Observing Light-by-Light Scattering at the Large Hadron Collider

David d'Enterria[1,*] and Gustavo G. da Silveira[2]

[1]Physics Department, CERN, 1211 Geneva, Switzerland

[2]Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium

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Elastic light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) is open to study at the Large Hadron Collider thanks to the large quasireal photon fluxes available in electromagnetic interactions of protons (p) and lead (Pb) ions. The $\gamma\gamma \to \gamma\gamma$ cross sections for diphoton masses $m_{\gamma\gamma} > 5$ GeV amount to 12 fb, 26 pb, and 35 nb in p-p, p-Pb, and Pb-Pb collisions at nucleon-nucleon center-of-mass energies $\sqrt{s_{\rm NN}} = 14$, 8.8, and 5.5 TeV, respectively. Such a measurement has no substantial background in Pb-Pb collisions where one expects about 20 signal events per run, after typical detector acceptance and reconstruction efficiency selections.

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Introduction.—The elastic scattering of two photons in vacuum ($\gamma\gamma \to \gamma\gamma$) is a pure quantum-mechanical process that proceeds at leading order in the fine structure constant, $\mathcal{O}(\alpha^4)$, via virtual one-loop box diagrams containing charged particles (Fig. 1). Although light-by-light (LbyL) scattering via an electron loop has been precisely, albeit indirectly, tested in the measurements of the anomalous magnetic moment of the electron [1] and muon [2], its direct observation in the laboratory still remains elusive today. Out of the two closely related processes—photon scattering in the Coulomb field of a nucleus (Delbrück scattering) [3] and photon splitting in a strong magnetic field ("vacuum" birefringence) [4,5]—only the former has been clearly observed [6]. Several experimental approaches have been proposed to directly detect $\gamma\gamma \to \gamma\gamma$ in the laboratory using, e.g., Compton-backscattered photons against laser photons [7], collisions of photons from microwave wave-guides or cavities [8] or high-power lasers [9,10], as well as at photon colliders [11,12] where energetic photon beams can be obtained by Compton-backscattering laser-light off electron-positron (e^+e^-) beams [13]. Despite its fundamental simplicity, no observation of the process exists so far.

In the present Letter, we investigate the novel possibility of detecting elastic photon-photon scattering using the large (quasireal) photon fluxes of the protons and ions accelerated at TeV energies at the CERN Large Hadron Collider (LHC). In the standard model (SM), the box diagram depicted in Fig. 1 involves charged fermions (leptons and quarks) and boson ($W^\pm$) loops. In extensions of the SM, extra virtual contributions from new heavy charged particles are also possible. Thus, the study of the $\gamma\gamma \to \gamma\gamma$ process—in particular at the high invariant masses reachable at photon colliders—has been proposed as a particularly neat channel to study anomalous gauge-couplings [11,12], new possible contributions from charged supersymmetric partners of SM particles [14], monopoles [15], and unparticles [16], as well as low-scale gravity effects [17,18] and noncommutative interactions [19].

Photon-photon collisions in "ultraperipheral" collisions of proton [20,21] and lead (Pb) beams [22] have been experimentally observed at the LHC [23–27]. All charges accelerated at high energies generate electromagnetic fields which, in the equivalent photon approximation (EPA) [28], can be considered as γ beams [29]. The emitted photons are almost on mass shell, with virtuality $-Q^2 < 1/R^2$, where R is the radius of the charge, i.e., $Q^2 \approx 0.08$ GeV^2 for protons with $R \approx 0.7$ fm, and $Q^2 < 4 \times 10^{-3}$ GeV^2 for nuclei with $R_{\rm A} \approx 1.2A^{1/3}$ fm, for mass number $A > 16$. Naively, the photon-photon luminosities are suppressed by a factor $\alpha^2 \approx 5 \times 10^{-5}$ and only moderately enhanced by logarithmic corrections $\propto \ln^3(\sqrt{s_{\rm NN}})$, compared to the corresponding hadronic beam luminosities. However, since each photon flux scales as the squared charge of the beam, Z^2, $\gamma\gamma$ luminosities are extremely enhanced for ion beams, up to $Z^4 = 5 \times 10^7$ in the case of Pb-Pb collisions. The photon spectra have a typical E_γ^{-1} power-law falloff up to energies of the order of $\omega_{\rm max} \approx \gamma/R$, where $\gamma = \sqrt{s_{\rm NN}}/(2m_{\rm N})$ is the Lorentz relativistic factor of the proton ($m_{\rm N} = 0.9383$ GeV) or ion (with nucleon mass $m_{\rm N} = 0.9315$ GeV), beyond which the photon flux is exponentially suppressed. Although the γ spectrum is harder for smaller charges—which favors proton over nuclear beams in the production of diphoton systems with large invariant masses—the

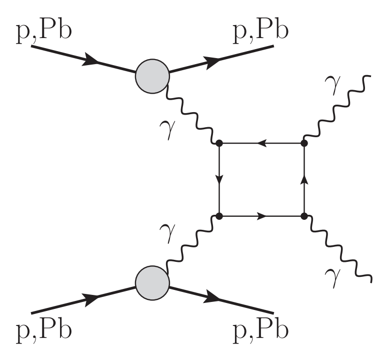

FIG. 1. Schematic diagram of elastic $\gamma\gamma \to \gamma\gamma$ collisions in electromagnetic proton and/or ion interactions at the LHC. The initial-state photons are emitted coherently by the protons and/or nuclei which survive the electromagnetic interaction.

TABLE I. Parameters for the $\gamma\gamma \to \gamma\gamma$ measurement in AB collisions at the LHC: (i) nucleon-nucleon c.m. energy, $\sqrt{s_{\rm NN}}$, (ii) integrated luminosity $\mathcal{L}_{AB} \cdot \Delta t$ (where $\mathcal{L}_{AB}$ are the beam luminosities—for low pileup in the p-p case, see text—and a year is defined as $\Delta t = 10^7$ s for p-p, and 10^6 s for p-Pb and Pb-Pb), (iii) beam Lorentz factor, γ, (iv) effective radius of the (largest) charge, R_A, (v) photon energy tail in the c.m. frame, $\omega_{\rm max}$, (vi) maximum photon-photon c.m. energy, $\sqrt{s_{\gamma\gamma}^{\rm max}}$, (vii) exclusive $\gamma\gamma \to \gamma\gamma$ cross section for diphoton masses above 5 GeV, and (viii) expected number of signal counts per year after selection cuts (see text).

System	$\sqrt{s_{\rm NN}}$ (TeV)	$\mathcal{L}_{AB} \cdot \Delta t$ (per year)	γ	R_A (fm)	$\omega_{\rm max}$ (GeV)	$\sqrt{s_{\gamma\gamma}^{\rm max}}$ (GeV)	$\sigma^{\rm excl}_{\gamma\gamma\to\gamma\gamma}$ [$m_{\gamma\gamma} > 5$ GeV]	$N^{\rm excl}_{\gamma\gamma}$ (per year) [$m_{\gamma\gamma} > 5$ GeV, after cuts]
p-p	14	1 fb^{-1}	7455	0.7	2450	4500	12 ± 1 fb	3
p-Pb	8.8	200 nb^{-1}	4690	7.1	130	260	26 ± 3 pb	2
Pb-Pb	5.5	1 nb^{-1}	2930	7.1	80	160	35 ± 7 nb	18

$\gamma\gamma \to \gamma\gamma$ cross section decreases rapidly, as the square of the c.m. energy $\sim s_{\gamma\gamma}^{-1}$ from its peak at $\sqrt{s_{\gamma\gamma}} \approx 3m_e$ [30], which favors the comparatively softer Pb photon beams for the observation of LbyL scattering. In Table I, we summarize the most relevant parameters for ultraperipheral p-p, p-Pb, and Pb-Pb collisions at the LHC [22,31].

The final-state signature of interest here is the exclusive production of two photons, $AB \xrightarrow{\gamma\gamma} A\gamma\gamma B$ where the diphoton final-state is measured in the central detector, and the incoming hadrons $A, B = p,$ Pb survive the electromagnetic interaction and are scattered at very low angles with respect to the beam. The very same final-state can be mediated by the strong interaction through a quark loop in the exchange of two gluons in a color-singlet state, $AB \xrightarrow{gg} A\gamma\gamma B$ [32]. Such "central exclusive production" (CEP), observed in p$\bar{\rm p}$ collisions at Tevatron [33] and searched for at the LHC [24], constitutes an important background for the $\gamma\gamma \to \gamma\gamma$ measurement in p-p but not for Pb-Pb collisions as discussed later.

Theoretical setup.—The elastic $\gamma\gamma$ production cross section via photon-photon fusion in the collision of hadrons A and B factorizes into the product of the elementary cross section for $\gamma\gamma \to \gamma\gamma$ at $\sqrt{s_{\gamma\gamma}}$, convoluted with the EPA spectra from the two colliding beams:

$$\sigma^{\rm excl}_{\gamma\gamma\to\gamma\gamma} = \sigma(AB \xrightarrow{\gamma\gamma} A\gamma\gamma B) = \int d\omega_1 d\omega_2 \frac{f_{\gamma/A}(\omega_1)}{\omega_1} \frac{f_{\gamma/B}(\omega_2)}{\omega_2} \sigma_{\gamma\gamma\to\gamma\gamma}\left(\sqrt{s_{\gamma\gamma}}\right), \tag{1}$$

where ω_1 and ω_2 are the two photon energies, and $f_{A,B}(\omega)$ are the photon fluxes at energy ω emitted by the hadrons A and B. The photon energies determine the rapidity y of the produced system $y = 0.5 \ln(\omega_1/\omega_2)$ and the c.m. energy $\sqrt{s_{\gamma\gamma}} = m_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$ which, for symmetric systems, is maximal at $y = 0$ when $\omega_1^{\rm max} = \omega_2^{\rm max} \approx \gamma/b_{\rm min}$ with $b_{\rm min}$ the minimum separation between the two charges of radius $R_{A,B}$. We use the proton γ–spectrum obtained from its elastic form factor [34] and, for the ion γ–spectrum, the impact-parameter dependent expression integrated from $b_{\rm min}$ to infinity [35] with the requirement $b_{\rm min} = R_{A,B}$ plus a correction equivalent to the geometrical condition $|\vec{b}_1 - \vec{b}_2| > R_A + R_B$ [36] to ensure that all collisions occur without hadronic overlap and breakup of the colliding beams. Propagated uncertainties to the final cross sections are of order $\pm 10\%$ ($\pm$ 20%) for p-p and p-Pb (Pb-Pb) collisions, covering different form-factor parametrizations and the convolution of the nuclear photon fluxes.

We use the MADGRAPH v.5 Monte Carlo (MC) [37] framework to implement the elastic p and Pb photon fluxes, the leading-order expression for the $\sigma_{\gamma\gamma\to\gamma\gamma}$ cross section [30] including all quark and lepton loops, and the running of α. We omit the $W^\pm$ contributions which are only important for diphoton masses $m_{\gamma\gamma} \gtrsim 2m_W$. Inclusion of next-to-leading-order QCD and QED corrections increases $\sigma_{\gamma\gamma\to\gamma\gamma}$ by a few percent [30], but taking into account a gap survival factor of $\hat{S}^2 = 0.9$–1.0—encoding the probability to produce fully exclusively the diphoton system without any other hadronic activity from soft rescatterings between the colliding hadrons [32]—would reduce the yields by about the same amount.

Results.—Our $\gamma\gamma \to \gamma\gamma$ calculations are carried out for a minimum diphoton mass $m_{\gamma\gamma} = 5$ GeV. Such a choice is driven by three considerations. First, the final state lies in the continuum region above the range where contributions from two-photon decays from exclusively produced hadronic resonances dominate—the p-wave scalar and tensor charmonium states $\chi_{\rm c0,c2}$ at masses 3.4–3.9 GeV are the heaviest particles with an observed $\gamma\gamma$ decay [38] before the Higgs boson (the $\chi_{\rm b0,b2}$ at around 10 GeV should also have a diphoton decay but it has not been observed so far). Second, experimentally, one needs a signal of a few GeV in the calorimeters in order to reliably trigger the acquisition of the event above noise and avoiding exclusive final-states with softer photons from decays of lower-mass hadrons (π^0, η, $K^0_s, \ldots$) with much larger cross sections. Third, the $\gamma\gamma$ cross section for diphoton masses below 5 GeV has larger theoretical uncertainties as the hadronic LbyL contributions are computed less reliably by the quark boxes [30]. Using the theoretical setup described in the previous section, we obtain the values of $\sigma^{\rm excl}_{\gamma\gamma\to\gamma\gamma}[m_{\gamma\gamma} > 5$ GeV] at the LHC listed in Table I. In Fig. 2 (left), we show the predictions for the three systems in a wider range of c.m. energies, $\sqrt{s_{\rm NN}} = 1$–20 TeV. The cross sections are in the 10 fb range for p-p collisions, few tens of pb for p-Pb, and few tens of nb for Pb-Pb, clearly showing the importance

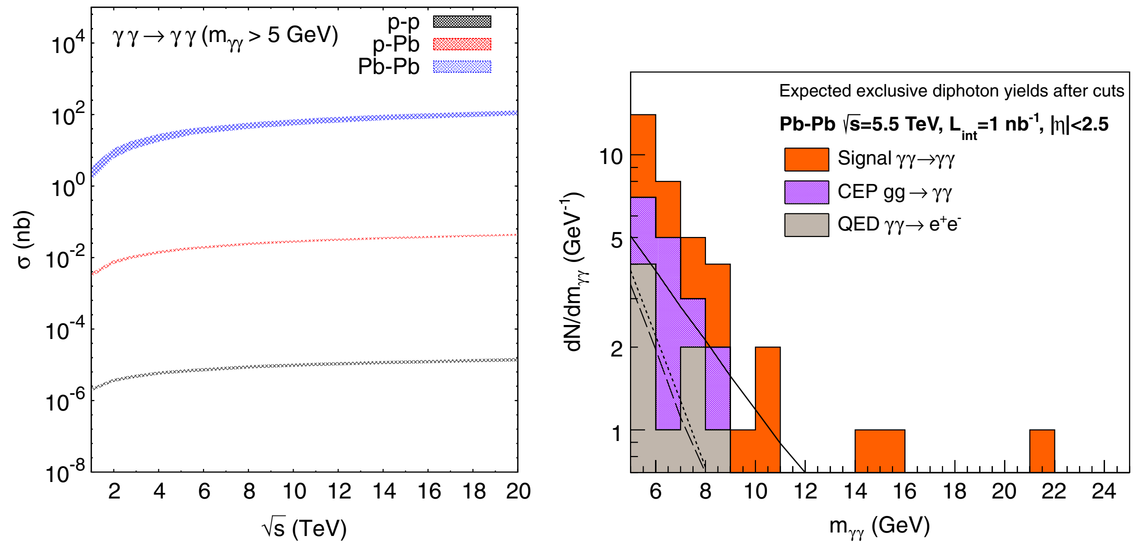

FIG. 2 (color online). Left: Cross sections for exclusive $\gamma\gamma \to \gamma\gamma$, with pair masses above 5 GeV, in ultraperipheral Pb-Pb (top curve), p-Pb (middle) and p-p (bottom) collisions as a function of the nucleon-nucleon c.m. energy in the range $\sqrt{s_{\rm NN}} =$ 1–20 TeV. Right: Stacked diphoton yields as a function of invariant mass for elastic $\gamma\gamma$ and backgrounds (CEP $\gamma\gamma$ and QED e^+e^-) expected in 1 nb^{-1} Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV after analysis cuts (see text). The three superimposed curves indicate the underlying individual LbyL, CEP, and QED distributions.

of the Z^2 single photon-flux enhancement factor for ions compared to protons. Our p-p result at 14 TeV is consistent with the one obtained in [32], whereas those for p-Pb and Pb-Pb are calculated in this Letter for the first time.

Realistic estimates of the detectable number of $\gamma\gamma \to \gamma\gamma$ events at the LHC can be obtained by considering the luminosity for each colliding system, geometric acceptance of the detectors, experimental efficiencies, possible instrumental biases, and potential backgrounds. We focus on the ATLAS [39] and CMS [40] experiments which feature photon detection capabilities with tracking and calorimetry over 5 units of pseudorapidity ($|\eta| < 2.5$), plus forward detectors (up to at least $|\eta| = 5$) needed to tag rapidity gaps on both sides of the central diphoton system, and zero-degree calorimeters (ZDC) to veto very-forward-going neutral fragments in ion collisions which help to further reduce backgrounds (see below). Unfortunately, one cannot use the existing TOTEM [41] and ALFA [42] Roman Pots to tag the electromagnetically scattered protons because their acceptance below $m_{\gamma\gamma} \approx 200$ GeV is very small. (Proposed future proton spectrometers at ± 420 m [43] have a better acceptance for the lower diphoton masses of interest here.) The narrower single-photon acceptances of ALICE ($|\eta| \lesssim 0.9$) and LHCb ($\eta \approx 2$–5) would reduce the visible diphoton rates by at least a factor of four.

In order to carry out the measurement one needs beam luminosities which minimize the number of simultaneous collisions per bunch crossing ("pileup") so as to keep the rapidity gaps in both hemispheres adjacent to the central diphoton system free of hadronic activity from overlapping collisions. The p-Pb and Pb-Pb luminosities are low enough to keep the pileup well below one, and one can take their full expected integrated luminosity per run (Table I) as usable for the measurement. In the p-p case, the average pileup is as high as 30 and, thus, we will indicatively consider that only 1% of the nominal 100 fb^{-1}/year can be collected under low pileup conditions. In such scenarios, one can easily record $\gamma\gamma \to \gamma\gamma$ events with an $\varepsilon_{\rm trig} \approx 100\%$ efficient trigger based on two back-to-back photons in the central detector with at least one of them above, e.g., 2 GeV plus a large rapidity gap $\Delta\eta \gtrsim 2.5$, as done e.g., in [24]. We use the MADGRAPH MC code to generate elastic $\gamma\gamma$ scattering events and simulate the effect of the ATLAS and CMS geometrical acceptance. The requirement to have both photons within $|\eta| < 2.5$, reduces the yield by $\varepsilon_{\rm acc} \approx 0.5$ in p-p and p-Pb collisions, but only by $\varepsilon_{\rm acc} \approx 0.85$ in the Pb-Pb case where the photon fluxes are softer and the diphoton system is produced at more central rapidities. We further consider typical off-line photon reconstruction and identification efficiencies of order $\varepsilon_{{\rm rec,id}\gamma} \approx 0.8$ in the energy range of interest [24]. The final combined signal efficiency is $\varepsilon_{pp,p{\rm Pb}\to\gamma\gamma} = \varepsilon_{\rm trig} \cdot \varepsilon_{\rm acc} \cdot \varepsilon^2_{{\rm rec,id}\gamma} \approx 0.3$ for p-p and p-Pb and $\varepsilon_{\rm PbPb\to\gamma\gamma} \approx$ 0.55 for Pb-Pb. The number of events expected per year in ultraperipheral collisions at the LHC obtained from the product $N^{\rm excl}_{\gamma\gamma} = \varepsilon_{\gamma\gamma} \cdot \sigma^{\rm excl}_{\gamma\gamma} \cdot \mathcal{L}_{AB} \cdot \Delta t$, are listed in Table I. Clearly, the Pb-Pb system provides the best signal counting rates, with associated statistical uncertainties of order $\pm({\rm N}^{\rm excl}_{\gamma\gamma})^{1/2}$, i.e., $\pm 20\%$. The expected diphoton mass distribution for the elastic $\gamma\gamma \to \gamma\gamma$ signal, taking into account acceptance and efficiency losses, normalized by the expected integrated luminosity in one Pb-Pb run is shown in Fig. 2 (right) compared to the two main residual backgrounds (see below).

Backgrounds.—The central exclusive $\gamma\gamma$ measurements [24,33] confirm that standard off-line event selection criteria: (i) just two isolated photons within $|\eta| < 2.5$ with reconstructed invariant mass $m_{\gamma\gamma} > 5$ GeV, (ii) no other charged-particle activity associated with the interaction vertex, plus (iii) no other hadronic activity in the event above detector noise over $|\eta| < 5$; reduce to a negligible level any hadronic interaction except CEP and diffractive Pomeron-induced ($\mathbb{P}\mathbb{P}$, or $\gamma\mathbb{P}$) final states containing two photons plus rapidity gaps. As a matter of fact, for the p-p case in the range of $m_{\gamma\gamma}$ considered here, the LbyL signal is swamped by the CEP $gg \to \gamma\gamma$ cross section which scales with the fourth power of the gluon density and is 2–3 orders of magnitude larger than the former [32]. Using the SUPERCHIC (version 1.41) MC program [44], we obtain a cross section after acceptance cuts of $\sigma^{\rm CEP}_{gg\to\gamma\gamma} = 20^{\times 3}_{\times 1/3}$ pb, where the uncertainties include the choice of the parton distribution function (PDF) and $\hat{S}^2$ survival factor. Exclusive $\pi^0\pi^0$ or $\eta(')\eta(')$ production, decaying into multiphoton final states, can also be a potential background to the diphoton signal. These processes have cross sections $\mathcal{O}$(1–100 pb), but taking into account their γ branching ratios and acceptance plus $m_{\gamma\gamma}$ cuts results in a negligible final contribution compared to CEP $\gamma\gamma$ [45].

Various features can be used to separate $\gamma\gamma$ fusion from CEP and, in general, $\mathbb{P}$-mediated events. Whereas systems from quasireal photon fusion are produced almost at rest and, thus, the final-state photons are emitted back-to-back with balanced pair transverse momentum ($p_{\rm T}^{\gamma\gamma} \approx 0$, smeared by the experimental resolution), typical CEP photon pairs peak instead at $p_{\rm T}^{\gamma\gamma} \approx 0.5$ GeV and have moderate tails in their azimuthal acoplanarity $\Delta\phi_{\gamma\gamma}$. Central exclusive $\gamma\gamma$ production is the least reducible of all potential backgrounds as other diffractive and γ-induced final states with photons have larger $p_{\rm T}^{\gamma\gamma}$ and diphoton acoplanarities. By imposing very tight cuts in the pair momentum, $p_{\rm T}^{\gamma\gamma} \lesssim 0.1$ GeV and acoplanarity $\Delta\phi_{\gamma\gamma} - \pi \lesssim 0.04$ in our MADGRAPH and SUPERCHIC samples, we find that CEP $\gamma\gamma$ can be reduced by a factor of about 35 while only about 30% of the elastic $\gamma\gamma$ signal events are lost. However, the resulting LbyL/CEP ratio of order 50 is still too large to make feasible the LbyL observation with proton beams. The situation is more advantageous for p-Pb collisions where LbyL is only about 60 times smaller than CEP, as obtained scaling by $A = 208$ the p-p cross section at 8.8 TeV, $\sigma^{\rm CEP}_{gg\to\gamma\gamma} = 16^{\times 3}_{\times 1/3}$ pb, multiplied by the square of the Pb gluon shadowing ($R_g^{\rm Pb/p} \approx 0.7$, according to the EPS09 nuclear PDF [46] in the relevant range of gluon fractional momenta $x \approx 5 \times 10^{-4}$ and virtualities $Q^2 \approx 5$ GeV^2). A final LbyL/CEP ratio of order one is reachable applying the aforementioned $p_{\rm T}^{\gamma\gamma}$ and $\Delta\phi_{\gamma\gamma}$ cuts. Yet, given the low p-Pb event rates expected (Table I), a potential observation of LbyL scattering would require a tenfold increment of the integrated luminosity (which can be achieved increasing the p-beam intensity from its conservative default value [47]) and a careful control of the CEP background.

In terms of backgrounds, the situation is much more favorable in the Pb-Pb case where hard parton-mediated exclusive or diffractive cross sections (which scale as A^2 compared to p-p) play a comparatively much smaller role than in p-p thanks to the Z^4 enhancement of electromagnetic interactions. In addition, since the nucleus is a fragile object—the nucleon binding energy is just 8 MeV—even the softest CEP or $\mathbb{P}$-mediated interactions will result in the emission of a few nucleons from the ion, detectable in the ZDCs. Thus, studying the activity in the ZDCs can additionally help reduce any residual diffractive background. The Pb-Pb CEP cross section—as obtained by A^2 scaling the $\sigma^{\rm CEP}_{gg\to\gamma\gamma} = 13^{\times 2.5}_{\times 0.4}$ pb cross section in p-p at 5.5 TeV times the fourth power of the Pb gluon shadowing—is about four times $\sigma^{\rm excl}_{\gamma\gamma\to\gamma\gamma}$. Adding a simple $p_{\rm T}^{\gamma\gamma} < 0.2$ GeV condition, reduces the CEP background by 90% without removing any signal event. Other electromagnetic processes similarly enhanced by the Z^4 factor can, notwithstanding, constitute a potential concern if the final-state particles are misidentified as photons. Exclusive $\gamma\gamma \to e^+e^-$ events can be misidentified if neither electron track is reconstructed or if both electrons undergo hard bremsstrahlung. (Fake diphoton signals from other QED processes such as $\gamma\gamma \to \mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$ are much smaller as their final states include charged particles in the tracker and/or muon spectrometer.) Experimental studies indicate single-electron misidentification probabilities as low as $f_{e\to\gamma} \approx 0.5\%$ [48], which can be experimentally confirmed by imposing increasingly stringent photon identification cuts and observing the disappearance of the fake diphoton peak from exclusive $\Upsilon \to e^+e^-$ photoproduction [49]. Thus, the very large QED cross section in Pb-Pb, $\sigma^{\rm excl}_{\gamma\gamma\to e^+e^-}[m_{ee} > 5\ {\rm GeV}] \approx 5$ mb according to STARLIGHT [50]—reduced first by a factor of 10 when requiring both e^+ and e^- within the central acceptance [49] and second by the extra $f^2_{e\to\gamma}$ factor—results in a residual e^+e^- contamination of the order of 30% of the visible LbyL cross section. Additional (e.g., acollinearity) cuts [47] could be applied to remove any remaining QED difermion continuum (notably $\gamma\gamma \to q\bar{q} \to \pi^0\pi^0$) with very small signal loss. Figure 2 (right) shows the dominant CEP and QED backgrounds, expected after cuts in one Pb-Pb run, compared to the LbyL signal as a function of the diphoton mass. Both contaminations are softer than the signal and their total sum does not exceed the LbyL yields.

Summary.—Despite its fundamental simplicity, no direct experimental observation of light-by-light scattering exists so far. We have shown that elastic photon-photon scattering can be potentially observed at the LHC using the large (quasireal) photon fluxes in electromagnetic interactions of protons and ions accelerated at TeV energies. The $\gamma\gamma \to \gamma\gamma$ cross sections for diphoton masses in the continuum range above $m_{\gamma\gamma} = 5$ GeV are 12 fb for p-p, 26 pb for p-Pb, and 35 nb for Pb-Pb at the nominal c.m. energies, clearly showing the importance of the Z^4 enhancement of the photon fluxes in ion-ion collisions. The number of exclusive $\gamma\gamma \to \gamma\gamma$ events expected in ATLAS and CMS have been obtained taking into account realistic integrated luminosities and γ acceptance and efficiency cuts. In the p-p case, the dominant background due to exclusive gluon-induced production can be reduced imposing cuts on the pair p_T and acoplanarity but unfortunately not to a level where the signal can be observed. The signal/background ratio is better in the p-Pb case, but the small expected number of events makes the measurement of the light-by-light signal challenging without (reachable) luminosity increases. An unambiguous observation of the process is possible in Pb-Pb collisions which provide $N_{\gamma\gamma}^{excl} \approx 20$ elastic photon pairs per run after cuts, with controllable backgrounds. The unique measurement of elastic $\gamma\gamma$ scattering at the LHC will not only constitute the first experimental observation of a fundamental quantum mechanical process but may be sensitive to new-physics effects predicted in various extensions of the SM.

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*david.d'enterria@cern.ch

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