PHOTON 2005: PHOTONS IN A SPECIAL YEAR

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A brief historical introduction accompanies a review of the theoretical contributions presented at PHOTON2005 together with a short summary of the experimental presentations.

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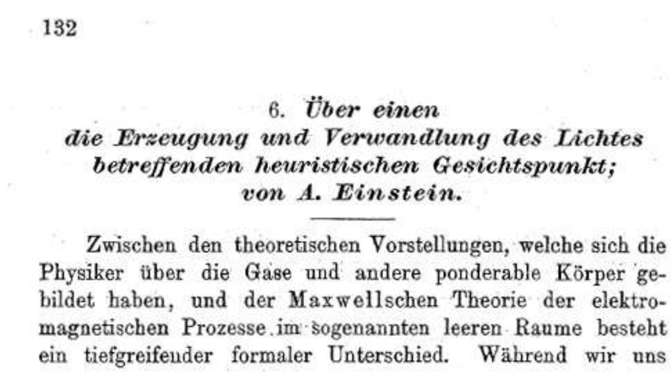
1. Introduction

This year the Conference was held under very special circumstances, marking one hundred years after the three great papers by Albert Einstein, in particular the one on the photoelectric effect [1], which we reproduce in Fig. 1, written during Einstein's *annus mirabilis* [2]. The conference itself was named after the photon's first hundred years and its program has included aspects of the photon beyond the traditional realm of particle physics.



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6. ***Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt; von A. Einstein.***

Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maxwellschen Theorie der elektromagnetischen Prozesse im sogenannten leeren Raume besteht ein tiefgreifender formaler Unterschied. Während wir uns

Fig. 1. The beginning of Einstein's paper on photoelectric effect. (Courtesy of M. Jacobi.)

Photon processes constitute a fundamental tool for investigating the properties of matter. The most important step forward into our exploration of both matter and the vacuum actually took place when electron–positron colliders went into operation with AdA in Frascati. Before starting with the summary of the conference, it may be worth remembering how electron–positron machines, which allowed first observations of $\gamma\gamma$ processes, came into existence. In the autumn of 1959 Pief Panofsky, then SLAC director, held a seminar in Rome and discussed the idea of colliding e^-e^- rings, being developed as a joint Princeton–Stanford project, as proposed by Gerard O'Neill. After Panofsky's seminar, to which Bruno Touschek participated, there ensued a discussion about the other possibility for center of mass collisions, electrons against positrons. This possibility had been discussed, but considered far from feasible. A few months later, in March 1960 in Frascati, Bruno Touschek came up with a concrete proposal for a prototype e^+e^- storage ring which was then called AdA [3], from Anello di Accumulazione, *i.e.* storage ring. As Brodsky reminded us in his talk on the history of $\gamma\gamma$ physics [4], soon after, Calogero, who had been one of Touschek's first students, together with Zemach wrote an early paper on the $e^+e^- \to e^+e^-\pi\pi$ process through photon–photon collisions [6]. In the following years, all the great storage ring machines of the 1960's were constructed and, in early 1970, photon–photon collisions became observable.

It is amazing how much foresight went into the calculations of photon–photon scattering in the late 1960's and early seventies [7–9]. As soon as ADONE and SPEAR started working, in 1970 Brodsky, together with Kinoshita and Terazawa [7] observed that $\gamma\gamma$ collisions could become dominant as the energy increased. More insight and precise recollections can be found in the review of the history of photon–photon collisions presented by Brodsky [4] and in the note about the early history of two photon physics by Ginzburg [5]. Ginzburg recalled that the first experimental observation of $\gamma\gamma$ processes was done by the Novosibirsk physicists [10], soon to be followed by production of μ pairs in Frascati [11]. The interest in such collisions and the initial measurements of these processes led to the first meeting on $\gamma\gamma$ physics held in Paris in 1973 [12]. This first photon–photon colloquium was then followed by meetings at somewhat irregular intervals, which matched the arrival of interesting new data or experiments. Because of the relevance of ep experiments at HERA, in 1995 the series named International Workshop on Photon–Photon Collisions briefly called Photon–Photon, changed its name simply into the Photon series.

The Conference is now moving towards a third phase, which will see the inclusion of project design studies and physics possibilities for a high energy Linear Photon Collider. Telnov reviewed this exciting project [13], where $\gamma\gamma$ and γe interactions will be obtained through Compton scattering of laser light at a few mm distance from the interaction point of the International Linear Collider (ILC), as discussed in a dedicated follow up of this Conference, held in Kazimierz in September 2005.

2. What is a photon?

After 100 years, we still find mysteries and unanswered questions about the photon. Okun [14] has recalled a 1951 phrase by Einstein, "All these fifty years of pondering have not brought me any closer to answering the question: what are light quanta?". Bialynicki-Birula [15] showed the wave character of the photon, while the astrophysical aspects were illustrated by Wrochna [16] through the many different shapes of the spectra of gamma ray bursts (GRB). The origin of GRB is still one of the unknown astrophysical phenomena. Also in particle physics, there still remain many questions. In its hadronic interactions, the photon has had different impersonations, one of the earliest that of a vector meson. Successively, as the energy increased, the photon was seen more as an infinite sum of vector mesons [17]. At the arrival of QCD the photon was described to interact with matter as a $q\bar{q}$ pair, a $q\bar{q}$ pair and one gluon, then many gluons. The hadronic content of the photon is now the main obstacle in reducing the theoretical precision with which the muon anomalous magnetic moment $(g-2)_\mu$ is determined [18, 19]. The present status of theory and measurement determinations of $(g-2)_\mu$ was reviewed by de Rafael. The history of this measurement shows that within the last 30 years, the precision with which we know $g-2$ of the muon has increased 500 times, in 1975 it was 27 ppm, it is now 0.5 ppm [20]. The theoretical precision has also increased, but is presently limited by two difficulties, respectively, related to the hadronic contribution from photon vacuum polarization and light-by-light diagrams. The hadronic contribution to vacuum polarization can be calculated making use of dispersion relations and saturating them with the measured cross-section for $e^+e^- \to$ hadrons [21]. The theoretical error coming from this contribution is therefore dependent on the experimental one, namely on the precision with which the hadronic cross-section can be measured. Progress in this direction has recently been done both in Frascati [22] and in Novosibirsk [23]. Interesting, in this context, is the fact that a different way to determine this contribution was proposed to be the study of τ-decays [19], which can be related to the direct e^+e^- hadronic cross-section through an isospin rotation. Barring, of course, some systematic errors in the measurements, the discrepancy between the direct measurement and τ-decays may perhaps be another indication that we do not completely understand isospin breaking at very low energy [24].

However, the hadronic contribution to the vacuum polarization is not the only remaining source of error. Another problem is represented by light-by-light scattering. This diagram, shown in Fig. 2, contributes $80 \pm 40 \times 10^{-11}$ [25, 26] or $136 \pm 25 \times 10^{-11}$ [27] to the total SM contribution whose error is presently around 100×10^{-11}. The uncertainty is due to our poor knowledge of the hadronic contribution to $\gamma\gamma \to \gamma\gamma$, mostly through η and π^0 exchange. Unfortunately, unlike the case of vacuum polarization, there is no dispersion relation which can be used here.

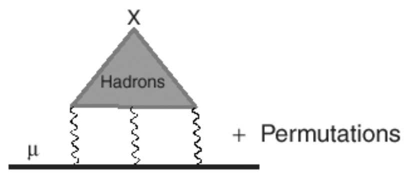

Fig. 2. The schematic light-by-light contribution, from de Rafael's talk.

Discrepancies between the Standard Model (SM) expectations for $(g-2)_\mu$ and the measurement could impose constraints on new physics or reveal its existence. However, while we certainly have more and more insight into $g-2$ of the muon, it is not yet possible to decide whether there is or not disagreement with the SM at a significant level. Djouadi showed examples of new physics, and how the limits imposed by the present $(g-2)_\mu$ measurement enter into determination of available parameters space for many models [28].

3. Structure functions

Parametrization of parton distributions in the photon were reviewed from their early start [29] by Buras [30]. There are at present more than 25 different parametrizations of the photon structure functions [31], with three most recent at Next-to-Leading-Order (NLO) [32–34], discussed in this Conference. Cornet [35] summarized the present situation. The two main differences between the existing parametrizations rely on different schemes for the introduction of heavy quark contributions and use of different inputs at low Q^2. For the Q_0^2 dependence in $F_j^\gamma(x, Q_0^2)$, one has the following cases:

- CJK [32]: 0.765 GeV^2
- SAL [33]: 2.0 GeV^2
- AFG [34]: 0.5 GeV^2
- GRV [36]: 0.25 GeV^2
- GRS [37]: 0.3 GeV^2

In the CJK parametrization, the input for the parton densities of the photon is obtained by assuming Vector Meson Dominance (VMD), namely that in the interaction between the electromagnetic field and hadronic matter, the photon behaves like the vector mesons ρ, ω and ϕ,

$$f^{\gamma}(x, Q_0^2) = \sum_V \frac{4\pi\alpha}{\hat{f}_V^2} f^V(x, Q_0^2), \tag{1}$$

where $\hat{f}_V^2$ is obtained from the leptonic decay width of the neutral vector mesons. Phenomenologically, the parametrizations are obtained by substituting the $\sum_V$ with a free parameter κ and using only the ρ-width. The form of the valence and gluon densities are taken to have the same functional dependence from x as those for the pion, namely

$$xv^{\rho}(x, Q_0^2) \ = \ N_v x^{\alpha}(1-x)^{\beta}\,, \tag{2}$$

$$xG^{\rho}(x, Q_0^2) \ = \ \tilde{N}_G xv^{\rho}(x, Q_0^2) = N_G x^{\alpha}(1-x)^{\beta}\,, \tag{3}$$

where $v^{\rho}(x, Q_0^2) = \frac{1}{4}(u^{\rho^+} + \bar{u}^{\rho^-} + d^{\rho^-} + \bar{d}^{\rho^+})(x, Q_0^2)$, N_v, N_G, α and β are left as free parameters, and the sea quark distribution is assumed to vanish at this scale.

Reviewing the new photon parametrizations in these Proceedings, Cornet discusses the AFG parametrization, which also uses VMD for the non-perturbative input, with the ρ-meson distributions like those of the pion, and only one free parameter, constituted by the overall normalization.

The third new entry for the photon parton densities, SAL, was presented by Slominski. This NLO parametrization is based on a fit to di-jet production in γp scattering and to both electron–positron and electroproduction data, namely $\gamma^*\gamma$ and $\gamma^* p$ cross-sections, respectively. At small x, the input comes from the proton, and the fit uses free parameters both for the point-like and hadronic part. The input from the proton is obtained using Gribov's factorization assumption for the total cross-sections. The comparison with other NLO parametrizations from DIS indicates for the gluon a more singular behaviour at low x and low Q^2 than all the other parametrizations, namely GRV, GRS, and CJK. At high Q^2, while there is still a factor 2 difference between SAL and GRS, the difference among the various parametrizations is much reduced.

Photon–parton splitting functions at NNLO were presented by Vogt [38]. Present predictions for many important processes are at Next-to-Leading-Order, but this is not accurate enough for a variety of important processes like Higgs studies at LHC or new physics searches. At LHC, the difference in the magnitude of the cross-section for the production of a 120 GeV Higgs boson, between LO and NLO is more than 5%. In the current program presented by Vogt, photon–parton splitting functions are calculated to

NNLO in perturbative QCD, as a spin-off of the three-loop computation of *ep* deep-inelastic scattering. The new densities show agreement with previous predictions and show that there is good convergence of the perturbative series at large-x.

From the experimental side, Kienzle-Focacci [39] presented L3 results on the photon structure function F_2^γ as a function of x and Q^2. The problem of transforming from the visible energy to the actual momentum-fraction carried by the photons has not been solved yet. One, still worrisome, consideration is that the difference between the MonteCarlo's is bigger than the differences among data from different LEP experiments [40]. For what concerns L3, for the range of Q^2 examined, the best agreement between data and PDF's was found using GRV-HO. In Fig. 3 data from all three experiments are compared with GRV-HO and CJK-HO. Differences among the experiments can be traced to the use of different analysis methods and different MonteCarlo's.

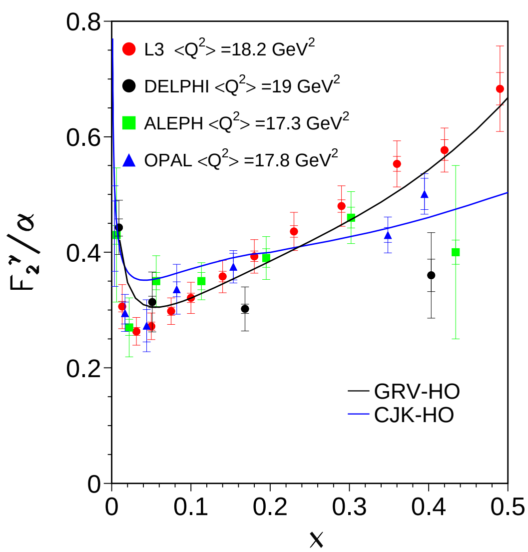

Fig. 3. F_2^γ/α as a function of x, from Kienzle's talk.

Stoesslein [41] reported on the first round of measurements and QCD analyses of Charged (CC) and Neutral Currents (NC) in DIS at HERAI, which is essentially concluded. Together with previous measurements on inclusive and di-jet production, CC and NC measurements actually can strongly constrain the PDF's [42]. Kurek summarized the present situation of the very active study of the spin structure of the nucleon [43], concluding that there is some evidence of non zero angular momentum.

A new proposal to measure the PDF's at LHC using W and Z production was presented by Tricoli [44]. Since at hadron colliders every cross-section is a convolution of a partonic cross-section and the parton density functions, any study of new physics signals requires both a knowledge of the PDF's and of the background cross-sections at LHC. Tricoli proposes to improve our knowledge of the parton densities by measuring direct single γ production (scattering qg or $q\bar{q}$ at LO), and $W^{\pm}$ or Z production, both of which, to leading order, are predominantly produced by quark–antiquark scattering. However, at the EW scale at LHC the partons x-value is very small, and it is the sea and the gluon distributions which really drive these processes. These uncertainties dominate over everything else, and this basically means that the gluon distribution (which by itself drives the sea) needs to be constrained. One interesting possibility is to constrain the gluon distribution through the process $bg \to Z + b -$ jet, which is sensitive to the b-quark content of the proton. Notice that $b\bar{b} \to Z$ constitutes 5% of the entire Z-production at LHC. Thus in order to know σ_Z with a 1% precision one requires a 20% precision of the b-parton densities. Such a precision is not available so far, but it could be obtained at HERAII.

4. DVCS and prompt photons

Deeply Virtual Compton Scattering (DVCS) processes, illustrated by the diagram of Fig. 4, give information not only on structure functions and integrated cross-section for $\gamma^\star p \to \gamma p$, but they can be considered the simplest and cleanest hard exclusive reaction which can be used to access Generalized Parton Distributions (GPD's). Kurek [43] reviewed results from HERA and from JLAB, showing the cross-section for the process $\gamma^\star p \to \gamma p$ measured by H1 and ZEUS in comparison with QCD calculations for Q^2 in the range $Q^2 \le 85$ GeV^2, as in Fig. 5.

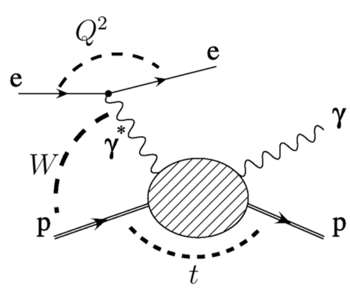

Fig. 4. Deeply Virtual Compton Scattering kinematics.

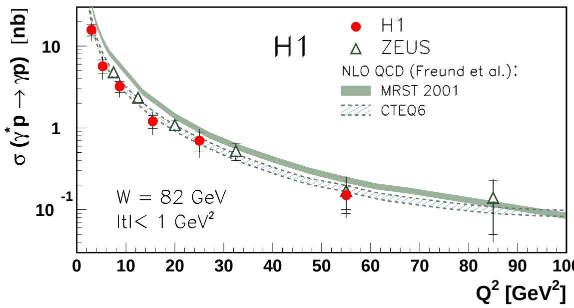

Fig. 5. H1 and ZEUS cross-section for $\gamma^\star p \to \gamma p$.

Prompt photon measurements at various experiments lead the way for their relevance as a trigger for direct coupling to partons: prompt photons are sensitive to the gluon content of hadrons involved in the initial reactions, since prompt photons are usually produced by gluon initiated processes. Initial state gluon resummation plays an important role, and theoretical advances in the k_{t}-factorization scheme are producing more and more precise tools. Results in prompt photon production were summarized by Gayler [45] and individually reported by Janssen [46] for prompt photon production at HERA in DIS, by Reygers [47] for nucleus–nucleus collisions at RHIC, by Söldner–Rembold for $p\bar{p}$ at the Tevatron.

The first measurements of the slope of the differential cross-section for $\gamma^\star p \to \gamma p$ as measured by H1 is shown in Fig. 6.

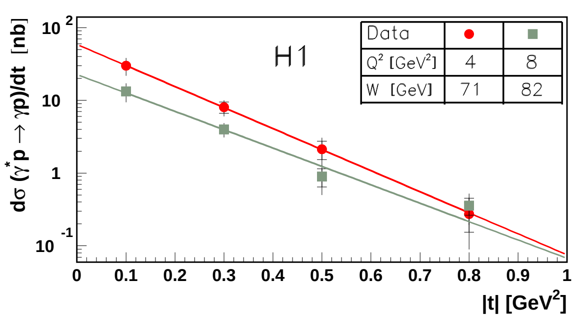

Fig. 6.

Scaling Au–Au results to pp, a comparison of prompt photon production *versus* π^0 production at RHIC for $p_{\mathrm{t}} < 6$ GeV indicates π^0 suppression at large values of participants number, as shown in Fig. 7. Since the ratio $\gamma_{\mathrm{direct}}/\pi^0$ as a function of p_{t}, as measured by PHENIX at RHIC, is in good agreement with NLO QCD calculations [47, 48] the current interpretation is that the medium is more transparent to photons than pions and that the suppression is not an initial state gluon saturation effect.

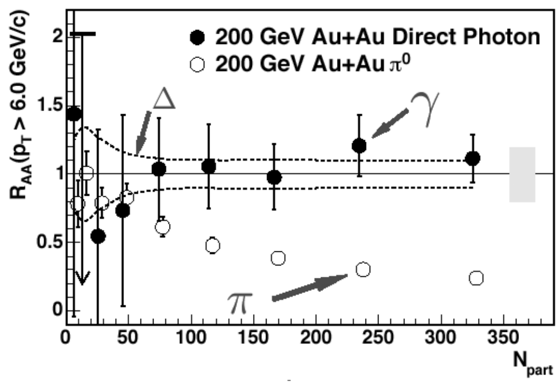

Fig. 7.

Söldner-Rembold [49] showed prompt photon distributions by D0 in good agreement with NLO calculations with JETPHOX [50], and latest CDF results on $\gamma\gamma$ exclusive production [51], a crucial background to Higgs production.

5. Jets and inclusive hadronic processes

A theoretical overview of jets and inclusive hadronic processes in photon induced collisions was provided by Chýla [52] and became the starting point of an extensive discussion on the role and number of different scales in QCD calculations. A variety of related hard processes both in hadron–hadron collisions as well as in photon initiated processes, with one or two real or quasi real photons in the initial state, was examined, namely:

- Jet production in γp and $\gamma^\star p$ collisions
- Inclusive particle production in $\gamma^\star p$ collisions
- Jets and inclusive particle production in $\gamma\gamma$
- Prompt photons and jet production
- Heavy quark production

It was pointed out that the theoretical uncertainties in various QCD calculations are the biggest problem in extracting physics from experimental data, and noticed that sometimes the uncertainties may depend on a confusion between LO and NLO definitions of QED effects and QCD ones. A clear example is the calculation of the ratio R from e^+e^- collisions, namely

$$R_{e^+e^-} \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \left(3\sum e_i^2\right)(1 + r(Q))\,, \tag{4}$$

where, having factorized the charge factor, $r(Q)$ is the genuine QCD term, where LO and NLO terms can now be individually examined. Unfortunately, in some photon induced hard processes this convention is not observed, thus leading to some confusion.

Theoretical "uncertainty" of QCD calculations conventionally comprises also several other components, such as :

- dependence on Parton Density (PDF) and Fragmentation Functions (FF);
- hadronization effects;
- scale and scheme effects;

the first two being more clearly defined than the third one. The problem of scales arises because of ambiguities in the treatment of singularities, and in the various factorization schemes which separate the short distance and long distance part of various scattering processes. What one sees is that

- at short distances the dominant effect is due to scale μ which depends on the renormalization scheme;
- at long distance there are scales which depend on the factorization scheme being used.

The freedom in the choice of renormalization and factorization scheme is not really exploited, often all the scales are reduced to just one. This is a natural choice, whose physical interpretation may be intuitive, but there is really no valid reason for such assumption and this practice introduces a theoretical error which is not easy to gauge.

Thus, the conventional way of estimating theoretical uncertainties due to the choice of scale is to identify all scales with a single "natural" one, say Q, and then plot the results of the given calculation with a band where the scale μ ranges between some $Q/2$ and $2Q$, where choosing the number 2 is rather arbitrary. This choice does not make much sense and is even misleading, as it hides most of the details of the factorization.

Another problem plaguing QCD calculations concerns MonteCarlo (MC) event generators on the one side and NLO parton level calculations. Some of the features of full NLO effects are mimicked within the MC generator, which use only LO partonic cross-sections, by means of parton showers and non collinear kinematics of initial state partons. To identify then genuine NLO effect is not so simple, especially because such LO MC also use different inputs extracted from global analysis of data. In photon initiated processes, there is the possibility to use virtual photon processes to include higher order direct photon term in the resolved photon method. However, ambiguities do not decrease at higher order. A discussion session during the Conference, following Chýla's talk, was led by Brodsky, who advocated the prescription to use observables to define QCD couplings. Notice that the transverse momentum dependence of partons in photons or protons also introduces a scale, through resummation of soft gluons. In the transverse momentum variable, one has at least two scales [53], namely

- a hard scale, relative to hard or semi-hard for parton–parton scattering, which is of the order of the final state parton-jet, say $p_{\rm t}^{\rm jet}$, which can be as low as 1–2 GeV (around the start of the asymptotic freedom region);

- a soft scale, for soft gluon emission from hard partons, where the soft gluon momenta can be at most 20% of the hard ($p_{\rm t}^{\rm jet}$) scale, and which depends on the energy and transverse momentum of the emitting parton, namely from x-parton and $p_{\rm t}^{\rm jet}$.

As final remark, Chýla noticed that in some apparently very clean case, like $\gamma\gamma$ collisions, perturbative QCD still has problems explaining L3 data on inclusive charged particle production [54].

Other uncertainties were addressed by Motyka [55], who illustrated an approach to go beyond the collinear approximation for the PDF. He noticed that $k_{\rm t}$ factorization models use unintegrated parton distributions. This has two advantages over the usual collinear approximation, phenomenologically because more parameters are available to fit a more complete set of data, but mostly because it is the theoretically correct thing to do.

Measurement of jets and inclusive reactions in ep and $e\gamma$ at HERA were reviewed by Schörner-Sadenius [56]. One of the most interesting results concerns the determination of $\alpha_{\rm s}$ at high Q^2 by H1 and ZEUS. The agreement between the world average value, $\alpha_{\rm s}(M_Z) = 0.1187 \pm 0.0020$ and the H1 (inclusive jets and 2/3 jets ratio) and ZEUS (inclusive jets) is quite nice. For $\gamma\gamma$ collisions, jets and di-jet production and the connection with hadron–hadron collision were discussed by Wengler [57].

6. Heavy flavour production

This session was mostly contributed by experimental talks, which spanned results on beauty production at LEP and HERA, charm production at HERA, heavy flavours by CDF. The session was introduced through a general review by Meyer [58], who extensively reviewed heavy flavour production in $ee, e\gamma, \gamma\gamma, ep, \gamma p, p\bar{p}$ processes, in addition to a discussion of the new heavy particle $X(3872)$ found by Belle and confirmed by BaBar, CDF and D0, with quantum numbers $J^{\rm PC} = 1^{++}$, whose mass determination by various experiments is shown in Fig. 8.

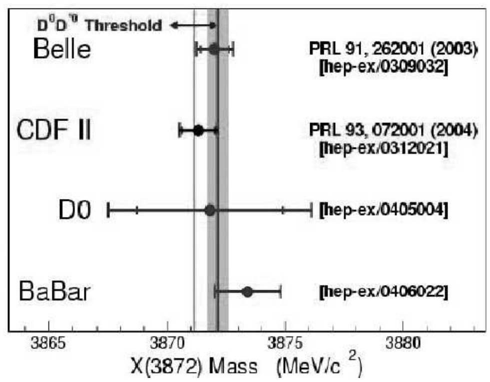

Fig. 8.

The good and bad news, according to Echenard [59], who reviewed two photon reactions at LEP, are that inclusive beauty production is in good shape at pp, in reasonable shape in γp, but the situation is still quite problematic in $\gamma\gamma$, as one can see from the compilation of all charm and beauty production cross-sections at LEP in Fig. 9.

Preliminary results from run II at the Tevatron were shown by Campanelli [60], for charm and b-production, including B-mesons from J/Ψ, high $p_{\rm t}$ b-jets, $b\bar{b}$ cross-sections and inclusive $b\gamma$ processes. We show in Fig. 10 the ratio between $b+\gamma$ and $c+\gamma$ cross-section, which shows good agreement with LO MonteCarlo simulations.

Beauty production at HERA was reviewed by Grab [61], representing both H1 and ZEUS collaborations, and also discussed by Thompson [62]. There are many QCD calculations for beauty production, and various MonteCarlo's, and the comparison between data and NLO QCD calculations shown in Fig. 11 indicates that while at large Q^2 the agreement between data and theory is reasonable, there are still a number of discrepancies at low Q^2.

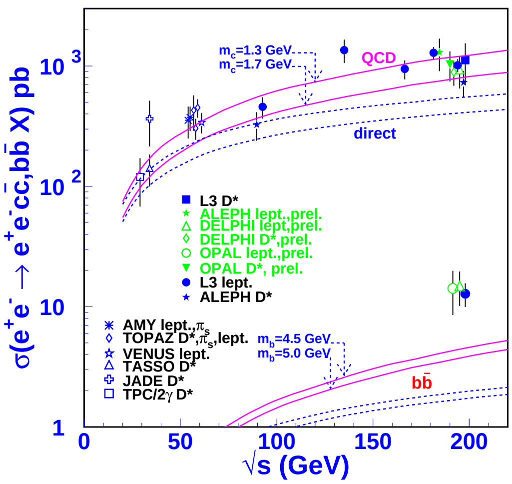

Fig. 9.

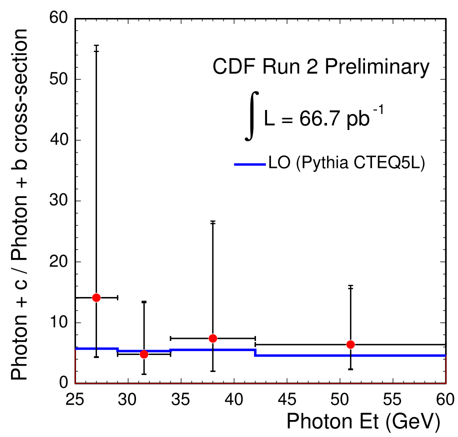

Fig. 10. Beauty and charm production as a function of the photon transverse energy E_{t} in GeV.

Charm production at HERA, as reviewed by Zambrana [63], showed that the general description by QCD is good, but fails to agree with experimental data in the details, like in the case of $D^{\star}$ photoproduction, where higher order contributions need a careful evaluation.

In the mini review of heavy quark production from k_{T}-factorization presented by Motyka, it was pointed out that this approach had been phenomenologically motivated by excess of $b\bar{b}$ production in both γp and $\gamma\gamma$ collisions and that in the k_{t} factorization approach one could obtain a significant enhancement of $p\bar{p} \to b\bar{b}$ cross-section. There are at present three main models, which were reviewed, CCFM gluon, KMR gluon and the Saturation model (discussed next).

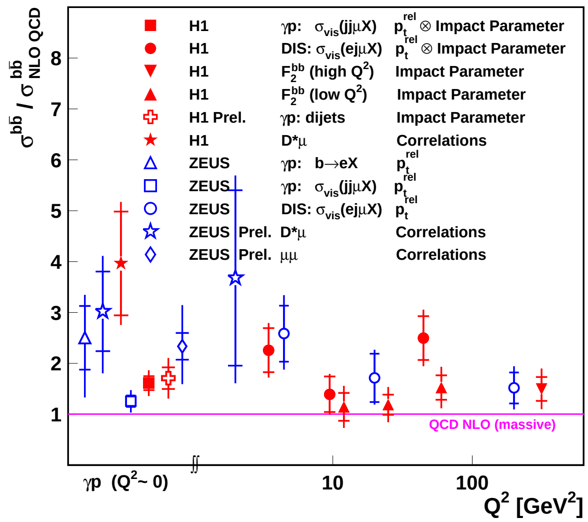

Fig. 11.

7. Total cross-sections and diffraction

The saturation model discussed by Motyka was also applied to total and diffractive cross-section calculations. In the saturation model the cross-section for $\gamma^\star p$ is described through the convolution of a basic cross-section of an extended object at impact parameter r and a momentum component in the variable z, namely

$$\sigma_i^{\gamma^* p}(Q^2, W^2) = \int_0^1 dz \int d^2\vec{r}|\Psi(z,\vec{r})|^2 \hat{\sigma}(x, r^2) \tag{5}$$

with

$$\hat{\sigma}(x, r^2) = \sigma_0 \left[1 - \exp\left(-\frac{r^2}{4R_0(x)^2}\right)\right]. \tag{6}$$

In the color transparency limit, for small dipoles with $r \ll R_0$ the dipole cross-section is simply proportional to r^2, whereas it goes to a constant for large dipoles. The transition between the two regimes is governed by the saturation radius $R_0(x)$ which has an x-dependence. It was pointed out that this model can easily be generalized to $\gamma^\star\gamma^\star$ scattering, with the introduction of two scattering dipoles of radii r_1 and r_2, respectively.

Diffractive interactions in ep collisions in H1 and ZEUS were presented by Melzer-Pellmann [64], who noticed that diffraction contributes substantially to the total cross-section. Data were compared with two models, the Color

Dipole Model and the soft color interaction model by Brodsky, Enberg, Hoyer and Ingelman [65] where rescattering plays an important role.

Real photon processes were also discussed by Motyka, and a good description of both total γp and $\gamma\gamma$ cross-sections were presented. The input physical processes were

- direct QED term;
- dipole contribution from parton–parton scattering for the process under study;
- Reggeon term of non-perturbative nature.

The energy dependence of the saturation scale was discussed by Schildknecht [66] for whom the photon fluctuates into a time-like vector state of on-shell quarks which then interact with other particles via two gluon exchanges. The cross-section then depends on the effective gluon transverse momentum, and this introduces a transverse momentum dependence which then brings into play a novel scale. This novel scale sets the energy dependence of the total cross-section for processes like $\gamma^\star p$, which could be studied through dedicated analyses to separate the longitudinal and transverse contribution in deep inelastic scattering.

In the resolved photon and multicomponent model of total photon cross-sections presented by Szczurek [67], the cross-sections were described through

- a direct QED contribution;
- a Vector Meson Dominance Model contribution;
- a $q\bar{q}$ dipole type contribution.

With respect to a previous model, here both VMD and dipole have been phenomenologically modified so as to reduce VMD at high Q^2 as well as the dipole contribution at large sizes. Performing a simultaneous fit to γp and $\gamma\gamma$ total cross-section one can obtain an optimal set of model parameters and thus make predictions for $\gamma^\star\gamma$ experimental data.

Other presentations in the total cross-section section included:

- a mini-review by Kowalski on small-x physics and diffraction;
- a discussion of non forward BFKLO at NLO by Fadin [69];
- a proposal by Ginzburg [70] to measure the Pomeron phase and discover the Odderon at HERA and LHC;
- a model for diffractive ρ production in $\gamma^\star\gamma^\star$ collisions by Wallon [71].

Kowalski described an implementation of the dipole saturation model, the impact parameter dipole saturation model, motivated also by the observation that diffraction indicates multigluon interactions at HERA. In a Glauber–Mueller, Levin, Capella, Kaidalov type-model, among the many, the scattering cross-section for one pair of particles is considered to occur among partons at a given impact parameter space value b and then integrated, *i.e.*

$$\frac{d\sigma_{q\bar{q}}(x,r)}{d^2b} = 2\left[1 - \exp\left\{-\frac{\pi^2}{6}r^2\alpha_{\mathrm{s}}(\mu^2)T(b)\right\}\right], \tag{7}$$

where $T(b)$ describes the proton shape in the impact parameter variable and the diffractive cross-section

$$\frac{d\sigma^{\mathrm{diff}}}{dt} \propto e^{Bt} \tag{8}$$

is related to the proton shape through

$$T(b) \propto e^{-b^2/2B}. \tag{9}$$

This model was then applied to exclusive double diffractive reactions at LHC, where the survival probability is defined as

$$S = \frac{\int M^2(s,b)e^{-\Omega(s,b)}d^2b}{\int M^2(s,b)d^2b}, \tag{10}$$

and the proton soft elastic opacity $\Omega(s,b)$ carries the effects of soft proton absorption and modulates the hard t-distribution. It is argued that t-measurements at LHC will allow to disentangle the effects of soft absorption from the hard behaviour.

Double diffractive ρ production in $\gamma^\star\gamma^\star$ collisions was proposed by Wallon [71] as a gold-plated experiment to test the dipole model in the best possible way. The measurement at ILC could give information on the underlying dynamics, because predictions from BFKL are 2–3 times larger than from DGLAP if proper cuts are imposed. Notice that the cross-section for

$$e^+e^- \to \rho\rho e^+e^- \tag{11}$$

requires tagging in order to impose the necessary cuts and select the interesting kinematics.

A study of double-tagged $\gamma^\star\gamma^\star$ events at LEP2 was presented by Pozdniakov [68] from DELPHI collaboration. Comparison of the rapidity distribution with BFKL predictions at leading and next-to-leading order is shown

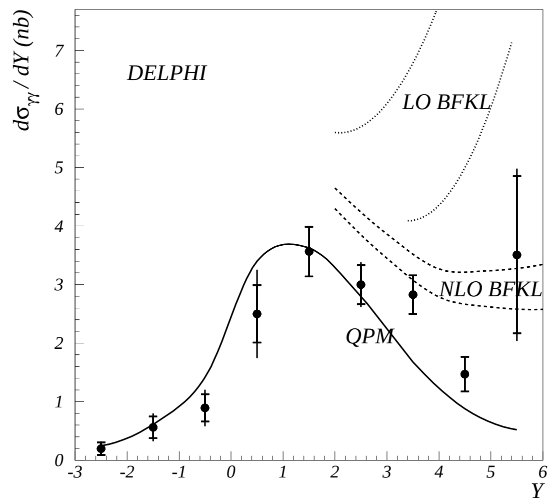

Fig. 12.

in Fig. 12, for a scale parameter chosen in a band $\{Q^2, 4Q^2\}$. The leading order calculations clearly disagree with the data, which are better described by the NLO.

The non-forward treatment of the BFKL equation presented by Fadin describes the scattering through

- scattering of two reggeized gluons;
- the Green's function for this scattering with the BFKL kernel, G;
- impact factor for the scattering particles, $\Phi_{JJ'}$

symbolically written as

$$\Phi_{AA'} \otimes G \otimes \phi_{BB'} \, . \tag{12}$$

This treatment, which is done for $t \neq 0$, represents an important improvement over the usual BFKL treatment at $t = 0$ because it will allow to construct from QCD non only total cross-sections but also differential elastic cross-sections, and also because the results are probably less dependent on the details of the infrared region. The complexity of the calculation is related to the presence of non-planar diagrams in the two gluon exchange contributions.

To further our understanding of the mechanisms which enter into the total cross-section, Ginzburg [70] proposed to study the possibility to measure the Pomeron phase and discover the Odderon in the processes, at HERA and LHC, respectively,

$$e + p \rightarrow e + p + \pi + \pi \,, \tag{13}$$
$$A + A \rightarrow A + A + \pi\pi \,. \tag{14}$$

The odderon is the $C = P = -1$ partner of the Pomeron, for which $C = P = +1$. It is a very elusive phenomenological object because there are *a priori* no reasons [72] why it should not contribute to total cross-section, and however it has not been observed so far neither in pp nor in $p\bar{p}$. There are some results from H1 at HERA, which however, seem to be below old expectations, but do not contradict new predictions by Donnachie *et al.* [73]. The asymmetry measurements proposed by Ginzburg could contribute to the resolution of this puzzle.

A different type of asymmetry measurements was advocated by Lukaszuk, who has obtained a parity violating analogue of the GDH sum rule from superconvergence relations. Saturation of the sum rule through polarized photon induced processes on proton targets can give information on the validity of different models of low energy dynamics. In the process $\gamma p \rightarrow p\pi$, it was argued that the measurement of the π^0 and π^+ asymmetries at threshold could give interesting contributions. Actual simulations seemed to confirm the feasibility of such experiments at TJLab [74].

8. Resonances and exclusive processes

In this section a general introduction, for the low energy region, was given by Pennington [75]. The special role played by $\gamma\gamma$ processes as ideal spectroscopy tool for all $C = +$ structures was emphasized, and a discussion of how one can disentangle the various contributions to scalar mesons was presented. When one deals with the light scalar mesons, the puzzle concerning their nature as a $q\bar{q}$, $qq\bar{q}\bar{q}$, gg state or $K\bar{K}$ molecule is still to be solved. Possibly, experiments at low energy machines may help find the answer [76].

Spectroscopy with two photons can also be done using $\gamma\gamma$ as final states, as in the case of the two light pseudoscalar mesons η and η', where the decay widths of $(\eta, \eta') \rightarrow \gamma\gamma$ contain important information on low energy QCD dynamics. Escribano [77] presented a phenomenological analysis on these decay processes as well as of the decays $V \rightarrow P\gamma$ and $P \rightarrow V\gamma$ in order to test the large $N_{\rm c}$ Chiral Perturbation Theory predictions for mixing angles and decay constants. Using a two mixing angle scheme for the $\eta - \eta'$ system and assuming Vector Meson Dominance for the light vector meson decays, the obtained theoretical expressions were compared with experimental data to fit the values of the mixing parameters. The presented results did not exclude a possible contradiction between the large $N_{\rm c}$ predictions and the values obtained from the fit, but further studies with higher statistics were recommended by Escribano before any conclusion could be reached.

An extension of $\gamma\gamma$ as spectroscopic probes to search for isotensor resonances in the process $\gamma\gamma^\star \to \rho\rho$ channel, was proposed by Anikin [78] who also advocated the QCD analysis of the process hadron hadron $\to \gamma\gamma^\star$ in the forward direction.

On the experimental side there were presentations on exclusive final states in $\gamma\gamma$ collisions, namely exclusive $\rho\rho$ production at LEP [79], where data compared favourably with the QCD model by Anikin *et al.* [78], and $K^0_{\rm S}\bar{K}^0_s$ production, presented by Belle [80], together with the observation of the new charmonium state $X(3930)$ in $D\bar{D}$ channel, a probable candidate for a χ'_{2c} recurrence, with a clear invariant mass spectrum shown in Fig. 13.

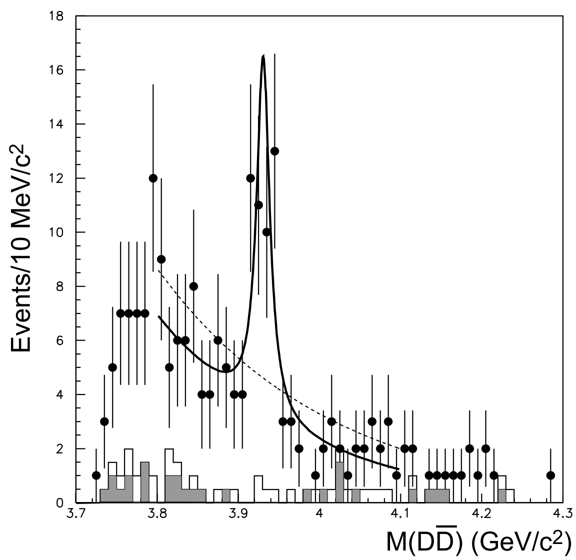

Fig. 13. Invariant mass spectrum of $X(3930)$.

This session was completed by Brodsky [81] and his description of how one can get new insight into QCD processes from photon induced reactions.

9. Related topics — QED and Quantum Optics

In this session, Serbo [82] presented the production of μ pairs in relativistic heavy ions collisions.

The importance of photons in medical studies was the subject of a special contribution in the final session of the Conference. This was provided by

Braccini [83]. In diagnostics, computer tomography and positron emission allow to explore the inner parts of the body and to determine with high precision location of body pathological areas. In the developed countries, according to Braccini, every 10 million inhabitants about 20000 oncological patients are irradiated every year with high energy photons produced by electron linacs installed in hospital based radiotherapy centers.

Finally, an original contribution to the understanding of soft photon physics came from Leo Stodolski [84]. The study of the number of photons radiated by a charge following some trajectory was discussed. This number is notoriously infinite because of the infrared catastrophe [85]. However, the surprising realization reached by Stodolsky is that there is a general class of situations where the infrared catastrophe is averted and he showed this by means of a novel integral invariant over curves. As a conclusion of this talk on the photon, I show one of the intriguing curves he displayed.

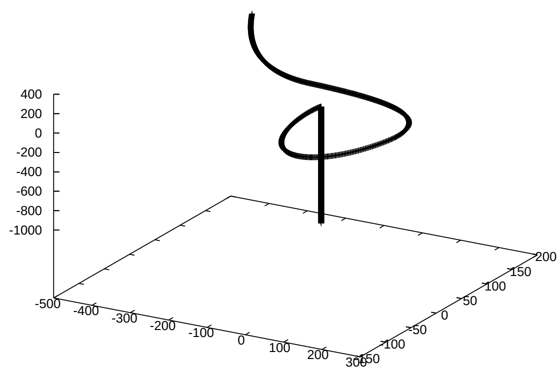

Fig. 14. A curve for $n = 38.8$ from Leo Stodolski's contribution.

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