# Two-photon and photon-hadron interactions at the LHC

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**Abstract**
The possibilities to extend the results from HERA by using the strong flux of equivalent photons associated with the proton and nuclear beams at the LHC are reviewed.

## 1 Introduction

Much of the focus of this workshop has been on how the parton distribution functions determined at HERA will be an integral part of the interpretation of the results from the LHC. We wish to point out, however, that the LHC offers an opportunity to directly extend the results from HERA on photoproduction, by using the strong flux of photons associated with the proton and nuclear beams.

Charged particles moving with relativistic velocities are surrounded by a cloud of virtual photons. For point particles, the energy of the virtual photons can in principle be as high as the energy of the charged particle itself. For extended objects, like protons and nuclei, the maximum photon energy is highly suppressed for energies above a fraction of the charged particle's energy because of the form factor. At the extreme energies of the LHC, this is not a serious limitation, however, and it will be possible to probe photon-induced interactions at energies much higher than at HERA both in proton-proton and nucleus-nucleus collisions. Photon-induced interactions can be studied in ultra-peripheral collisions where the impact parameter is larger than the sum of the projectile radii and no hadronic interactions occur. This is illustrated in Fig. 1.

The photon-induced interactions can be divided into two categories: exclusive interactions, where a certain final state is produced, while both beam particles remain intact; and inclusive interactions, where a certain final state is produced but where the photon target breaks up and additional particles may be produced. Exclusive interactions include two-photon and photon-Pomeron interactions. Inclusive interactions include, but are not limited to, direct photon-parton interactions. These two types of processes will be discussed in the following two sections. For two longer reviews of photon interactions at hadron colliders, see [1, 2].

## 2 Exclusive Production

The study of photon-induced interactions at hadron colliders has so far focused mainly on exclusive production, where both protons or nuclei remain intact. The cross sections for exclusive production are normally lower than for the corresponding inclusive reaction channel. The advantage is, however, that the exclusive events have a much clearer event topology, with rapidity gaps on both sides of the produced state, which makes it easy to separate them from background and hadronic processes.

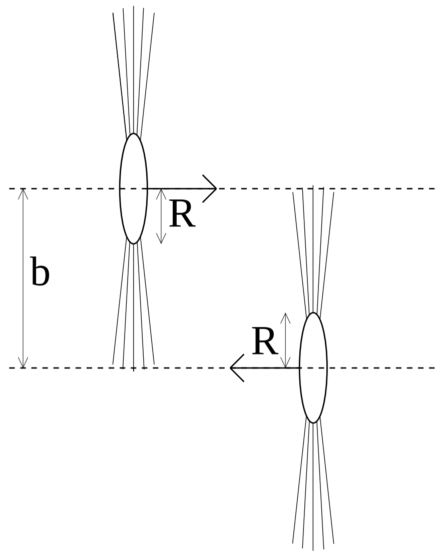


Fig. 1: An ultra-peripheral collision with impact parameter $b$ much larger than the sum of the projectile radii,$R$. The solid lines indicate the Lorentz contracted electric fields.

The early theoretical studies of electromagnetic processes at hadron colliders were concentrated on two-photon interactions. It was later discovered that exclusive production of vector mesons through photon-Pomeron fusion had much larger cross sections [3]. Exclusive photoproduction of vector mesons and two-photon interactions will be discussed in the following two subsections. One should note, however, that exclusive production of vector mesons can occur also through the hadronic process Odderon-Pomeron fusion; this possibility has attracted an increased interest recently [4].

### 2.1 Photon-hadron interactions

According to the Vector Meson Dominance model, the bulk of the photon-hadron cross section can be explained by the photon first fluctuating to a vector meson, with the same quantum numbers as the photon. While in the vector meson state, the photon will interact hadronically with the target. This interaction can be elastic or inelastic. In elastic scattering enough momentum can be transferred for the virtual vector meson to become real; this is the basis for exclusive photoproduction of vector mesons.

The cross section for exclusive production of the lightest vector meson, $\rho^0$, is very high in collisions with heavy ions, such as Au or Pb, reaching 50% of the total inelastic hadronic cross sections at the energies of the LHC [3]. At the Relativistic Heavy-Ion Collider (RHIC), the measured exclusive $\rho^0$ cross section in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is 530±19(stat)±57(syst), roughly 10% of the total inelastic cross section [5].

The momentum transfer from each projectile is limited by the form factor, and the vector meson production is therefore typically centered around mid-rapidity; the exact shape of the

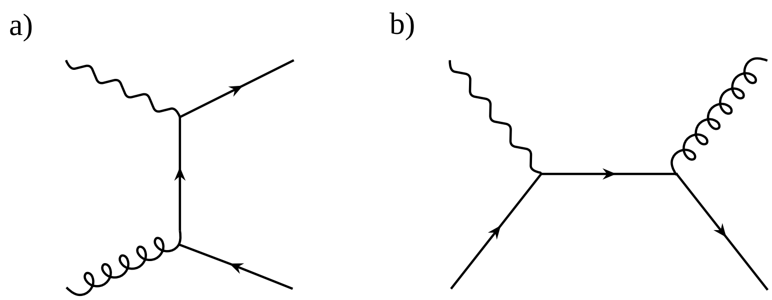


Fig. 2: Feynman diagrams for direct photoproduction of jets in ultra-peripheral collisions through photon-gluon fusion, $\gamma + g \rightarrow q + \overline{q}$, and the QCD Compton process, $\gamma + q \rightarrow g + q$. Direct photoproduction of heavy quarks is described by the diagram in a).

rapidity distribution varies somewhat with collision energy and vector meson mass.

Exclusive vector mesons have been studied by the STAR [5] and PHENIX [6] collaborations at RHIC, and by the CDF collaboration at the Tevatron [7].

The STAR collaboration at RHIC has studied exclusive photoproduction of $\rho^0$ mesons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The energy range probed by STAR, $7.6 \leq W_{\gamma p} \leq 20.6$ GeV, includes energies larger than have been studied in fixed target experiments with lepton beams on heavy nuclear targets. The measured cross sections are found to be in good agreement with models that include a Weizsäcker-Williams photon spectrum and Glauber-like models for the photonuclear cross section.

The PHENIX collaboration has studied exclusive production of J/$\Psi$ in Au+Au collisions in coincidence with Coulomb break-up of at least one of the nuclei. Coulomb break-up means that an additional, soft photon is exchanged in the interaction, leading to the break up of the "target" nucleus. The J/$\Psi$s have been studied around mid-rapidity in the $e^+e^-$ decay channel.

The CDF collaboration has studied exclusive J/$\Psi$ and $\Psi'$ production in the $\mu^+\mu^-$ decay channel in $p\overline{p}$ collisions at the Tevatron [7]. CDF has also seen hints of $\Upsilon$ mesons.

The outlook for studying exclusive vector meson production at the LHC is promising. The rates are very high. The J/$\Psi$ cross section, for example, increases by about a factor 100 from Au+Au collisions at RHIC to Pb+Pb collisions at the LHC. There are plans to study this reaction channel in both the CMS and ALICE experiments, in pp as well as in PbPb collisions.

### 2.2 Two-photon interactions

The cross section for two-photon production of lepton pairs scales as $Z^4$, where Z is the charge of the projectile. The total cross section for producing an $e^+e^-$–pair is several orders of magnitude larger than the total hadronic cross section in heavy-ion interactions at RHIC and the LHC. Most of these electrons/positrons are produced with very low invariant masses, however, and are emitted with small angles relative to the beam axis.

The pairs can be produced as free pairs or as bound-free pairs, where the electron (or the positron with anti-proton beams) binds to the beam particle. When a bound-free pair is produced, the rigidity of the capturing beam nucleus or proton changes and it is lost from the beam. This is the leading source of beam loss at high energy heavy-ion colliders such as RHIC and the LHC. Moreover, the projectile that has captured the electron will hit the wall of the beam pipe at a well-defined spot downstream from the interaction point. At the LHC, the resulting heat deposition could induce quenching of the superconducting magnets. The impact of copper ions with a captured electron about 140 m downstream from the interaction point has recently been observed at RHIC [8]. Bound-free pair production where the positron binds to the anti-proton has been used to observe anti-hydrogen at the Tevatron [9].

Free pair production has been studied in fixed target heavy-ion interactions, in Au+Au collisions at RHIC [6, 10], and, recently, by the CDF Collaboration in $p\overline{p}$ collisions at the Tevatron [11]. The results have generally been found to be in good agreement with lowest order perturbation theory. The limit on invariant mass used by the CDF Collaboration ($> 10$ GeV) is unfortunate, however, since it falls almost on top of the mass of the $\Upsilon(2S)$ meson. The yield from heavy vector mesons produced by photon-Pomeron fusion and decaying to di-lepton pairs is comparable or larger than the one from two-photon production over the relevant invariant mass range.

Two-photon production of mesons, e.g. at $e^+e^-$ colliders, is a useful tool in meson spectroscopy. In principle, such studies could be performed also at hadron colliders, but backgrounds from coherent photonuclear interactions pose a problem. A two-photon "standard candle" like the $f_2(1270)$ is likely to be obscured by continuum production of $\pi^+\pi^-$ through photon-Pomeron fusion. No results on two-photon production of mesons at hadron colliders have been reported.

Finally, it has been suggested to search for the Higgs boson in two-photon interactions at the LHC. Despite the enhancement by a factor $Z^4$ in heavy-ion collisions, the cross section for a standard model Higgs with mass around 100 GeV appears too low, only about 10 pb in Pb+Pb collisions, corresponding to an event rate of only $10^{-9}$ s$^{-1}$ [12]. With Ca beams the situation is a bit better because of the higher luminosity, but the event rate is not more than about $10^{-6}$ s$^{-1}$.

## 3 Inclusive Production

The bulk of the photonuclear particle production stems from events where the photon first fluctuates to a hadronic state, which then interact with the target nucleus or proton. Since the energy of the photon typically is much lower than that of the beam particle, these events resemble fixed target interactions. The photon can, however, also interact as a "bare" photon with one of the partons in the target nucleus or proton. The focus of this section will be on photon-parton interactions in nucleus-nucleus collisions. Direct processes that can be calculated using perturbative QCD include photoproduction of jets and heavy quarks. None of these processes have been investigated at RHIC or the Tevatron, but the prospects should be good at the LHC, particularly because of the strong increase in the cross sections with energy.

### 3.1 Photoproduction of jets

The Feynman diagrams for the two leading-order direct contributions to the jet yield, $\gamma + g \rightarrow q + \overline{q}$ and $\gamma + q \rightarrow g + g$, are shown in Fig. 2. The corresponding differential cross section can be written as a convolution of the equivalent photon flux with the parton distribution functions and the partonic cross sections

$$s^2 \frac{d^2\sigma}{dt du} = 2 \int_{k_{min}}^{\infty} n(k) dk \int_{x_{2_{min}}}^{1} \frac{dx_2}{x_2} \left[ \sum_{i=q,\overline{q},g} F_i(x_2, Q^2) s'^2 \frac{d^2\sigma_{\gamma i}}{dt' du'} \right] . \tag{1}$$

Here, $n(k)$ is the number of equivalent photons with energy $k$. $F_i(x_2, Q^2)$ is the parton density for parton $i$ at scale $Q^2$ and $x_2$ is the Bjorken-x of the parton in the target nucleus. The unprimed Mandelstam variables, $s, t, u$, refer to the hadronic system, whereas the primed variables, $s', t', u'$, refer to the partonic system. The minimum $x_2$ is given by $x_{2_{min}} = -u/(s+t)$ and $k_{min}$ is the minimum photon energy needed to produce the final state.

The cross section for photonuclear jet production is high at the LHC. The cross section to produce a jet with $p_T > 50$ GeV/c and rapidity $|y| < 1$ in Pb+Pb collisions is for example larger than 1 $\mu$b [13]. As can be seen from Eq. 1, the jet cross section is sensitive to the nuclear parton distributions. Calculations show that nuclear shadowing (and anti-shadowing) affects the yield by up to 10%, while the differences between individual parameterizations of shadowing differ by a few percent. It has also been noted that there is a significant contribution to the jet yield from resolved interactions, where a parton in the target interacts with a parton in the resolved photon; the resolved contribution is expected to be the leading production mechanism in certain regions of phase space, particularly for low $p_T < 50$ GeV/c [13].

### 3.2 Photoproduction of heavy quarks

For the production of heavy quarks, only the diagram in Fig. 2 a) contributes. The production cross section is thus a less ambiguous probe of the proton or nuclear gluon distribution. The cross sections are very high at the LHC, as can be seen in Table 3.2 (from [14] with updated numbers from [1]). Calculations are shown for two different parameterizations of the nuclear gluon shadowing and without shadowing. Shadowing has an enhanced effect on the cross section for $c\overline{c}$ pairs, where lower values of $x$ are probed. In Pb+Pb collisions, the two parameterizations correspond to reductions by 16% and 32%, respectively. For $b\overline{b}$ pairs, the effect of shadowing is smaller, 4% and 10% in the two cases.

The resolved contribution is smaller than for jet production. It is largest for $c\overline{c}$ pairs, but does not contribute more than 15-20 % to the total cross section.

The cross section for producing pairs of top quarks is too low for observation with the design LHC Pb+Pb luminosity. It might be possible with lighter ions or with protons.

## 4 Summary

The feasibility of studying at least a few reaction channels in ultra-peripheral collisions at collider energies has been shown by experiments at RHIC and the Tevatron. The measured cross sections have been found to be in general agreement with expectations, but the statistics have so far been

| | flavor | $\sigma$ [mb] No shadowing | $\sigma$ [mb] EKS98 | $\sigma$ [mb] FGS |
|---|---|---|---|---|
| Ar+Ar | $c\overline{c}$ | 16.3 | 14.3 | 12.3 |
| | $b\overline{b}$ | 0.073 | 0.070 | 0.066 |
| Pb+Pb | $c\overline{c}$ | 1250 | 1050 | 850 |
| | $b\overline{b}$ | 4.9 | 4.7 | 4.4 |

Table 1: Cross sections for $q\overline{q}$ photoproduction through direct photon-gluon fusion in Ar+Ar and Pb+Pb interactions at the LHC. The numbers in column 3 and 4 include nuclear gluon shadowing from the parameterizations by Eskola, Kolhinen, and Ruuskanen (EKS98) and Frankfurt, Guzey, and Strikman (FGS), respectively.

low. There are plans to study photon-induced processes in at least 3 of the 4 LHC experiments, although it is not the main focus of any of them. There is an overwhelming number of reaction channels that can be investigated at the LHC in “ordinary” hadronic interactions. Including photon-induced processes leads to an even greater number. It seems unlikely that all these will be investigated during the life-time of the LHC. It will be up to the experiments to judge which are the most interesting and to which the necessary trigger resources and bandwidths should be allocated. In this talk, we have tried to argue that at least some photon-induced processes should meet the criteria for feasibility and interest.

**References**


[1] A.J. Baltz et al., Phys. Rep. **458**, 1 (2008).

[2] C.A. Bertulani, S.R. Klein, J. Nystrand, Ann. Rev. Nucl. Part. Sci. **55**, 271 (2005).

[3] S.R. Klein, J. Nystrand, Phys. Rev. **C60**, 014903 (1999).

[4] A. Bzdak, L. Motyka, L. Szymanowski, J.R. Cuddel, Phys. Rev. **D75**, 094023 (2007).

[5] STAR Coll., B.I. Abelev et al., Phys. Rev. **C77**, 034910 (2008).

[6] PHENIX Coll., D. d’Enterria et al., *Coherent photoproduction of J/Psi and high-mass e+e- pairs in ultra-peripheral Au+Au collisions at sqrt(sNN) = 200 GeV* (unpublished). Nucl-ex/0601001.

[7] J. Pinfold, *presentation at this workshop*.

[8] R. Bruce et al., Phys. Rev. Lett. **99**, 144801 (2007).

[9] G. Blanford et al., Phys. Rev. Lett. **80**, 3037 (1998).

[10] STAR Coll., J. Adams et al., Phys. Rev. **C70**, 031902 (2004).

[11] CDF Coll., A. Abulencia et al., Phys. Rev. Lett. **98**, 112001 (2007).

[12] CMS Coll., G. Baur et al., Eur. Phys. J. **C32**, s69 (2003).

[13] M. Strikman, R. Vogt, S. White, Phys. Rev. Lett. **96**, 082001 (2006);
R. Vogt, *Jet Photoproduction in Peripheral Heavy-Ion Collisions* (unpublished).
Hep-ph/0407298.

[14] S.R. Klein, J. Nystrand, R. Vogt, Phys. Rev. **C66**, 044906 (2002).