expectations of the process $e^+e^- \to \gamma\gamma$, puts a lower limit between 120 GeV to 180 GeV, on λ_{NC} as a function of η. The time dependence gives similar constraints as a function of the azimuthal angle ζ.

4.3. Hadronic contribution to $(g-2)_\mu$

Evaluation of the hadronic correction to the $(g-2)_\mu$ has become a very important subject due to the highly accurate measurements of $(g-2)_\mu$ that have become available recently and the consequent effectiveness of this quantity as a probe for physics beyond the SM. The precision of the experimental measurement will increase further after the full data set has been analyzed. The currently reported deviations of the experimental measurement from the prediction in the SM, are of the same order as the error in the theoretical evaluation of the hadronic contribution to $(g-2)_\mu$ and hence it is the limiting factor in the accuracy of the theoretical prediction of the SM for the $(g-2)_\mu$ The subject was reviewed at the conference[48] and it was pointed out that the evaluation of this hadronic contribution uses the experimental data on hadron production in e^+e^- annihilation for $\sqrt{s} < 2$ GeV. Analyses using just the experimental data alone have an accuracy of $\sim 1.3\%$. The accuracy of theoretical predictions is improved in a data driven analyses which replace data by perturbatively calculated R-ratios (the ratio of hadronic cross-section in units of the $e^+e^- \to \mu^+\mu-$). A large theoretical effort is underway as to how to reduce the theoretical errors in the evaluation of the hadronic contribution to $(g-2)_\mu$, by calculation of EW radiative corrections to the quantities involved. Further, a much more reliable evaluation of the vacuum polarization tensor by using the data, is possible if one uses the Adler function monitored evaluation. It is concluded that the necessary accuracy in the prediction, so as to become truly sensitive to physics beyond the SM, can be achieved only if R ratio is measured to better than 1% up to the J/ψ energies.

4.4. New calculational techniques for high energy processes

Accurate theoretical predictions of different SM processes at the current and future high energy colliders, require a very high level of computational effort in calculating the required scattering amplitudes. Hence numerically stable and efficient methods for calculating these are always welcome. At this meeting a new method to calculate jet like QED processes, whose cross-sections do not drop with increasing energy was discussed[49]. These typically involve exchange of a virtual photon in t channel. The dominant contribution to these cross-sections comes from the small scattering angles. The authors are able to write, for arbitrary helicities of the initial state leptons, the matrix element in a factorized form $\mathcal{M}_{fi} = \frac{s}{q^2} J_1 J_2$ where the impact factors J_1, J_2 are analytical, compact expressions independent of s. Thus essentially the spinor structures for real or virtual leptons have got replaced by transition vertices for real leptons. The approximation made in deriving these expressions omits only terms of the order of ${\theta_i}^2, m_i/E_i\theta_i$ or m_i^2/E_i^2, where $\theta_i = P_T^i/E_i$. Since terms of the order m_i/P_i^T are kept this is a quite different approximation than used in (say) CALCUL. Further, the factors J_1, J_2 are calculated after the compensating terms are canceled analytically. Hence the evaluation of the helicity amplitudes is numerically stable. This method, still to be set for QCD, certainly holds a lot of promise for the automatic evaluation of helicity amplitudes.

5. Concluding remarks

It is somewhat unnatural to give a summary of a summary talk. I want to simply end by saying that this conference has proved that the world of physics of photons and physics that we can do with the photons is a very alive subject. Various developments discussed at this conference have implications for a lot of issues in QCD, QED and even for the physics beyond the SM. In the coming years, analyses of the data from HERA-II, Hermes, Compass and e^+e^- experiments at Frascati, SLAC, Novosibirsk, Bejiing, KEK etc. will provide additional information to answer some of the questions that have been raised at this conference. Structure of the virtual photon, particle and heavy flavour production in $\gamma\gamma$, γp and $\gamma^* p$ reactions need to be studied at higher orders in QCD, as the data have thrown certain challenges to the theorists here. These along with the areas of diffractive, soft as well as forward physics from HERA are the areas to look for further developments. Future of photon physics at future colliders is very bright indeed, as it is clear that such Compton Colliders, if they are realized will not only complement the high energy leptonic colliders to solve conclusively the physics of the spontaneous symmetry breaking, but will also prove an enormously rich QCD laboratory.

6. Acknowledgment

It is a pleasure to thank the organizers and especially Giulia Pancheri for organizing an excellent physics conference and provide very enjoyable atmosphere for stimulating discussions. This work was partially supported by the Department of Science and Technology, India, under project number SP/S2/K-01/2000-II.

REFERENCES

1. For an early review, see for example, M. Drees and R. M. Godbole, J. Phys. **G 21** (1995) 1559. [arXiv:hep-ph/9508221].
2. A. Finch, Experimental summary talk in these proceedings.
3. E.-E. Woehrling, Talk in these proceedings.
4. R. Nisius, Phys. Rep. **332** (2000) 165.
5. M. Glück, E. Reya and A. Vogt, Phys. rev. **D 46** (1992) 1973.
6. M. Glück, E. Reya and I. Schienbein, Phys. Rev. **D 60** (1999) 054019; Erratum, ibid **D 62** (2000) 019902.1
7. M. Krawczyk, Talk in these proceedings.
8. F. Cornet, P. Jankowski, M. Krawczyk and A. Lorca, Phys. Rev. D **68** (2003) 014010 [arXiv:hep-ph/0212160].
9. W. Da Silva, Talk in these proceedings.
10. S. Kretzer, C. Schmidt and W. Tung, in *Proceedings of New Trends in HERA Physics, Ringeberg Castle, Tegernsee, Germany, 2001*, J. Phys. G 28 (2002) 983; M. A. G. Aivazis, J.C. Collins, F.I. Olness and W.K. Tung, Phys. Rev. **D 50** (1994) 3102.
11. A. Gehrmann-De Ridder, H. Spiesberger and P-M. Zerwas, Phys. Lett. **B 469** (1999) 259.

12. M. Klasen, T. Kleinwort and G. Kramer, Eur. Phys. J. directC **1** (1998) 1 [arXiv:hep-ph/9712256].
13. L. Bertora, Talk in these proceedings.
14. M. Drees and R. M. Godbole, Proceedings of *10th Workshop on Photon-photon Collisions (PHOTON '95), Sheffield, England, 8-13 Apr 1995* 123 (1996). arXiv:hep-ph/9505297.
15. U. Karshon, Talk in these proceedings.
16. ZEUS Collaboartion, Phys. Lett. **B 565** (2003) 87, [arXiv:hep-ex/0302025].
17. S. Frixione and P. Nason, JHEP **0203** (2002) 053 [arXiv:hep-ph/0201281]; S. Frixione, P. Nason and G. Ridolfi, Nucl. Phys. B **454** (1995) 3 [arXiv:hep-ph/9506226]; S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, Phys. Lett. B **348** (1995) 633 [arXiv:hep-ph/9412348].
18. B. A. Kniehl, G. Kramer and M. Spira, Z. Phys. C **76** (1997) 689 [arXiv:hep-ph/9610267]. B. A. Kniehl, M. Kramer, G. Kramer and M. Spira, Phys. Lett. B **356** (1995) 539 [arXiv:hep-ph/9505410];
19. M. Cacciari, S. Frixione and P. Nason, JHEP **0103** (2001) 006 [arXiv:hep-ph/0102134]; M. Cacciari and M. Greco, Z. Phys. C **69** (1996) 459 [arXiv:hep-ph/9505419].
20. G. Kramer, Talk in these proceedings; G. Kramer and H. Spiesberger, Eur. Phys. J. C **28** (2003) 495 [arXiv:hep-ph/0302081]; G. Kramer and H. Spiesberger, Eur. Phys. J. C **22** (2001) 289 [arXiv:hep-ph/0109167].
21. J. Turnau, Talk in these proceedings.
22. G. Kramer and B. Potter, Phys. Lett. B **453** (1999) 295 [arXiv:hep-ph/9901314]; Nucl. Phys. Proc. Suppl. **79** (1999) 484.
23. J. Kwiecinski, A.D. Martin and J.J. Outhwaite, Eur. Phys. J. **C 9** (1999) 611.
24. A. Daleo and R. Sassot, arXiv:hep-ph/0309073.
25. P. Aurenche, R. Basu, M. Fontannaz and R.M. Godbole, in preparation.
26. P. Bussey, Talk at this conference.
27. S. Catani and M. H. Seymour, Nucl. Phys. B **485** (1997) 291 [Erratum-ibid. B **510** (1997) 503] [arXiv:hep-ph/9605323]; S. Catani and M. H. Seymour, Phys. Lett. B **378** (1996) 287 [arXiv:hep-ph/9602277].
28. B. Potter, Comput. Phys. Commun. **119** (1999) 4 [arXiv:hep-ph/9806437]; M. Klasen, G. Kramer and B. Potter, Eur. Phys. J. C **1** (1998) 261 [arXiv:hep-ph/9703302].
29. F. Kapusta, Talk in these proceedings
30. B. Andersson *et al.* [Small x collaboration], Eur. Phys. J. **C 25** (2002) 77, [arXiv: hep-ph/0204115].
31. M. Hansson and H. Jung, arXiv: [hep-ph/0309009]
32. P. J. Mulders and R. D. Tangerman, Nucl. Phys. B **461** (1996) 197 [Erratum-ibid. B **484** (1997) 538] [arXiv:hep-ph/9510301].
33. S. Aoki, M. Doui, T. Hatsuda and Y. Kuramashi, Phys. Rev. D **56** (1997) 433. [arXiv:hep-lat/9608115].
34. D. Hasch, Talk presented at this conference.
35. A. Mastroberardino, Talk in these proceedings.
36. D. Lincoln, Talk in these proceedings.
37. M. Kapishin, H1 Collaboration, Talk presented at the X^{th} Blois Workshop on 'Elastic and Diffractive Scattering', June 23-26, 2003, Helsinki, Finland.
38. M. Block, Talk in these proceedings.
39. Y. Srivatsva, Talk presented at this conference.
40. G. Pancheri, Talk in these proceedings.
41. A. de Roeck, Proceedings of the *Photon 2000, Ambelside, U.K., Aug 2000* [arXiv:hep-ph/0101075]
42. A. de Roeck, Talk in these proceedings.
43. M. Kramer and S. Soldner-Rembold, Summary of Photon-2000, Ambleside, England, 26-31 Aug 2000, 457-478.
44. P. Niezurawski, A. F. Zarnecki and M. Krawczyk, arXiv:hep-ph/0307175; arXiv:hep-ph/0211455; arXiv:hep-ph/0211405.
45. R. M. Godbole, S. D. Rindani and R. K. Singh, Phys. Rev. D **67**, 095009 (2003) [arXiv:hep-ph/0211136].
46. I. F. Ginzburg, Talk in the proceedings.
47. T. Kawamoto, Talk in these proceedings.
48. H. Jegerlehner, Talk in these proceedings.
49. V.G. Serbo, Talk in these proceedings.