High-energy photon collisions at the LHC - dream or reality?
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We discuss the potential of high-energy photon collisions at the LHC for improving our understanding of QCD and studying the physics beyond the Standard Model. After reviewing briefly the legacy of past photoproduction experiments at LEP and HERA, we examine the gold-plated channels proposed for a photon collider at the ILC for their potential in a hadron collider environment. We stress that initial-state photon interactions have indeed been observed at RHIC and at the Tevatron. Three promising channels at the LHC are then presented in some detail: exclusive vector-meson production, measurements of possibly anomalous electroweak gauge-boson or top-quark couplings, and slepton production.

1. Introduction

Until quite recently, high-energy photon interactions have been the exclusive domain of lepton accelerators. The emission of photons by electron beams has been known for many years to be not only a nuisance to accelerator physicists (although many interesting results have been recently obtained using initial-state radiation at B-factories), but also a useful tool for various domains of science, including biophysics and material science, but also particle physics. It was hoped that an International Linear Collider (ILC) might be built soon and include a laser-backscattering facility, turning it into a photon collider with up to 80% of the center-of-mass energy of the parent ILC.

The recent funding cuts in the United Kingdom and the United States represent unfortunately serious set-backs for the prospects of studying photon interactions at lepton colliders. The search for short- or medium-term alternatives has thus become imperative. With the observation of photoproduction events at existing hadron colliders such as RHIC or the Tevatron and the imminent start-up of the LHC, the latter has emerged as a serious candidate for studying high-energy photon collisions in the near future.

In this review, we motivate these studies beyond the famous quote from Genesis 1, 3-4, where

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God said: ‘Let there be light,’ and there was light. God saw that the light was good, and he separated the light from the darkness. We first discuss the legacy of past photoproduction experiments at LEP and HERA and the gold-plated channels proposed for a photon collider at the ILC. We then present the emerging experimental results from RHIC and the Tevatron and three promising channels at the LHC: exclusive vector-meson production, measurements of possibly anomalous electroweak gauge-boson or top-quark couplings, and slepton production. We close with an outlook on other channels that might be interesting to study further in the future.

2. Photon physics at lepton colliders

At circular lepton accelerators such as LEP and the electron-ring at HERA, spalike, almost real bremsstrahlung photons are exchanged during the hard collision. At a future ILC, large particle bunch densities are needed to reach high luminosities. Then additional beamstrahlung photons will be created before the hard interaction by the coherent action of the electromagnetic field of one bunch on the opposite one. If the electron beams are collided with additional high-energy laser beams, real photons can be produced through Compton scattering. Thus three different mechanisms contribute to photon scattering...
at high-energy lepton colliders: bremsstrahlung, beamstrahlung, and laser backscattering.

2.1. LEP

The LEP collider was operated at CERN in two phases, i.e. in the years 1989 to 1996 at a center-of-mass energy of 91 GeV and from 1998 to 2000 at center-of-mass energies between 161 and 209 GeV. The photoproduction events allowed for a large variety of QCD studies. They were divided into three categories: those with no, one, or two identified electrons (positrons).

Untagged events were e.g. exploited by the L3 and OPAL collaborations for measuring the total photon-photon cross section with the result that both collaborations found consistently evidence for soft-pomeron and reggeon, but no hard-pomeron exchanges \[1\]. They disagreed, however, on the inclusive-jet production cross section, where only OPAL found agreement with the next-to-leading order (NLO) QCD prediction \[2\]. Similar agreement was found by OPAL for the dijet cross section, whose direct, single-resolved, and double-resolved components could be separated by reconstructing the observed photon momentum fractions \(x_\gamma^\pm\) from the transverse momenta \(p_T\) and rapidities \(\eta\) of the final jets. Both L3 and OPAL measured inclusive hadron photoproduction, finding (in the case of L3 considerably) harder \(p_T\)-spectra than observed in photon-proton collisions at HERA. This could, at least partly in the case of L3, be attributed to the direct interactions of the two photons.

In single-tagged events, where the virtuality \(Q\) of one of the photons provides a hard scale, inclusive cross section measurements allowed to improve considerably our knowledge about the QED and hadronic structure of the photon. The light, but also heavy (charm) quark densities \(f_{q/\gamma}\) became directly accessible down to relatively low values of \(x_\gamma \simeq 0.01\), and QCD evolution could be tested up to \(Q \simeq 20\) GeV. In this way, the gluon density could at least be indirectly constrained and even the strong coupling constant \(\alpha_s\) could be measured with competitive accuracy \[3\]. Recently, parton density function (PDF) analyses for the proton have been performed at the next-to-next-leading order (NNLO) level. In the future, this should, of course, also be done for photons, where the direct contribution plays a particularly important role \[4\].

The direct contribution rises, of course, in the transition region from real to virtual photons, which has been studied at LEP through double-tagged events, whereas the genuine hadronic (vector-meson dominance) contribution diminishes. The QED and hadronic structure functions of virtual photons, or equivalently electrons, have been extracted, and also the total \(\gamma^*\gamma^*\) cross section has been measured. For a more complete experimental review see \[5\].

2.2. HERA

At HERA, where electrons of energy 27.5 GeV were collided from 1992 to 2000 with protons of energy 820 GeV and from 2003 to 2007 with protons of 920 GeV, photoproduction events were abundant and allowed for QCD studies in at least four different respects \[6\]. We concentrate in the following on dijet production, but similar discussions also apply to light- and heavy-flavor and prompt-photon production.

First, the distribution in the center-of-mass scattering angle permitted to distinguish regions, where the dijet cross section was dominated by spin-1/2 quark exchanges, from those, where it was dominated by spin-1 gluon exchanges. Both distributions were very different from the pure phase space distribution and provided evidence of the underlying QCD dynamics.

Second, a separation of low- (less than 0.1) and high- \(x_p\) (more than 0.1) contributions allowed not only to confirm the shape of the quark distributions in the photon determined at LEP (see above), but also to learn more about the photon’s gluon distribution than could be achieved in \(e^+e^-\) collisions.

Third, restricting the measurements to high- \(x_\gamma\) contributions (more than 0.8) permitted to obtain information on the proton’s gluon distribution that was complementary to the one obtained in deep-inelastic scattering (DIS).

Fourth, the production of forward jets in the transition region from real to virtual photons offered the interesting possibility to compare the predictions made by the BFKL \(x\) and DGLAP
Q^2) evolution equations, respectively.

The question whether diffractive dijet photo-production can be described by factorizing the hadronic cross section into universal pomeron fluxes, PDFs and a perturbative partonic cross section or is rather subject to initial-state rescattering is still under discussion [7]. At least the H1 data seem to indicate a global suppression (or rapidity-gap survival probability) of about 0.5 of the NLO cross section [8], whereas theoretical predictions based on a two-channel eikonal model predict a suppression by about a factor of three for the resolved-photon contribution [9].

Exclusive production of vector mesons or deeply virtual Compton scattering may actually be easier to understand in the sense that consistent values of the t-slope parameter or interaction size b of the pomeron can be extracted [10] or generalized PDFs may be extracted [11].

While the final HERA data has reached a quite good experimental accuracy, in particular thanks to the high-luminosity running in the second phase, the theoretical predictions still suffer from a variety of uncertainties, even though virtually all two-to-two photoproduction processes have now been calculated and cross-checked at NLO [12].

The choice of renormalization/factorization schemes e.g. is of particular importance in photoproduction due to the direct-photon initial-state singularity, which can be more effectively resummed in the DIS, than in the \( \overline{\text{MS}} \) scheme. For heavy-quark production, considerable progress has recently been made by interpolating between the massive and zero-mass variable flavor schemes through the general-mass variable flavor scheme.

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The most promising physics case for a photon collider has always been a precise Higgs-boson mass measurement (a precision of about 100 MeV in one year of running), made possible through the reaction [16]

\[
\gamma\gamma \rightarrow h (H, A) \rightarrow b\bar{b}.
\] (1)

Other quantities that could thus be determined with high precision include the Higgs partial widths to two photons, W- and Z-bosons or top quarks. Should SUSY particles exist, pair production of the heavier SM partners such as se-
lectrons might not be accessible with the limited ILC energy. In this case, the associated production of a light neutralino with a heavier selectron in photon-electron collisions would represent another promising possibility allowing to search for physics beyond the SM. Also, left- and right-handed anomalous $Wtb$ couplings might be determined with better accuracies than possible certainly at the Tevatron, but also at the LHC and even in $e^+e^−$ collisions.

A more complete list of “gold-plated” channels at a photon collider has been compiled in Vol. 6 of the TESLA TDR, shown here as Tab. 1 [17]. We have added an extra column to this table, pointing the reader to perceived difficulties in adapting the respective production channels to the LHC or, when applicable, to the relevant contribution in these proceedings.

3. Photon physics at hadron colliders

With the realization of a photon collider option and the ILC itself being now more uncertain than ever, the biggest advantage of using a hadron collider for photoproduction experiments is that such colliders (RHIC, the Tevatron and LHC) exist. The energies that can be reached are in fact quite comparable: $\sqrt{s_{\gamma\gamma}} = 400$ GeV at a 500 GeV ILC vs. $\approx 486$ GeV in OO collisions at the LHC and even more in pp collisions. In addition, hadron colliders offer the possibility to not only study photon-photon, but also photon-proton or photon-ion collisions, in particular at low $x$-values [18].

The disadvantages are quite obvious: Much less bremsstrahlung is emitted by the heavier protons than by electrons, but this loss in luminosity may be compensated by the large electrical charge $Z$ of heavy ions. Elastic scattering of nucleons and nuclei is not only induced by photons, but also by pomeron (also reggeons and possibly odderon), and the two are not easily separated; one option is to consider only electroweak final states, which do not couple to pomeron. And then perturbative QED may no longer be applicable at large $Z$, rendering a reliable luminosity calculation for heavy ion beams difficult. In ultraheavy-ion collisions with impact parameter $b$ larger than the sum of the colliding-ion radii, radiation is emitted coherently by the whole nuclei, making them vibrate, generating resonances and inducing large soft cross sections and electron-positron pair production. The latter can furthermore lead to electron capture and eventually beam loss [19,20]. Fortunately, the calculational difficulties can be overcome by using reactions like $\gamma\gamma \rightarrow l\bar{l}$ as a luminosity monitor, as had already been proposed for the ILC.

In CMS this reaction has been studied and found to be of sufficient quality once a $p_T$-cut of 3 (6) GeV for muon (electron) pairs has been imposed and the lepton pair has been forced to have an azimuthal angle $\Delta\phi$ larger than 2.9 (2.7) [21]. Its applicability may, however, be reduced to low-luminosity runs at the LHC.

The Krakow-Paris collaboration estimates that the $p_T$-cut may even be reduced to 0.2 (6) GeV or completely abandoned, provided that an additional detector allows to cut on $\Delta\phi > 3.1$ [22].

In both cases, identifying photon interactions at hadron colliders will probably require detection of the forward protons [23,24]. First, good knowledge of the proton transport in the beampipe is required and can indeed be obtained with the HECTOR simulation tool, validated by MAD-X. Second, the protons must be detected and their energies measured at 420 and/or 220 meters from the primary vertex with the FP420 and/or FP220 detectors. This allows then to determine the energy of the exchanged photon in the range 20 ... 120 GeV with a precision of 1 ... 2 GeV and/or in the range 120 ... 900 GeV with a precision of 10 ... 12 GeV. The virtuality of the photon can be derived from the $p_T$ of the proton, which can be measured in the range 0.1 ... 1 GeV with a precision of approximately 0.14 ... 0.77 GeV.

High-energy photon collisions at hadron colliders have been reviewed in [25] and more recently for ultraheavy-ion collisions in [26] and for proton-proton scattering at the LHC in [27].

3.1. RHIC

The Relativistic Heavy Ion Collider (RHIC) at BNL has started operation in 2000 colliding nuclei with nucleon-nucleon center-of-mass energies
“Gold-plated” channels at a photon collider and their potential at an ILC as well as potential difficulties in their adaption to the LHC and/or pertinent contribution in these proceedings.

| Channel | ILC potential | LHC potential |
|---------|---------------|---------------|
| $\gamma \gamma \rightarrow h \rightarrow bb$ | SM (or MSSM) Higgs, $M_h < 160$ GeV | $\mathcal{P} > \gamma$ |
| $\gamma \gamma \rightarrow h \rightarrow WW(WW^*)$ | SM Higgs, $140$ GeV $< M_h < 190$ GeV | needs survival |
| $\gamma \gamma \rightarrow ZZ(ZZ^*)$ | SM Higgs, $180$ GeV $< M_h < 350$ GeV | probab. $S^2$ |
| $\gamma \gamma \rightarrow H,A \rightarrow b \bar{b}$ | MSSM heavy Higgs, for intermediate $\tan \beta$ | similar to $h$ |
| $\gamma \gamma \rightarrow S[\tilde{t}\tilde{t}^*]$ | Large cross sections, possible observations of FCNC | [15,53] |
| $\gamma \gamma \rightarrow e^- e^0$ | $\tilde{t}^* \tilde{t}^*$ stoponium | ? |
| $\gamma \gamma \rightarrow W^+W^-$ | Anomalous $W$ interactions, extra dimensions | [44,46] |
| $\gamma \gamma \rightarrow W^-\nu_e$ | Anomalous $W$ couplings | [56] |
| $\gamma \gamma \rightarrow \gamma\gamma$ | Strong $WW$ scatt., quartic anomalous $W,Z$ couplings | insufficient $\sqrt{s}$ |
| $\gamma \gamma \rightarrow t\bar{t}$ | Anomalous top quark interactions | Low rate $\rightarrow \gamma g$ |
| $\gamma \gamma \rightarrow \gamma \gamma$ | Total $\gamma\gamma$ cross section | [57] |
| $\gamma \gamma \rightarrow e^-X$ and $\nu_eX$ | NC and CC structure functions (pol. and unpol.) | ? |
| $\gamma \gamma \rightarrow q\bar{q}, c\bar{c}$ | Gluon distribution in the photon | ? |
| $\gamma \gamma \rightarrow J/\psi J/\psi$ | QCD Pomeron | [40,41] |

of up to 200 GeV, and photon interactions have indeed been observed. A typical diagram is shown in Fig. 1, where a $\rho$ vector meson decaying to two pions is produced resonantly in photon-pomeron collisions. The colliding gold nuclei are sometimes excited and emit identifiable forward neutrons. These events are characterized by a low multiplicity in the central detector, typically only one primary vertex and two tracks with low $p_T$.

The STAR collaboration has measured the rapidity distribution of the produced pion pair and found agreement with theoretical calculations based on (generalized) Vector-Meson Dominance (VMD) models, which predict that the photon preferably fluctuates into hadronic states with the same quantum numbers. Disagreement was found with a calculation based on the color-dipole approach, but this may only be a normalization problem of the photon flux. The distribution in the angle $\phi$ between the $\rho$ decay and production planes has also been measured and been found to be in agreement with $s$-channel helicity conservation [28].

The production of 52 electron-positron pairs

![Figure 1. Typical Feynman diagram of photon-pomeron scattering in heavy-ion collisions, leading here to the production of a $\rho$ vector meson that decays subsequently into a pion pair. The nuclei (gold in this case) may be rescattered and/or excited, which may lead to additional forward-neutron production.](image)
at rather low $p_T$ has also been observed by STAR, making it clear that photon interactions at hadron colliders are indeed happening. Both the invariant-mass and $p_T$ distributions agree with full QED calculations taking into account nuclear Coulomb excitation, e.g. of the giant dipole resonance. The factorized approach based on the Equivalent-Photon or Weizsäcker-Williams Approximation (EPA or WW A) also describes the data well with the exception of the very lowest $p_T$-bin [28].

The PHENIX collaboration have observed exclusive $J/\psi$ photoproduction, again in gold-gold collisions at $\sqrt{s_{NN}} = 200$ GeV, in the $e^+e^-$ decay channel at central rapidity. The measured cross section $d\sigma/dy (y = 0) = 44 \pm 16$ (stat.) $\pm 18$ (syst.) $\mu$b agrees well with predictions based on coherent photon radiation and/or quasi-elastic scattering, but one has to caution that so far only a single data point at $y = 0$ is available [29].

### 3.2. Tevatron

After a first run during the years 1992 to 1996, the (slightly) higher hadronic center-of-mass energy of $\sqrt{s} = 1.96$ TeV and, more importantly, the higher luminosity and the considerably improved detectors available since 2001 at Run II of the Tevatron have made it possible to observe photon interactions there in three different channels: $e^+e^-$, $\gamma\gamma$ and quarkonium production. The CDF collaboration have managed to do so after accumulating 532 pb$^{-1}$ and 1.48 fb$^{-1}$ by using only their miniplug calorimeter covering the range $|\eta| \in [3.5; 5.5]$ and their beam shower counters in the range $|\eta| \in [5.5; 6]$, but no Roman pots for proton/antiproton identification [30].

16 events of exclusive $e^+e^-$ production with $E_T > 4$ GeV have been observed, where the inclusive and dissociation background was only expected to be $1.9 \pm 0.3$ events. The signal corresponds to a total cross section of $1.6^{+2.5}_{-0.3}$ (stat.) $\pm 0.3$ (syst.) pb and agrees nicely with the QED prediction of the LPAIR Monte Carlo (1.71 $\pm 0.01$ pb) [31], as do the distributions in invariant mass and azimuthal angle.

Three photon pairs have also been observed in the same data sample. Since photoproduction of photons is a one-loop process, these events come rather from double-pomeron exchange (or gluon-gluon scattering plus initial-state rescattering), and one is even likely be due to pion decay. Subtracting this event one obtains a total cross section of $90^{+120}_{-30}$ (stat.) $\pm 16$ (syst.) fb. The theoretical prediction lies a factor of three below [32]. However, as discussed above for diffractive photoproduction at HERA, calculations of the rapidity-gap survival probability may still have large theoretical uncertainties.

A preliminary analysis with the higher luminosity has lead to 334 events with muon pairs with clearly visible $J/\psi$ and $\psi'$ mass peaks and many candidate events pointing to intermediate $\chi_c$ production. At higher masses, also the $\Upsilon(1S)$ and its 2S and possibly 3S excitations are visible in a sample of 145 events. The quarkonium analyses are, however, yet to be finalized and published.

### 3.3. LHC

In contrast to electrons or positrons, for which the energy spectrum of the radiated photons can be simply described by the equivalent photon approximation for a charged pointlike particle [33], protons and nuclei have constituents, which make it necessary to take in addition their charge distributions into account through inelastic or elastic form factors.

(Valence) quarks have charges similar to the one of the proton itself, so that inelastic exceed elastic photoproduction cross sections for proton collisions. Form factors can be reliably computed in this case in the plane-wave formalism.

The nuclear charge $Z$ can, on the other hand, be much larger than one, so that elastic scattering of heavy ions can lead to strong coherent radiation of photons with wavelength (or inverse energy/transverse-momentum/virtuality) larger than the nuclear radius $R \simeq 1.2A^{1/3}$ (with $A$ being the nucleon number), i.e. the nuclear structure is not resolved. The spectrum for strong electromagnetic fields may be more reliably calculated in the semiclassical approximation in impact parameter $(b)$ space. This makes it also possible to take into account absorptive corrections from strong initial-state interactions, which are, however, generally excluded by imposing $b > R_1 + R_2$. By imposing $b_{1,2} > R_{1,2}$, also strong in-
interactions from produced hadrons with the initial ions may be excluded.

In Tab. 2 we summarize the nucleon-nucleon center-of-mass energies and luminosities and the resulting maximal photon-nucleon and photon-photon center-of-mass energies for various colliding ion combinations at the LHC.

3.3.1. ATLAS, CMS, and ALICE forward detectors

During this workshop, the forward capabilities of three of the four main LHC detectors were discussed: ATLAS, CMS, and ALICE. It is interesting to note that most of the LHC collision energy in pp collisions will be deposited in the rapidity range \(|\eta| < 8\), while the main ATLAS and CMS calorimeters only cover the range \(|\eta| < 5\), ALICE even only the range \(|\eta| < 0.9\). The forward detectors will therefore play an essential role in the LHC physics program, not only for QCD studies at low-\(x\) and in diffraction, but also to identify high-energy photon collisions in pp or heavy-ion collisions.

While the main ATLAS hadronic calorimeter allows already for the selection of single or double rapidity-gap events, the identification of elastically scattered protons requires additional forward detectors. The Luminosity Cerenkov Integrating Detector (LUCID) is currently being installed in the ATLAS cavern and will cover the range \(5.4 < |\eta| < 6.1\). As for the Zero Degree Calorimeter (ZDC), only a simplified version will be (at least initially) installed and allow to cover very large rapidities of \(|\eta| > 8.1\). The installation of Roman pots to measure the Absolute Luminosity For ATLAS (ALFA) with 2 to 3\% accuracy is planned in mid-2009. They would cover the range \(10 < |\eta| < 14\) \[34\] .

The CMS rapidity coverage will be extended by CASTOR to \(5.2 < |\eta| < 6.6\), thereby also enhancing its hermiticity, although funding has so far only been made available for a detector on one side of the interaction point to be installed in July 2008. Similarly to ATLAS, a Zero Degree Calorimeter (ZDC) with rapidity coverage above \(|\eta| > 8.4\) is already installed. The particularity of CMS is its symbiosis with TOTEM, a relatively independent experiment hoping to measure the total cross section and LHC luminosity with 1\% accuracy using forward tracking detectors \[36\].

TOTEM and ATLAS (ALFA) Roman pots will be located at 220 m (FP220) covering the proton longitudinal momentum fractions in the range \(0.02 < x_{1,2} < 0.2\). Both ATLAS and CMS have advanced plans to install high-precision silicon tracking and fast timing detectors at 420 m (FP420), which would cover the range \(0.002 < x_{1,2} < 0.02\) \[37\]. Since photon events have lower \(x\)-values than pomerons, these detectors might prove indispensable to study photon interactions at high luminosities. If approved, they could be installed with either experiment in 2010 \[16\].

While the ALICE central hadronic calorimeter covers only the rapidity range \(|\eta| < 0.9\), its particularity consists in a \(p_T\) threshold which at 0.1 GeV is much lower than those of ATLAS (0.5 GeV) and CMS (0.2 GeV). Additional forward detectors such as the muon spectrometer (2\% \(|\eta| < 4\) and particularly the neutron Zero Degree Calorimeter should allow for energy vetoes and thus the classification of single- or double-diffractive and possibly photon events. However, no installation of Roman pots to identify elastically scattered protons is planned at this point \[38\].

3.3.2. Quarkonium production

One of the most interesting channels for high-energy photon collisions at the LHC will be the production of vector mesons such as heavy quarkonia. As their exclusive photoproduction proceeds through double-gluon exchange from the heavy-ion target, this channel will provide a very sensitive test of the nuclear gluon density, which is essentially unknown below values of \(x \simeq 0.1\) \[39\].

The potential of the CMS detector to measure exclusively produced \(\Upsilon(1S)\) mesons in ultrarepulsive PbPb collisions is quite promising with an expected detection rate of about 500 events for an integrated luminosity of 0.5 nb\(^{-1}\). This estimate is based on a Starlight Monte Carlo simulation, giving a signal cross section of 173 \(\mu b\) and background cross sections of 2.8 and 1.2 mb in the electron and muon decay channels. The invariant-mass distribution of the lepton pairs produced in
Table 2
Nucleon-nucleon center-of-mass energies and luminosities and the resulting maximal photon-nucleon and photon-photon center-of-mass energies for various colliding ion combinations at the LHC.

| NN'   | $\sqrt{s_{NN'}/\text{TeV}}$ | $\mathcal{L}_{NN'}/\text{mb}^{-1}$ | $\sqrt{s_{\gamma N}}/\text{GeV}$ | $\sqrt{s_{\gamma\gamma}}/\text{GeV}$ |
|-------|-----------------------------|---------------------------------|-------------------------------|---------------------------------|
| OO    | 7                           | 160                             | 1850                         | 486                             |
| ArAr  | 6.3                         | 43                              | 1430                         | 322                             |
| PbPb  | 5.5                         | 0.42                            | 950                          | 162                             |
| pO    | 9.9                         | 10000                           | 2610                         | 686                             |
| pAr   | 9.39                        | 5800                            | 2130                         | 480                             |
| pPb   | 8.8                         | 420                             | 1500                         | 260                             |
| pp    | 14                          | $10^7$                          | 8390                         | 4504                            |

Figure 2. Simulated invariant-mass distribution for exclusive di-electron production through $\gamma\gamma$ scattering or the decay of photoproduced $\Upsilon$ mesons in PbPb collisions at $\sqrt{s} = 5.5$ TeV in CMS [39,40]. A similar result is obtained for dimuon production.

PbPb collisions at $\sqrt{s} = 5.5$ TeV is shown in Fig. 2 where the peak due to the $\Upsilon$ resonance is clearly visible with a mass resolution of about 150 MeV [39,40].

For ALICE one may expect the detection of about 400 $\Upsilon$ mesons, which will be visible only in the electron channel. However, about $10^5$ $J/\psi$ mesons and even as many as $2 \cdot 10^8$ $\rho$ mesons will be produced and detected. For exclusively photoproduced $J/\psi$ mesons with only 1.5h of design luminosity, the invariant-mass distribution has been simulated for the electron decay channel. In pp collisions, where 1400 reconstructed $J/\psi$ mesons are expected with 250h of ALICE luminosity, the signal will even be much cleaner [41].

The production mechanism for inclusively produced quarkonia is still not fully understood. While NLO color-singlet calculations correctly predict the $p_T$-spectrum of $J/\psi$ mesons in photoproduction at HERA, LO predictions for hadroproduction at the Tevatron fail by more than one order of magnitude and require the introduction of additional color-octet contributions as predicted by NRQCD. $J/\psi$-production in photon-photon collisions at LEP can then be correctly described [42], but this is unfortunately not the case for the polarization of hadroproduced quarkonia. More experimental information such as the one expected from the LHC may help to clear up the puzzle. This is particularly important, as $J/\psi$ suppression remains to be one of the key signatures of the quark-gluon plasma. The $p_T$-distributions for inclusive $J/\psi$ and $\Upsilon$ photoproduction have been evaluated for this workshop for pp as well as pPb and PbPb collisions, using the Monte Carlo program MadOnia and taking into account additional photon and gluon as well as open $c\bar{c}$ radiation [43].
3.3.3. Anomalous gauge-boson and top-quark couplings

A second promising possibility for high-energy photon collisions at the LHC is the determination of anomalous vector-boson couplings, which can either be parameterized in a process-specific way by form factors or process-independently with effective Lagrangians after or before electroweak symmetry breaking. In the latter case, the Lagrangian can be constrained by imposing the equations of motion and lepton/baryon number conservation, leaving only ten dimension-six operators with their dimensionless couplings $h_i \sim \mathcal{O}(v^2/\Lambda^2)$ in the effective Lagrangian, four of which are $CP$-violating. These may be determined in $W$-boson pair production not only at the ILC, but also at the LHC, although with less precision. When clean lepton final states and optimal observables from fully differential cross sections are chosen, the precision for the couplings not involving Higgs or $B$-bosons might be considerably improved at the LHC over present bounds from LEP, SLD and the Tevatron [44].

The triple ($WW\gamma$) [45] and quartic ($WW\gamma\gamma$) [46] gauge-boson couplings have been investigated with an effective Lagrangian after electroweak symmetry breaking. With 30 fb$^{-1}$ of luminosity, the former may be determined with two to 15 times higher precision than presently available from the Tevatron, while the latter might even be improved by a factor of $10^4$ over present LEP bounds with an integrated luminosity of 10 fb$^{-1}$. However, these couplings are most strongly enhanced at high invariant masses, where unitarity becomes violated. Implementing a unitarity bound through an energy-dependent form factor then creates unfortunately some model-dependence.

The unitarity problem arises also when trying to constrain the quartic couplings in the pp-mode of LHC through $W$-boson fusion in the channel $WW \rightarrow \gamma\gamma$. A considerable improvement over current LEP bounds and a precision similar to the photon-photon case may be achieved [47].

The production of single $W$-bosons has been measured at HERA by combining the full Run-I and Run-II data sets with a total luminosity of about 1 fb$^{-1}$ and the H1 and ZEUS analyses. A small excess is observed in the H1 data sample, which is, however, not significant in the combined analysis. A search for anomalous single top-quark production in flavor-changing neutral currents has also been performed, leading to the current world’s best limit on the magnetic coupling $\kappa_{t\gamma} < 0.14$ [48].

Such a coupling would lead to an LHC photoproduction cross section that is about 100 times larger than the HERA cross section, so that there may be much room for improvement. For low (high) luminosities of 1 (30) fb$^{-1}$, one may expect the magnetic up-quark coupling limit to improve to 0.044 (0.029), and a first limit on $\kappa_{t\gamma}$ of about 0.077 (0.050) may be obtained. At the same time, the CKM-matrix element $V_{tb}$ can be measured, albeit only with a similar precision to the one already achievable in regular pp collisions [49].

3.3.4. Higgs-boson production

While the resonant production of Higgs bosons is clearly one of the main motivations for adding a photon collider option to a future ILC, the situation looks much less promising for Higgs production in photon-photon collisions at the LHC. For masses of 120 GeV, a few events per year may still be expected in the $bb$ decay channel, in particular in OO and pp collisions, but clearly not enough to perform the precision studies of quantum numbers and couplings that would be possible at an ILC. For masses of 185 GeV the rate (now in the four-lepton channel) drops even to less than one event per year [50].

The situation is slightly better for the associated photoproduction of $W$ and Higgs bosons, which constitutes about 5% of the total inclusive rate. With an integrated luminosity of 100 fb$^{-1}$, a significance of up to 3$\sigma$ may be achieved for masses of about 170 GeV by combining different semileptonic channels. However, this is clearly not enough to render $WH$ photoproduction a discovery channel [51].

The event topology of Higgs production in photon-photon collisions is quite similar to the now well-known weak-boson fusion channel, with the important difference that rates are much higher here and two additional forward jets are
available for event selection. A central jet veto allows to suppress most of the QCD background, so that a significance of $5\sigma$ can already be achieved with 30 fb$^{-1}$ for masses between 110 and 140 GeV in the $\tau\tau$ decay channel; for larger masses, the $W$-boson decay channel may be used. With 200 fb$^{-1}$, the partial widths and couplings can be measured with 10-30% and 5-15% errors, respectively [52].

3.3.5. Slepton production

In $R$-parity conserving supersymmetry (SUSY), sleptons decay into leptons and a neutralino, which is often the lightest SUSY particle (LSP) and thus escapes undetected. In inelastic hadron collisions, these events are selected by triggering on missing transverse energy, as the longitudinal-momentum balance from the colliding partons is unknown. In photon-photon collisions, however, the forward protons can be detected and their energy measured, thus providing additional information on the total center-of-mass energy and the longitudinal momenta of two charged decay leptons. This allows for improved rejection of the Drell-Yan, $W$- and $\tau$-decay backgrounds and better extraction of the slepton mass and slepton-neutralino mass difference through kinematic edges [15].

A detailed study of slepton-pair production has been performed for the LM1 benchmark point, where a common scalar mass of $m_0 = 60$ GeV induces light sleptons with masses between 100 and 200 GeV and thus large signal cross sections of about 2.2 fb, which is only slightly reduced by acceptance cuts to 0.7 fb [53]. Additional background suppression was achieved here by requiring the decay leptons to share the same flavor and the events to be coplanar. A $5\sigma$ discovery might then be achieved with only 25 fb$^{-1}$ of luminosity for selectrons and muons, while for staus at least 100 fb$^{-1}$ would be needed. The mass resolution should be of the order of a few GeV, which would be very similar to the mass resolution achievable in photon-photon collisions at the ILC [54].

The production of light charginos has also been investigated in the same study, since their decays into $W$-bosons and neutralinos may lead to a similar signal, provided that decays into intermediate sleptons are forbidden. This would be the case for heavy sleptons as predicted by the LM9 benchmark point with a heavy common scalar mass of 1450 GeV. The important difference is that in this case the decay leptons can also be of different flavor and acoplanar, so that background suppression is less efficient and at least 100 fb$^{-1}$ of luminosity would be needed for a $5\sigma$ discovery. In

![Figure 3. Photon-photon invariant mass for benchmark point LM1 with $\int L dt = 100$ fb$^{-1}$. Cumulative distributions for signal with two detected leptons ($p_T > 3$ GeV, $|\eta| < 2.5$), two detected protons, with same (top) or different flavor (bottom). The WW background has been downscaled by the quoted factor 53.](image)
4. Outlook

After the shutdowns of LEP, HERA, and soon the Tevatron and in the absence of an ILC, the LHC will provide an almost unique environment to study high-energy photon collisions, rivaled only by the continuing RHIC program. Event rates at the LHC will in fact be dominated by forward scattering and include many elastic events and low-level nuclear excitation. Proton (and neutron) identification will be crucial to exploit these events, and as we have seen a number of detectors are either already being installed or planned to match this purpose in the ALICE, ATLAS and CMS experiments.

Traditionally, forward scattering has been the domain of diffractive or low- \( x \) QCD studies, and elastic vector-meson production is indeed one of the promising channels which may allow for a better determination of the proton’s low- \( x \) gluon density, pomeron slope, and maybe discovery of the elusive odderon. However, also the poorly understood inclusive quarkonium production mechanism may be elucidated, and open jet and light- or heavy-quark production will provide unique channels to determine the badly constrained nuclear parton densities. This domain should clearly be investigated further and in particular by adapting the existing NLO codes from the HERA and LEP analyses to the LHC environment.

A precision determination of the top-quark charge might also be possible, but here the potential of photon-photon and photon-proton scattering has to be compared with the one of associated \( t\bar{t}\gamma \) production in inelastic hadron collisions [55].

The sensitivity for anomalous couplings of vector bosons certainly looks also very promising, as we have seen in several studies presented at this workshop. However, these studies are still lacking a common theoretical framework. They should be based on the same effective Lagrangian, implement the unitarity bound in the same way, and agree on a common set of old limits to be improved, so that photon-photon scattering can be reliably compared with weak-boson fusion.

Unfortunately, the production of Higgs bosons seems pretty hopeless in \( \gamma\gamma \) and difficult in \( \gamma p \) scattering. SUSY Higgs bosons and in particular charged Higgs bosons might be more promising, but have not been discussed here. More work along these lines is clearly needed.

As we have seen, sleptons and charginos are certainly one of the promising channels in the realm of physics beyond the Standard Model. Apart from sleptons and gauginos, the SUSY spectrum includes also strongly interacting squarks and gluinos. They therefore receive contributions not only from photon, but also pomeron exchange, and it might be interesting, although challenging, to compare and disentangle both contributions. Extended SUSY models, such as those containing \( R \)-parity violation or extended scalar sectors as in the NMSSM, and other models, such as extra-dimensional or little-Higgs models, would certainly also be worth a close look.

In conclusion, this first workshop on “High-energy photon collisions at the LHC” has proven that there is a large potential for interesting physics studies and opened many perspectives for improvement of existing and undertaking of a wide variety of future studies. The community is therefore looking forward to many years of stimulating scientific discussion in this field.

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