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Tagging two-photon production at the CERN Large Hadron Collider

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Tagging two-photon interactions offers a significant extension of the CERN LHC physics program. The effective luminosity of high-energy $\gamma\gamma$ collisions reaches 1% of the proton-proton luminosity. The standard detector techniques used for measuring very forward proton scattering will allow a reliable separation of interesting two-photon interactions. Particularly exciting is the possibility of detecting exclusive Higgs boson production via the $\gamma\gamma$ fusion.

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I. INTRODUCTION

Two-photon physics has been widely studied at e^+e^- colliders since there are large fluxes of virtual photons associated with the electron beams. The proton beam energy of the CERN Large Hadron Collider (LHC) will be so high that the effective luminosity of $\gamma\gamma$ collisions will permit new studies of high energy $\gamma\gamma$ collisions. These measurements are complementary to the ''base-line'' pp studies and can be carried out simultaneously.

This paper considers the experimental feasibility of tagging two-photon interactions in proton-proton collisions at the LHC. The effective $\gamma\gamma$ luminosity of the tagged two-photon collisions is calculated and used to estimate the physics potential of such measurements.

II. LHC AS A $\gamma\gamma$ COLLIDER

For the majority of two-photon processes the equivalent photon approximation (EPA), sometimes called the Weizsäcker-Williams approximation, can be used [1]. In the EPA, two-photon interactions at the LHC proceed in two steps: first, the photons are emitted by incoming protons, and then the photons collide producing a system X. In the *elastic* production, $pp\to(\gamma\gamma\to X)\to ppX$, the protons remain intact, while in the *inelastic* production, $pp\to(\gamma\gamma\to X)\to pNX$, one proton dissociates into a low mass system N. The case when both protons dissociate is not considered here. The proton-proton cross section is a product of the photon-photon cross-section ($\sigma_{\gamma\gamma}$) and the photon spectra (dN):

$$\mathrm{d}\sigma_{pp}=\sigma_{\gamma\gamma}\ \ \mathrm{d}N_1\ \ \mathrm{d}N_2\,.$$

In the EPA the photon spectrum is a function of the photon energy ω and its virtuality Q^2:

$$\mathrm{d}N=\frac{\alpha}{\pi}\frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}Q^2}{Q^2}\left[\left(1-\frac{\omega}{E}\right)\left(1-\frac{Q^2_{min}}{Q^2}\right)F_E+\frac{\omega^2}{2E^2}F_M\right], \tag{1}$$

where α is the fine-structure constant, E is the incoming proton energy and Q^2_{min} is the minimum photon virtuality given by $Q^2_{min}\simeq[M_N^2E/(E-\omega)-M_p^2]\omega/E$. In this expression M_p is the proton mass and M_N is the invariant mass of the final state N. For the elastic production, the dipole approximation for the proton form factors is used: $F_M=G_M^2$ and $F_E=(4M_p^2G_E^2+Q^2G_M^2)/(4M_p^2+Q^2)$, where $G_E^2=G_M^2/7.78=(1+Q^2/0.71\,\mathrm{GeV}^2)^{-4}$. For the inelastic production $F_M=\int\mathrm{d}xF_2/x^3$ and $F_E=\int\mathrm{d}xF_2/x$, where $F_2(x,Q^2)$ is the proton structure function and $x\simeq Q^2/M_N^2$.

In both cases the photon spectrum is strongly peaked at low ω, so that the photon-photon center of mass energy $W\simeq2\sqrt{\omega_1\omega_2}$ is much smaller than the total center of mass energy of the pp system of 14 TeV. In the elastic production the typical photon virtuality is so low, $\langle Q^2\rangle\approx0.01\,\mathrm{GeV}^2$, that the proton scattering angle is very small, $\lesssim20\ \mu$rad.

The luminosity spectrum of photon-photon collisions, $S_{\gamma\gamma}$, can be calculated in the EPA by integrating the product of the photon spectra given by Eq. (1) over the photon virtualities and energies keeping W fixed. Figure 1 shows such a spectrum for integration intervals of 5 GeV$<\omega<E$ and $Q^2_{min}<Q^2<2\,\mathrm{GeV}^2$; $S_{\gamma\gamma}$ and its integral $\int^{W>W_0}\mathrm{d}WS_{\gamma\gamma}$ are shown as a function of W and the lower integration limit, W_0, respectively. The calculation is done for the elastic production. The integral gives a fraction of the pp LHC luminosity available in the photon-photon collisions at $W>W_0$. It is remarkable that for $W_0=50$ GeV this fraction is about 3×10^{-3}, and for the nominal pp luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

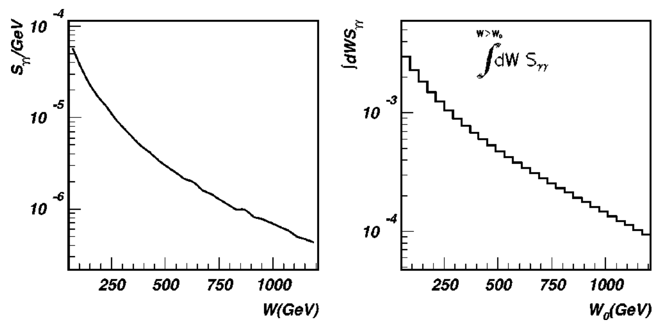

FIG. 1. Elastic $\gamma\gamma$ luminosity spectrum and its integral $\int^{W>W_0}dWS_{\gamma\gamma}$ at the LHC, for the range of photon energy and virtuality, 5 GeV$<\omega<$7000 GeV and $Q^2_{min}<Q^2<2\,\mathrm{GeV}^2$.

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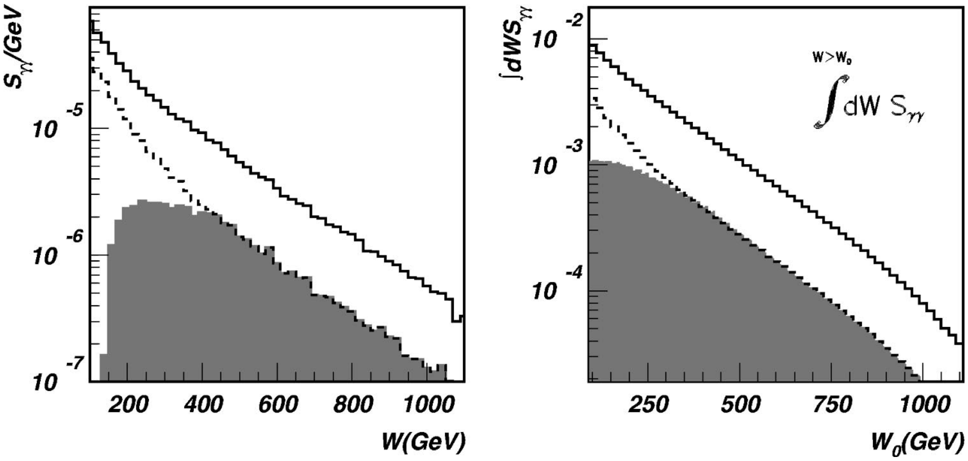

FIG. 2. Tagged photon-photon luminosity spectrum $S_{\gamma\gamma}$ and its integral $\int^{W>W_0} dWS_{\gamma\gamma}$ assuming double tags (shaded histograms) and single tags, for all events (solid line) and for elastic events (dashed line); the tagging range is $70<\omega<700$ GeV and $Q^2_{min}<Q^2<2\ \mathrm{GeV}^2$.

the $\gamma\gamma$ luminosity at $W>200$ GeV is $10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. For the inelastic two-photon production $S_{\gamma\gamma}$ is even larger and is discussed below.

III. TAGGING TWO-PHOTON PRODUCTION

Tagging two-photon production at the LHC serves two purposes. First, when both elastically scattered protons are detected (double tag) the $\gamma\gamma$ center of mass energy W can be calculated from the proton spectra, which improves the overall reconstruction of the final state X. Secondly, tagging is needed to suppress backgrounds. In particular, the proton scattering angle can be used to extract the two-photon signal both for the case of double and single tags when only one forward proton is detected.

At the nominal running conditions the LHC beam at the interaction point (IP) has Gaussian lateral widths of $\sigma_x^*=\sigma_y^*=16\ \mu$m and angular divergences in the horizontal and vertical planes $\sigma^*_{\theta_x}=\sigma^*_{\theta_y}=32\ \mu$rad. However, for the initial running at a medium luminosity of $10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ almost two times smaller lateral beam sizes as well as angular divergences are expected. At the same time, the event pile-up in the central detectors is not prohibitively large. The beam energy spread will be $\Delta E/E=10^{-4}$ [2]. The beam divergence is comparable to the typical proton scattering angle in the two-photon processes; hence protons leave the IP at a zero-degree angle. These protons, however, have smaller energies than the beam protons and are more strongly deflected by the beam-line magnets. The standard method of measuring such forward scattered protons utilizes position sensitive detectors installed far away from the IP and very close to the beam envelope.

The detector layouts so far considered by the TOTEM [3] and ATLAS [4] Collaborations, mainly in the context of measuring the total and elastic pp cross-sections have a significant acceptance for zero-angle protons which have lost at least a few percent of their initial energy. Such protons correspond to tagged photon energies of several hundred GeV and would therefore limit the studies of two-photon production only to a domain of very large W.

However, to improve sensitivity to very low angle elastic pp scattering, it was recently proposed [5] to add new detector stations further away (≈ 240 m) from the IP. This is also an excellent position for tagging two-photon production since (for the nominal LHC beam optics) at this location in the horizontal plane the betatron phase advance is $\approx\pi$, the beam size has a minimum, and the dispersion D is large, about 100 mm. In this position a detector can be moved close to the beam. At the same time the average horizontal displacement Δx with respect to the beam axis due to the proton energy loss is large, $\Delta x = D\omega/E$. In this case a measurement of Δx specifies the tagged photon energy. In addition, the angle between the proton momentum vector and the beam axis, θ_x, is proportional to the equivalent angle at the IP, $\theta_x \simeq \theta_x^*/3$.

In the vertical plane the betatron phase advance at this location is $\approx\pi/2$, so that the angle θ_y is proportional to the proton vertical displacement at the IP, whereas the vertical proton displacement $\Delta y[\mathrm{mm}]\simeq 0.01\times\theta_y^*[\mu\mathrm{rad}]$. Hence, the measurement of θ_x and Δy gives direct information on the proton transverse momentum at the IP, p_T, and hence on the photon virtuality $Q^2\simeq p_T^2\simeq E^2(\theta_x^{*2}+\theta_y^{*2})$.

To ensure enough room for the beam steering and to keep the detectors in a ‘shadow’ of the beam collimators a 1 mm minimum distance between the detector edge and the beam axis should be assumed [3]. Since the proton beam size in the horizontal plane is small, $\sigma_x\simeq 3\sigma_x^*\lesssim 50\ \mu$m, this distance corresponds to more than 20 beam widths—far away from the beam core. The minimum approach of 1 mm corresponds to a minimum tagged photon energy of 70 GeV. The maximum tagged energy is about 700 GeV because of the geometrical acceptance of the beam-line. For such a large energy loss the dispersion D changes with the scattered proton energy, making the energy measurement less reliable.

The photon-photon luminosity spectrum in this tagged energy range is shown in Fig. 2, for both the double tagging and single tagging cases. The photon virtuality is restricted to $Q^2_{min}<Q^2<2\ \mathrm{GeV}^2$. Figure 2 shows that the $\gamma\gamma$ luminosity for the double tagging is sizable in the range $200\lesssim W\lesssim 500$ GeV, whereas the single tagging preserves a major fraction of the total elastic $\gamma\gamma$ luminosity. Including the inelastic contribution to the single tagged spectrum increases $S_{\gamma\gamma}$ by about a factor of three, for a maximum dissociative mass M_N of 20 GeV. For this mass the decay products of the

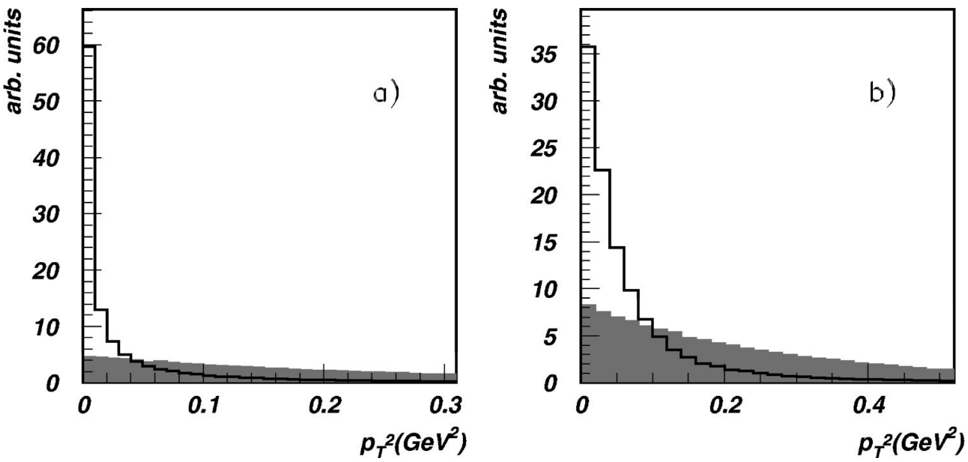

FIG. 3. (a) Distribution of the transverse momenta squared of the scattered protons for the two-photon (empty histogram) and Pomeron-Pomeron (shaded histogram) collisions assuming the diffractive slope $b=4\ \mathrm{GeV}^{-2}$; (b) the same distributions smeared by the beam size and divergence for the initial running conditions. Distributions have the same normalization for $p_T^2<2\ \mathrm{GeV}^2$ and correspond to a 100 GeV proton energy loss.

system N are not observed in the central detectors.

The forward detectors are small, with a sensitive area of each detector plane of about 2 cm^2, but they require an excellent spatial resolution in the 10–20 μm range. Two detector stations separated by 2–4 m are needed to ensure a precise measurement of the direction of the proton momentum. Silicon micro-strip or pixel sensors are the most probable technology choice. The crucial alignment of the detector sensors with respect to the beam axis can be done using the elastic pp events when protons cross several detector planes. Setting the final momentum scale requires a precise knowledge of the integral of the magnetic field along the scattered proton trajectory. However the photon energy scale might be set using the data where the final state X is fully detected in the central detectors so that a precise and independent determination of W is possible.

For the above spatial resolutions, the final resolution on W and photon virtualities is determined by the geometrical beam properties at the IP. In this case, the horizontal displacement due to proton energy loss Δx is smeared by $\sigma_x \lesssim 50\ \mu$m, leading for example to a 5 GeV uncertainty at $W=200$ GeV.

The same reaction, $pp\to ppX$, also occurs in strong interactions, via fusion of two colorless objects, Pomerons, which will interfere with the two-photon fusion. However, this so-called central diffraction usually results in much larger transverse momenta of the scattered protons. The slope b of the distribution $\exp(-bp_T^2)$ is expected to be $b\simeq 4\ \mathrm{GeV}^{-2}$ [6]. The total Pomeron-Pomeron interaction has several orders of magnitude larger cross-sections than the $\gamma\gamma$ case, but for the hard sub-processes the cross-sections are of similar size (see below). Therefore, the measurement of the proton p_T spectrum is vital for extracting the $\gamma\gamma$ signal. Figure 3 shows the true distributions of p_T^2 and those smeared by the beam size and divergence. The two processes are assumed to have the same cross-sections integrated up to $p_T^2=2\ \mathrm{GeV}^2$. In such a case the two-photon signal is clearly visible and can be well extracted. For $p_T^2<0.05\ \mathrm{GeV}^2$ the Pomeron-Pomeron contribution (neglecting interference effects) is about 20%. One should note that for the double tagged events the separation is even clearer since the p_T of each proton can be used independently.

IV. EXAMPLES OF TAGGED TWO-PHOTON PHYSICS

The exclusive $\gamma\gamma$ production of one or two heavy particles, as for example in $\gamma\gamma\to H, t\bar{t}$, or W^+W^- processes, is particularly interesting. These events are clean—two (or one) very forward protons measured far away from the IP and only one or two particles produced and decaying in the central detectors.

In leading order the exclusive production of the Higgs boson involves a diagram in which the photons couple via a fermion loop. The resulting cross section is sensitive to any new fermion state, even significantly beyond the W scale, hence to possible departures from the standard model (SM).

The number N_H of the SM Higgs bosons produced in the two-photon process is given by [7]

$$N_H=\frac{4\pi^2\Gamma_{\gamma\gamma}}{M_H^2}L_{pp}S_{\gamma\gamma}(W=M_H),$$

where L_{pp} is the proton-proton integrated luminosity, M_H is the Higgs boson mass and $\Gamma_{\gamma\gamma}$ is the $H\to\gamma\gamma$ width. Figure 4 shows N_H for an integrated pp luminosity of 30 fb^{-1}. The latter corresponds to three years of the LHC running at medium luminosity. It shows that the double-tagged Higgs boson production is statistically very limited at low M_H values, but the single-tagged production is not negligible for $M_H \geqslant 100$ GeV.

For the same luminosity more than five thousand double-tagged W^+W^- pairs would be exclusively produced at $W>200$ GeV, assuming an asymptotic value of $\sigma_{\gamma\gamma\to WW}\simeq 200$ pb. The corresponding number of the exclusive $t\bar{t}$ pairs is more than one-hundred times smaller. The exclusive W^+W^- production also constitutes an ''irreducible'' background for the events when the Higgs boson decays into W^+W^-. Therefore, for $M_H\gtrsim 200$ GeV the signal $H\to ZZ$ is preferable. Given significant backgrounds and low signal statistics, such two-photon measurements cannot be used for a Higgs boson search, but they will provide an important handle on $\Gamma_{\gamma\gamma}$ at the LHC [8].

The same event topology results from Pomeron-Pomeron interactions. Recent studies [6] show that the Pomeron-Pomeron exclusive Higgs boson production has a similar

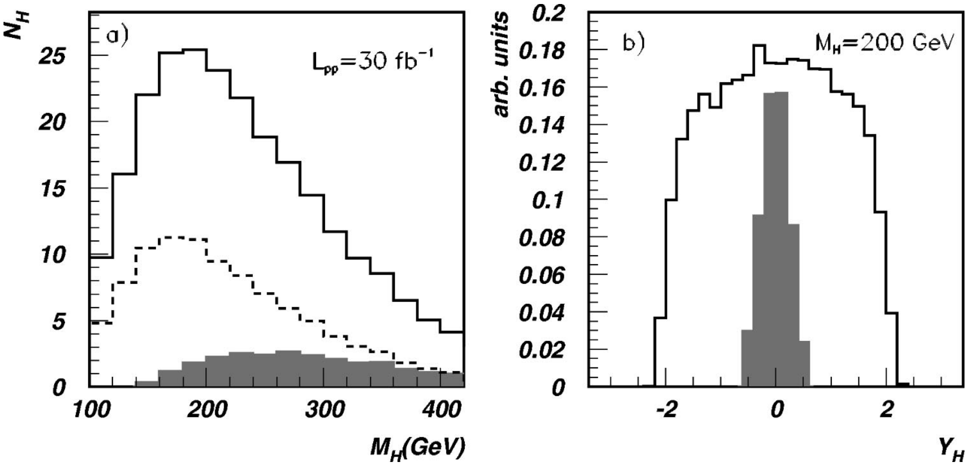

FIG. 4. (a) Number of the SM Higgs boson events as a function of its mass, exclusively produced in $\gamma\gamma$ collisions for the integrated pp luminosity of 30 fb^{-1}, assuming double tags (shaded histograms), and single tags for all (solid line) and only for elastic (dashed line) scattering; (b) rapidity distribution for the tagged Higgs boson production.

cross-section to the two-photon case; therefore the two-photon signal can be statistically extracted using the distributions of the proton p_T. The Pomeron-Pomeron cross-section cannot be reliably predicted due to soft final-state interactions and the associated survival probability. In contrast, provided that Q^2 is not too large, the two-photon cross-section is much less sensitive to these effects [6]. On the other hand, interference between the Pomeron-Pomeron and $\gamma\gamma$ amplitudes might give information about the behavior at energies beyond those available at the LHC.

The photon-photon measurements would also extend the searches for the new physics at the LHC. In particular, search for new particles expected in supersymmetric models would be complementary to a large extent to the corresponding proton-proton studies [9].

Many interesting QCD studies will also be possible, for example measurements of the exclusive production of multi-jets with large transverse energy, or the vector meson and photon production at very high transverse momenta [10].

V. SUMMARY

The initial studies presented in this paper indicate that the installation in the LHC at about 240 m from the IP of recently proposed detectors might permit studies of $\gamma\gamma$ collisions at high energies. The significant luminosity of the tagged photon-photon collisions opens an exciting possibility of studying the exclusive production of the Higgs boson, as well as searches for new phenomena.

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[1] V. M. Budnev *et al.*, Phys. Rep. **15**, 181 (1975).
[2] LHC Conceptual Design Report, CERN/AC/95–05.
[3] TOTEM Collaboration, Technical Proposal, CERN/LHCC/99–07.
[4] ATLAS Collaboration, Technical Design Report, CERN/LHCC/99–01.
[5] A. Faus-Golfe *et al.*, ''Precise measurement of the total cross-section and the Coulomb scattering at the LHC,'' Proceedings of the EPAC2000 Conference at Vienna, p. 352.
[6] V. A. Khoze *et al.*, Eur. Phys. J. C **14**, 525 (2000).
[7] D. L. Borden *et al.*, Phys. Rev. D **48**, 4018 (1993).
[8] E. Papageorgiu, Phys. Lett. B **352**, 394 (1995).
[9] J. Ohnemus *et al.*, Phys. Lett. B **328**, 369 (1994).
[10] N. G. Evanson and J. R. Forshaw, Phys. Rev. D **60**, 034016 (1999).