Experimental Summary

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I summarise the content of the experimental talks of the conference.

1 Introduction

In this account, I am attempting to summarise a substantial collection of very diverse experimental talks, all of which carry some kind of association with the physics of photons. This was of course a particle physics conference, and so we are dealing with photons that in some sense behave as elementary particles. However this does not necessarily mean that the photons treated in a given context were always of high energy. It is part of the richness of the subject that the photons in the experiments presented here could vary in energy by orders of magnitude, and yet still maintain the connection with elementary particle physics. I intend to depart from the presentational order of the talks and start with those that involved photons of lowest energy, finishing with those of the highest. Much material has had to be omitted, but it can be found in the respective single-topic talks. These should in any case be consulted for more details and for references to the published work. The following sections, therefore, are very much an "invitation to further reading".

2 Axions and their relatives

Axions and their relatives constitute a wide class of hypothetical neutral particles that couple to photons. They have been proposed in different contexts, and in his talk Joerg Jaeckel presented the motivations for looking for these various objects. There is a theoretical problem with explaining why CP is conserved in QCD, the so-called "strong CP problem", since the theory's vacuum structure permits a CP violation. The axion is a proposed particle whose presence prevents this from happening. It must be very light and very weakly interacting, but it should couple to two photons. It is an example of a more generic class of "WISPs" –

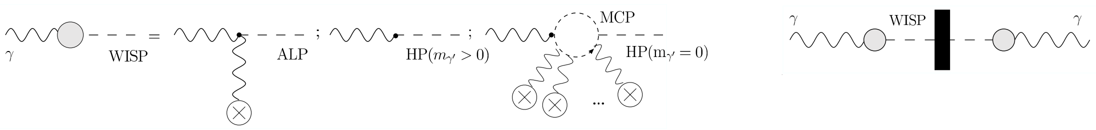

Figure 1: Schematic production and detection of WISPs (Lindner).

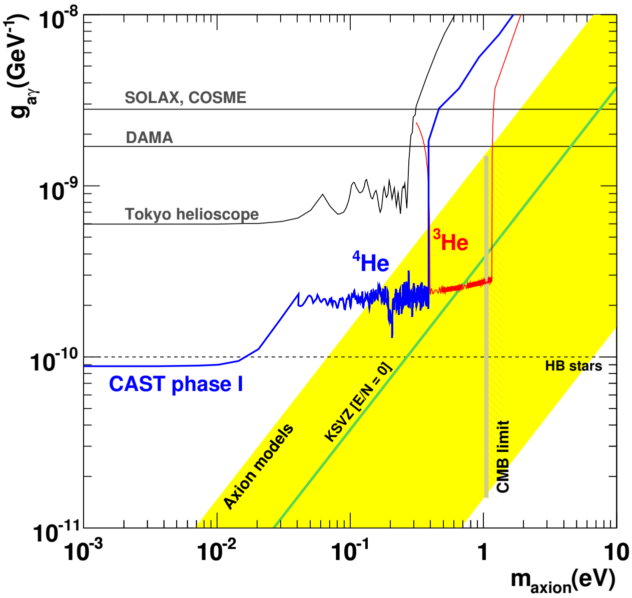

Figure 2: Present limits from ALP experiments (Cantatore).

Weakly Interacting Sub-eV Particles. In the case of axion searches, one approach is to use a strong magnetic field to supply a virtual photon, with which photons from a strong laser beam interact, hopefully generating some axions. A barrier then absorbs the remaining laser beam and everything else except the axions, which proceed through the barrier into a further region of magnetic field, where they regenerate a photon that may be observed. Thus "light shines through a wall" (Fig. 1).

Giovanni Cantatore provided a comprehensive review of a diversity of attempts to discover WISPs: in general the search is for ALPs, "Axion-Like Particles". The lowest energy photons featuring in this conference were those of the ADMX collaboration, in which cosmological relic axions are invited to interact with microwaves in a cavity. Within a relatively narrow band of axion masses in the micro-eV region, this experiment is currently unique in actually reaching the sensitivity of the theories; however no signal was found. The CERN axion search CAST points a powerful magnet at the sun to detect ALPS in the meV energy range, as does the Tokyo Helioscope (Fig. 2). PVLAS approaches the problem by using an intense laser beam to look for an effective vacuum dichroism in a magnetic field. Its former claimed result has now been disconfirmed. So no signal has been found yet, but the searches go on since the sensitivity in most cases still needs to be improved substantially. Axel Lindner described a far-ranging collection of further proposed theoretical end experimental ideas for improved ALP and WISP searches of various kinds. There are hypothetical "Mini-Charged Particles" and even a class of "Hidden Photons" that do not need a magnetic field but will just appear in a vacuum tube! Clearly this area is proving an immensely fertile ground for theoretical imagination as well as experimental ingenuity.

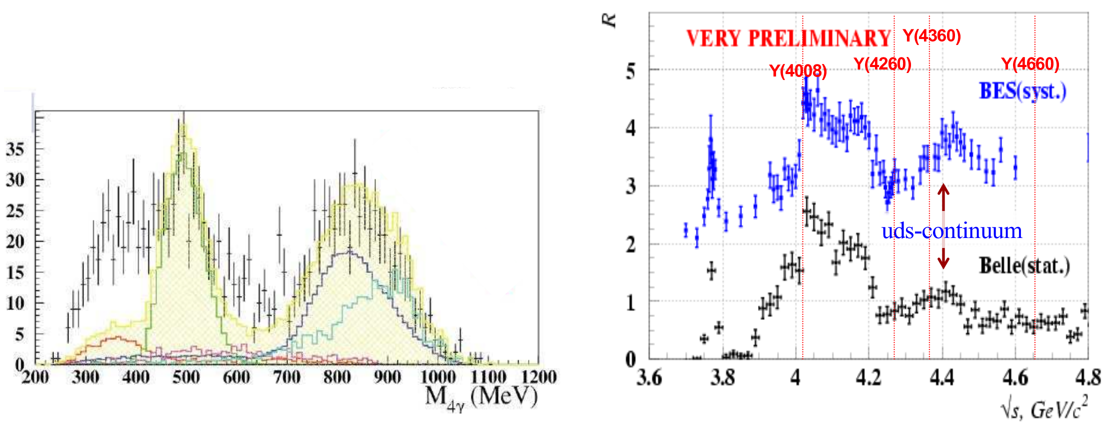

Figure 3: (a) 4-photon mass spectrum showing a low-mass excess at KLOE (Di Donato); (b) R ratio of hadrons to muon pairs in e^+e^- collider data showing the charm threshold and resonances (Wang).

3 Photons at electron-positron colliders

The electron-positron colliders from which results were presented at this conference were DAΦNE, BaBar and Belle. Data taking at DAΦNE ended in 2006, with 2.5 fb^{-1} of data at the ϕ mass, and BaBar have finished with 553 fb^{-1} of data. Many results on radiative ϕ decays and photon-photon processes are now becoming available, a selection of which was presented by Camilla Di Donato. The radiative ϕ decays that were studied include those in which a single light meson is accompanied by a photon, and those where two mesons are produced. There are open questions here regarding the existence and properties of scalar mesons below 1 GeV in mass, which these data are uniquely posed to answer. In particular, there is the long-standing question of whether a $\sigma(600)$ meson exists. Production of a $2\pi^0$ final state shows an anomaly that could indicate the presence of a new effect in this channel, but apparently at a lower energy than 600 GeV (Fig. 3(a)). A gluonium content within the η' is indicated, and analyses have been started on the decay of the η and η' into $\pi^+\pi^-\gamma$.

Initial-state photon radiation is able to make a number of resonant states available for study at the B factories. A wide range of masses is scanned in this way, and the high statistics available are generating some interesting results. Xiao Long Wang showed how exotic charm structures referred to as $Y(4008)$, $Y(4260)$, $Y(4360)$, $Y(4660)$ are now under study. They are formed from charmonium plus hadron pairs and are not yet all fully understood – a topic of considerable interest in the context of the quark model of mesons (Fig. 3(b)). It is interesting that when two charm mesons are observed in the final state, no evidence of the Y states is seen. There is also the $Y(2175)$, which may be an excited strange quark state, and its presence has been confirmed at BES. Here are some ongoing investigations where Belle is best placed to give further answers.

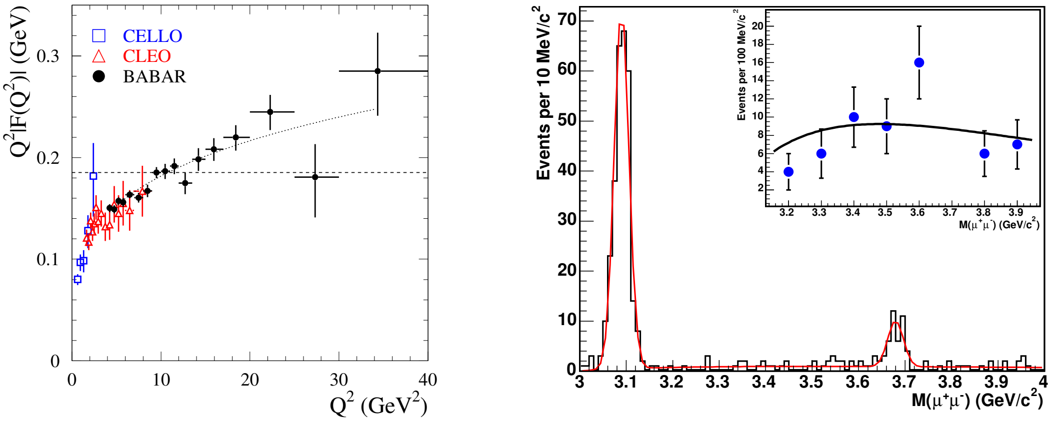

Figure 4: (a) Transition form factor of π^0 with latest BaBar measurements (Li); (b) Exclusive dimuon spectrum in CDF, with diffractive peaks on $\gamma\gamma \to \mu^+\mu^-$ background (Nystrand).

4 Two-photon processes

Selina Li presented some major new photon-photon studies at BaBar and Belle, reminding us again of the original subject-matter of the Photon series of conferences! The process $\gamma\gamma \to \pi^0\pi^0$ has been accurately measured by Belle for dipion masses above 0.6 GeV, and BaBar have measured the π^0 transition form factor in a single-tagged analysis, matching up with data from CLEO and also CELLO at DESY's PETRA collider (Fig. 4(a)). These are just a few topics, and there remains a rich field of work here to be continued by Belle.

Klaus Dehmelt reminded us of the photon leptonic structure function, as measured by L3. More results are coming out in this area, in particular determinations of the structure functions as a function of both photon virtualities; unsurprisingly, the results are in good agreement with the QED calculation. Richard Nisius surveyed the current state of play with the hadronic photon structure function. There are many contributions to an overall fit, but most of the precision points are provided by LEP, especially by OPAL. Although the low-x reach of the measurements is limited, so that the predicted low-x rise is not yet experimentally established, a charm contribution is evident. We keenly await further results from BaBar and Belle, which should soon appear.

Two-photon collisions have now been observed at hadron colliders! Joakim Nystrand showed how CDF have events of the type $\gamma\gamma \to \mu^+\mu^-$ (Fig. 4(b)) and PHENIX have $\gamma\gamma \to e^+e^-$, seen in their studies of diffractive photoproduction of the J/ψ and ψ'. So here, the background is almost as interesting as the signal.

5 Diffraction

A number of new results were presented on diffraction in photoproduction. At STAR at RHIC, again a hadron collider experiment, photoproduced ρ mesons have been observed and their angular distribution measured. Andrzej Sandacz showed results from the COMPASS experiment at CERN, using a 160 GeV muon beam on a polarised ammonia target. In addition to a strong muoproduction programme, the experiment has measured a variety of asymmetry parameters

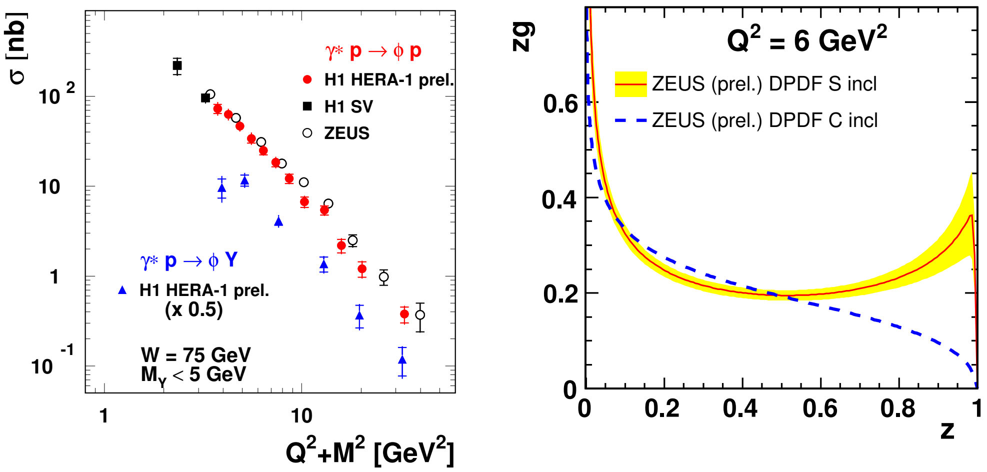

Figure 5: (a) Cross sections for exclusive ϕ production at HERA (Kananov); (b) Gluon density function in pomeron (Newman).

in ρ photoproduction from both protons and deuterons, and have proceeded to extract spin density matrix elements. Results for ϕ production are expected and there are plans for further measurements concentrating on Deeply Virtual Compton Scattering (DVCS).

Most of the work in diffractive physics in recent years has come from HERA. Sergey Kananov presented a general survey of what we have learnt on vector meson photoproduction. There is now an impressive collection of results from H1 and ZEUS on this subject, and he made a comparison of vector meson production without and with a hard scale in the process. Elastic photoproduction of light mesons, namely the ρ, ω and ϕ shows the normal properties of soft diffraction, with parameters gently varying with the centre of mass energy W. The same also holds in electroproduction measured as a function of W. However when a hard scale is present, typified by a heavy quark or large value of Q^2, the cross sections rise with W while falling with $Q^2 + M^2$ (Fig. 5(a)). These features are compatible with hard diffraction as evaluated within the framework of perturbative QCD.

One of HERA's major achievements, of course, has been the study of diffractive physics from the point of view of the pomeron as a hadronic object with a partonic substructure. Paul Newman presented a broad overview of the extensive H1 and ZEUS analyses in this area. Diffractive structure functions have been measured with precision, as illustrated by recent ZEUS results (Fig. 5(b)), and a variety of detailed ideas can be tested, such as the factorisation properties of the proton vertex as the diffractive process at higher Q^2 looks more and more like a kind of hard gluon exchange. Different analysis approaches give consistent results, and a pure DIS or rapidity-gap approach can be successfully compared with the ZEUS data with forward proton or neutron detection. H1 have presented the first diffractive F_L determination. For the future, the full HERA II data need to be analysed, and the H1 and ZEUS data combined for overall measurements.

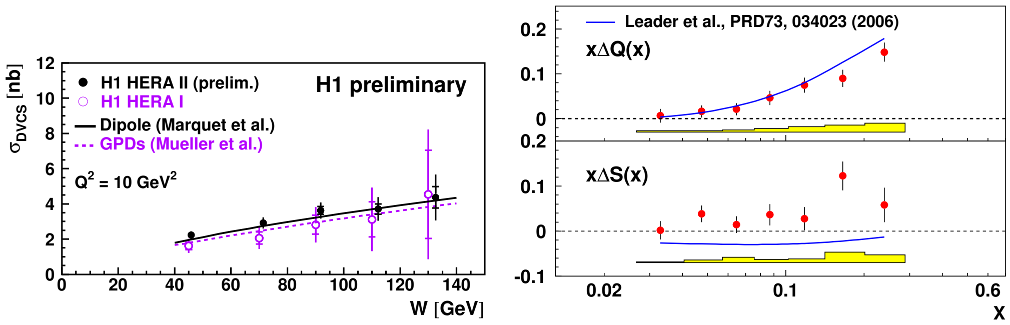

Figure 6: (a) DVCS cross sections at H1 (Schoeffel); (b) Nucleon quark helicity distributions at HERMES (Hillenbrand).

6 DVCS and proton structure

Several results on Deeply Inelastic Compton Scattering were presented, a topic that requires fairly high integrated luminosities in order to obtain useful statistics. Photons are scattering off protons – this is high energy photon microscopy! Laurent Schoeffel described results from H1 and ZEUS. At these low x values, for $x < 0.01$ in the proton, the relevant gluon density is high and one might need to think about saturation effects. Direct DVCS can be measured and the Q^2 and W dependence analysed. However there is an irreducible Bethe-Heitler background of a similar magnitude. Both HERA experiments have presented new cross sections and H1 show that both a dipole model and a Generalised PDF model can fit the data. Are GPDFs as opposed to simple PDFs needed? H1 present clear evidence that argues for a skewing effect, in support of the idea of GPDFs. In their upgrade, COMPASS are making DVCS a major focus and will continue these investigations. Measurements of the Beam Charge Asymmetry will provide an important tool for more detailed studies, and first measurements of this quantity have already been made by H1.

Frank Sabatié gave a dedicated talk on DVCS measurements at JLAB. High statistics are available making use of intense electron beams, enabling several angular correlations to be measured and asymmetries to be determined, together with detailed determinations of the amplitude properties evaluated from suitable cross section differences. It is found that the data are badly described by several of the simpler models, suggesting the presence of more complex or higher order effects.

A further perspective on DVCS was given by Achim Hillenbrand in a presentation of a variety of highlights from the HERMES experiment. HERMES have measured many aspects of nucleon structure using hydrogen targets as well as different atomic nuclei. A particular emphasis has been on spin structures (Fig. 6(b)), a topic also taken up by Joerg Pretz in a discussion of the helicity contribution of gluons to the proton spin structure, measured by means of charmed meson distributions in the COMPASS experiment. Max Klein discussed one of HERA's major showpieces, the DIS study of the PDFs of the proton, using combined H1 and ZEUS data. A new fit has been made to these results, confirming the global utility of perturbative QCD, and comparisons are being made to data from the Tevatron. Specific proton structure functions are being evaluated for charm and beauty production. More will come at higher values of Q^2 and y as well as for the heavy flavours, together with more on F_L, which has now been measured by

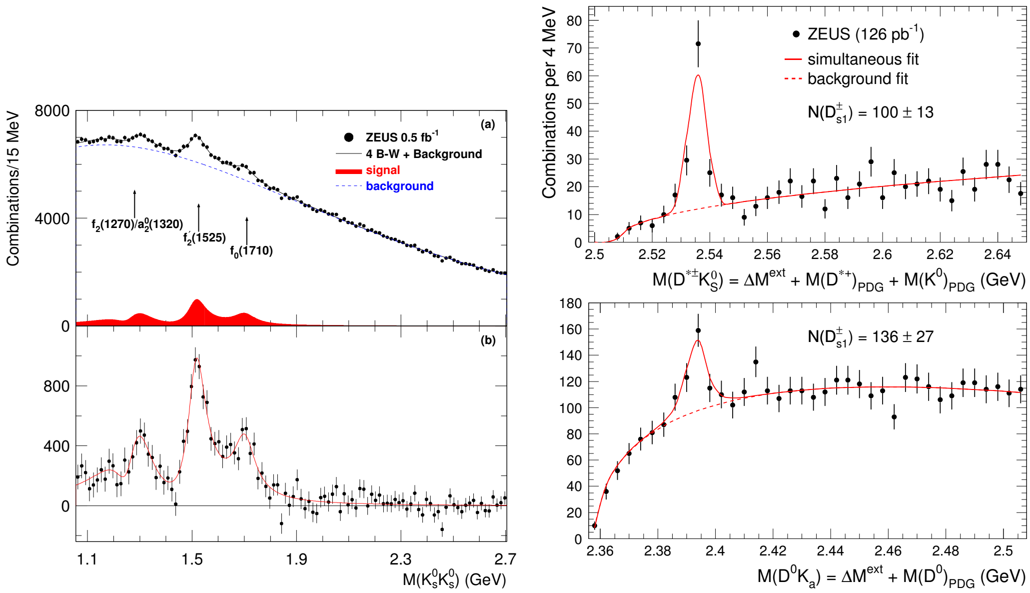

Figure 7: (a) Structure in K^0K^0 spectrum at ZEUS; (b) $D(2536)$ signal in mass difference spectrum (Karshon).

H1 and ZEUS. It can be said that quarks are pointlike down to 0.7×10^{-18} m, making HERA also the world's best electron microscope.

7 Resonance production

As a high energy collider, HERA produced final states containing the usual variety of hadronic resonances. This has provided the opportunity to search for new or exotic resonances that had in some cases been reported at other colliders. Uri Karshon presented results on several such searches, one being for glueballs in the $K_s^0K_s^0$ system. The scalar meson sector contains too many 0++ states to fit into the normal quark model, and it is natural to investigate these as possible glueballs, the lightest of which is predicted by lattice gauge calculations to have a mass in the range 1550-1750 MeV. The state $f_0(1710)$ is an interesting glueball candidate, for several reasons including an apparently high decay BR into strange quarks. The $K_s^0K_s^0$ system is therefore an attractive area to look for confirmation of these ideas. ZEUS have observed evidence for several $K_s^0K_s^0$ resonances in this mass region and the $f_0(1710)$ is present with good statistical significance. It is argued, however, that the state is not a pure glueball.

H1 had earlier proposed a charm pentaquark signal at 3.1 GeV. However ZEUS did not see this, and with more HERA II statistics this peak has gone away and presumably must be treated as a statistical fluctuation, albeit a rather enigmatic one.

ZEUS are studying excited charm states, which are well observed even in the HERA I data set. A variety of states are observed, and the availability of the HERA II data with a better vertex detector makes this a very promising prospect for the future.

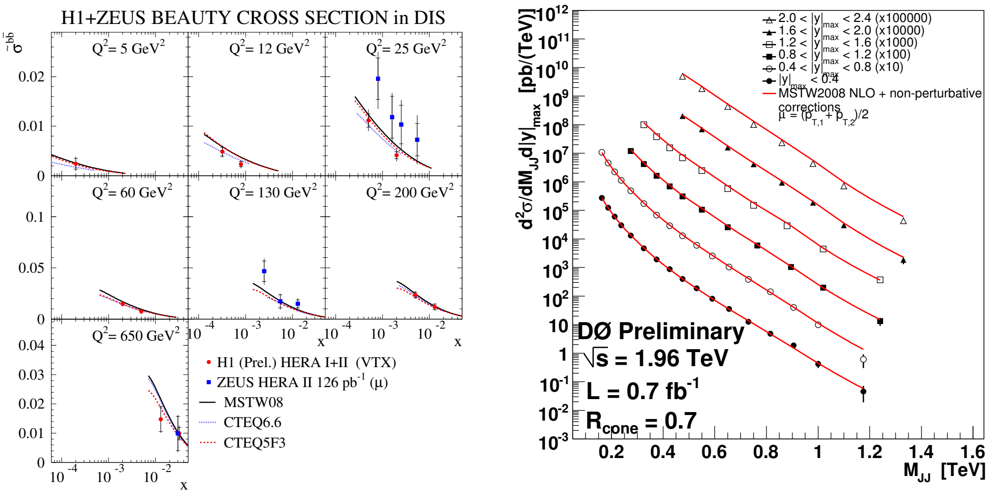

Figure 8: (a) Combined HERA beauty DIS data (Grindhammer); (b) D0 dijet mass spectrum (Yu).

8 Jet physics

The theme of heavy flavours formed a major aspect of Günter Grindhammer's discussion of the physics at different hard scales. Both in photoproduction and in DIS, the presence of a heavy quark facilitates the use of perturbative QCD and encourages the calculation of theoretical models. It is found that the HVQDIS model describes charm production in DIS well, but predicts too low cross sections for beauty. Overall, however, NLO and NNLO calculations do a good job at describing the features of the data (Fig. 8(a)). Results from the final HERA data sets are very eagerly anticipated. In another part of this talk, the evaluation of α_S from jet measurements at HERA was surveyed. H1 and ZEUS are able to do this in various ways and many of the measurements are very competitive on a world basis. It remains the case that with the increasing experimental precision, theoretical uncertainties dominate most of these determinations.

The story is continued with the study of jets at the Tevatron, presented by Shin-Shan Yu. Both CDF and D0 have accumulated in their data very large samples of jets, produced up to transverse momentum values above 600 GeV/c. At one time, high-p_T anomalies were suggested but at present everything is well described by the latest fits to the proton structure which are based on lower-p_T data. Everything about inclusive jets and dijets currently looks very satisfactory (Fig. 8(b)). Studies of W and Z accompanied by jets and, specifically, by heavy flavours have been carried out. These will be of particular relevance in connection with Higgs searches. Anne-Marie Magnan took the view to a higher energy level, presenting projected jet features at LHC. Not only are the extensive studies being performed here important with regard to understanding QCD and the proton structure in more depth, they will be esssential in understanding the backgrounds to searches for exotics and Higgs at LHC.

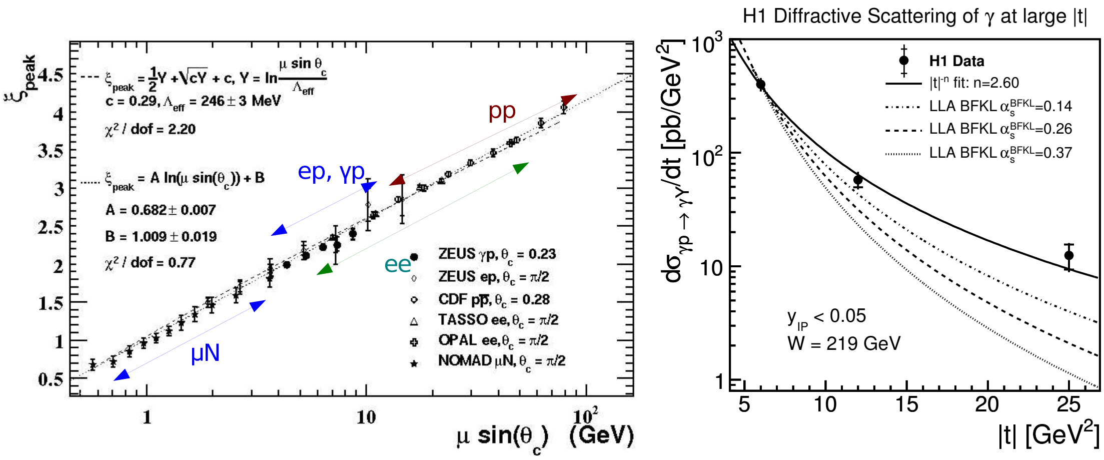

Figure 9: (a) Universal properties of scaled momentum in fragmentation; (b) high-t photon distribution (Müller).

9 Photoproduction

Most of the events recorded in the two larger HERA experiments lie in the category of photoproduction, in which the virtuality of the exchanged proton is very much lower than 1 GeV^2. A thorough survey of many aspects of these processes was given by Katherina Müller. Hard photoproduction may be specified as comprising processes in which either the photon itself or a parton within it undergoes hard scattering, commonly giving rise to jets in the final state. The photon in this way often behaves as if it has a hadronic parton structure. Inclusive jets, dijets and the properties of dijets have been measured and show no unusual properties; neither does the topology of the jets nor the fraction of the photon momentum that is taken up in the jet formation.

In a recent analysis, ZEUS have given measurements of scaled momentum distributions in photoproduced jets, testing our understanding of fragmentation and its universality when this is compared with appropriately scaled measurements from other regimes; again, all is in order (Fig. 11(a)). However the diffractive scattering of high-t photons was found by H1 to be higher than expected and the topic well merits further study (Fig. 9(b)).

10 Prompt photons

In the study of high energy collisions involving hadrons, events in which an isolated high-energy photon is observed provide a direct probe of the underlying parton process, since the emission of these photons is largely unaffected by parton hadronisation. The study of such "prompt" photons gives new perspectives on QCD processes, allowing the theory to be tested from new viewpoints. Prompt photons may be emitted in hard partonic interactions, and were the subject of part of the talk on photoproduction. H1 have measured prompt photons in photoproduction accompanied by a jet, giving cross sections and distributions in the azimuthal separation of the photon and the jet (Fig. 10(a). These distributions are compared with models of the photon,

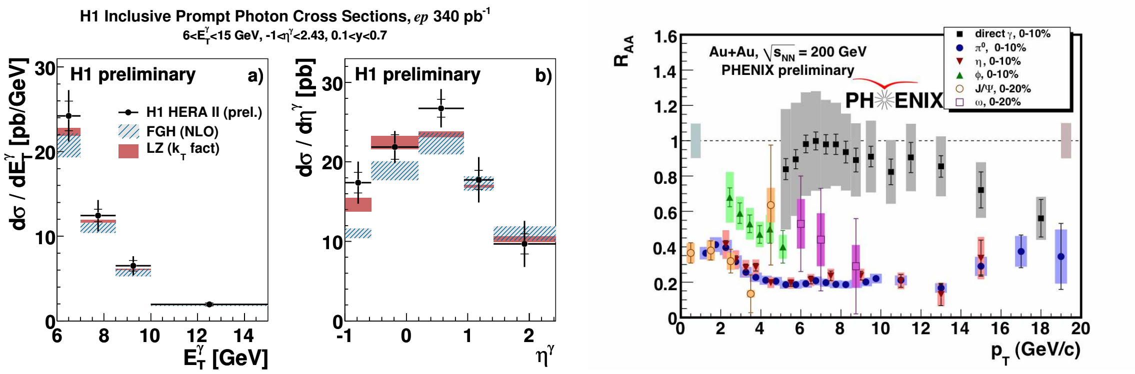

Figure 10: (a) H1 prompt photon + jet in photoproduction (Müller)); (b) PHENIX enhanced prompt photon ratio, compared to other emitted particles (Reygers).

with fair but not perfect agreement.

Recent results on prompt photons in DIS in ZEUS were presented by myself. In this process, attention must be paid to the radiation of the photon by either the incoming or outgoing lepton. Agreement with theoretical models is fair but shows some serious disagreements in some kinematic regions.

At the Tevatron, the story was continued by Ashish Kumar. Both CDF and D0 are active in the prompt photon area. This process is sensitive to the structure of the proton, as well as to the possibility of new physics. CDF and D0 find good agreement with theory, to within some fairly substantial theoretical uncertainties, for prompt photons at transverse momenta above 50 GeV. Below this CDF see a discrepancy while with D0 the situation is suggestive but a little ambiguous – this region clearly merits further study. Measuring a jet as well as the photon does not bring the situation fully under control, as measured by D0. Demanding a b-jet does achieve agreement with theory, but there are serious disagreements if the photon is accompanied by a c-jet. Again, more study is indicated.

Prompt photons also form an important topic of investigation at the RHIC collider, as reported by Klaus Reygers. The PHENIX results in proton-proton collisions are consistent with a large collection of results from other colliders. However, in nucleus-nucleus collisions, it is understood that the colliding nuclei are likely to form a quark-gluon plasma or fireball, out of which prompt photons can emerge. At photon energies of a few GeV this effect has apparently been observed by PHENIX using gold-gold collisions. There is indeed an enhancement of these photons compared to the distributions observed in proton-proton collisions (Fig. 10(b)), confirming the idea that a quark-gluon plasma is being formed.

11 The present high energy frontier

As energies rise, we enter the realm of electroweak physics, and of many possibilities of new physics. Luca Stanco presented some updated HERA cross sections comparing neutral current and charged current exchange. The already classic HERA I results are now augmented by preliminary HERA II measurements, giving further accuracy, and we see how pure photon exchange merges into Z exchange at the same level as W exchange, with differences between

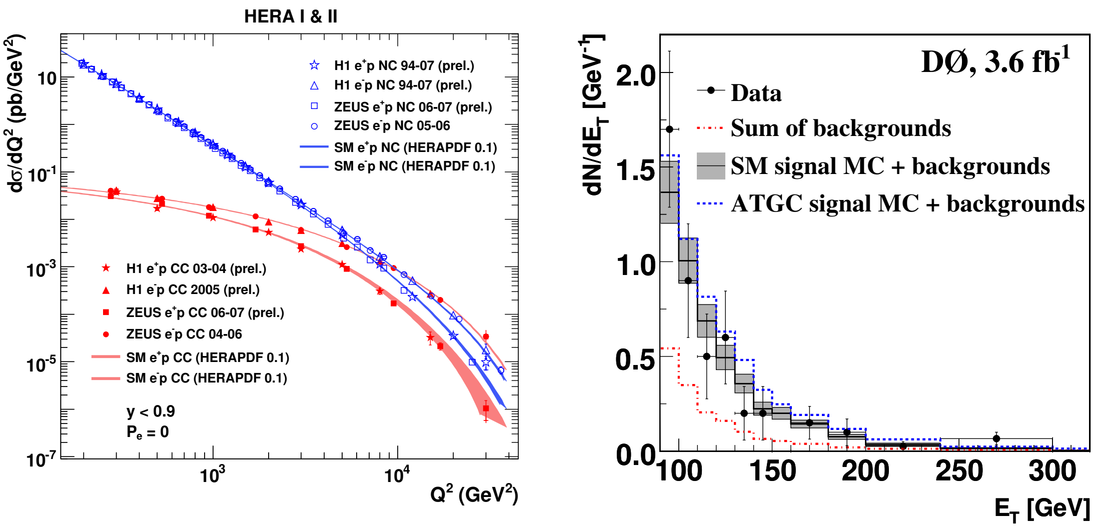

Figure 11: (a) H1 + ZEUS electroweak DIS cross sections (Stanco); (b) D0 data showing no evidence for anomalous triple gauge couplings (Krop).

electron and positron cross sections (Fig. 11(a)). The beam polarisation asymmetries illustrate the physics equally powerfully.

At the Tevatron, Dan Krop pointed out the plethora of theoretically proposed new processes that involve photons. These range from the familiar area of Higgs physics, through SUSY models and extra dimensions, to Compositeness, new generation(s) and Technicolor. All these areas are the subject of searches at the Tevatron and all the searches have so far proved unsuccessful. The anomalous coupling of the photon to the Z is one such example (Fig. 11(b)), although the search has given the first observation (by D0) of the production of $Z\gamma \to \nu\nu\gamma$ at the Tevatron. There has also been an unsuccessful search for "dark photons" that might explain certain excesses seen in astroparticle physics experiments. No Higgs signal, which would be non-SM under present conditions in the photon-photon channel, has been observed. There are many other possibilities, limited only by the imagination of theorists, for anomalous physics to be observed in conjunction with photons. These searches will continue until the Tevatron terminates and LHC takes over the baton.

At LHC, as explained by Suen Hou, there will be a lot of work to do in connection with photons. There are many Standard Model processes that involve high energy photons, all of which should be studied. Some of these are standard processes, such as W and Z production, in which a photon is radiated by an incoming quark line: a correct understanding of this kind of process will help ensure that we understand the basic W and Z production correctly. Of course, the search for anomalous couplings will be extended. The decay of the Higgs into two photons will be a major focus of LHC work, as elaborated by David Joffe in a talk that presented much information on the techniques of photon detection at ATLAS and CMS. While we are waiting for the Higgs to be discovered, it will be interesting to measure the proton-proton total cross section (Hasko Stenzel).

Finally, there are interesting prospects for photoproduction physics at the LHC, since the high energy protons are quite efficient at radiating photons. Vincent Lemaître outlined this photoproduction programme, concentrating on the possibility of single top production via an incoming photon. The process will be tagged, it is hoped, by installing forward silicon detectors close to the beamline downstream of the detectors. Nicolas Schul extended this discussion to a programme of photon-photon physics at the LHC, epitomised by SUSY searches which can be performed in a very effective way using this approach.

12 A high energy photon collider?

For the far future, plans have been under development for many years to construct a high energy photon photon collider as a part of the International Linear Collider project. Talks by Valery Telnov and Tohru Takahashi presented some technical ideas that might be able to turn this project from aspiration into reality, while Jeff Gronberg discussed the possible benefits of constructing an "early photon collider" that could, for example, become a kind of Higgs factory by manufacturing the Higgs out of pairs of photons, the converse of the decay process that will be eagerly sought at the LHC. Unfortunately, these are financially very difficult times, and the present climate of opinion is unfavourable to the pursuance of this option.

13 Final remarks

In this overview I have attempted to give an impression of the remarkable range of talks given at the Photon 2009 conference. There is an enormous diversity of particle physics processes in which photons, whether incoming or outgoing, real or virtual, play an important role. The fact that a particle is ubiquitous does not make it less interesting than those that are rarer; quite on the contrary, the humble photon provides a key to the deeper understanding of many things. From low energies to high, from the firmly established to the speculatively hypothetical, we have seen how important photon physics is to all aspects of our subject. It seems that there is no other particle in the universe that serves us in so many ways.

I must express regrets with respect to those topics which this review has had to omit. These include the DESY laboratory's extensive programme of "low-energy" photon research, and the entire area of new developments in photon detectors. I have also not been able to cover the subject of photons in astroparticle physics. These topics are treated in their own papers in this volume.

Above all, I would like to thank the organisers of the conference for their dedication in making possible such an excellent week of presentations and discussions, in which an outstanding breadth of fascinating physics was presented. We all look forward keenly to the next conference in the Photon series.