

## Improved modeling of photon-photon processes in ultraperipheral collisions at hadron colliders

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The CERN LHC is not only the current energy-frontier collider for parton-parton collisions, but has proven a powerful photon collider providing photon-photon ( $\gamma\gamma$ ) collisions at center-of-mass energies and luminosities never reached before. The latest theoretical developments implemented in the gamma-UPC Monte Carlo (MC) event generator [1], which can calculate arbitrary exclusive final state produced via  $\gamma\gamma$  fusion in ultraperipheral collisions (UPCs) of protons and/or nuclei at the LHC, are presented. These include azimuthal modulations of dilepton pairs produced in the  $\gamma\gamma \rightarrow \ell^+\ell^-$  process, and neutron emission probabilities for photoexcited lead ions in PbPb UPCs. A few comparisons of the results of the updated gamma-UPC v.1.6 code to relevant RHIC and LHC data are presented.

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## 1. Introduction

Over the past decade, the CERN Large Hadron Collider (LHC) has been accelerating hadrons to achieve collisions at unprecedented nucleon-nucleon c.m. energies (up to  $\sqrt{s_{\text{NN}}} = 13.6$  TeV) and integrated luminosities (several hundred  $\text{fb}^{-1}$  per year). Beyond the unique studies of hadronic collisions conducted since 2010, the LHC has also studied photon-photon ( $\gamma\gamma$ ) collisions at an hitherto unexplored kinematic regime by exploiting the large fluxes of quasireal photons emitted by the accelerated hadrons [2, 3]. Such  $\gamma\gamma$  processes can be studied in particularly clean conditions in the so-called ultraperipheral collisions (UPCs) where the colliding hadrons interact with transverse separations larger than their matter radii, i.e. without hadronic overlap, and survive their purely electromagnetic interaction [4]. The phenomenological study of  $\gamma\gamma$  collisions in UPCs has been significantly facilitated with the recent development of the gamma-UPC code [1], which allows the automated computation of arbitrary  $\gamma\gamma \rightarrow X$  processes (including Standard Model, and beyond, final states), in combination with the MADGRAPH5\_AMC@NLO (MG5\_AMC hereafter) [5] or HELAC-ONIA [6, 7] event generators. Using gamma-UPC, photon-fusion processes have been calculated for the first time up to next-to-leading-order (NLO) accuracy in quantum electrodynamics (QED) and/or quantum chromodynamics (QCD) [1, 8–10]. In these proceedings, we present additional extensions of the gamma-UPC code including the effect of the polarization state of the colliding quasireal photons on the azimuthal modulation of dileptons produced in the  $\gamma\gamma \rightarrow \ell^+\ell^-$  process, as well as the probabilities for photoexcitation and subsequent neutron emission of the Pb ions in UPCs at the LHC. Both developments, plus others (gamma-UPC v.1.6<sup>1</sup>), will be presented in detail elsewhere [11].

## 2. Azimuthal modulation in UPC lepton pair production

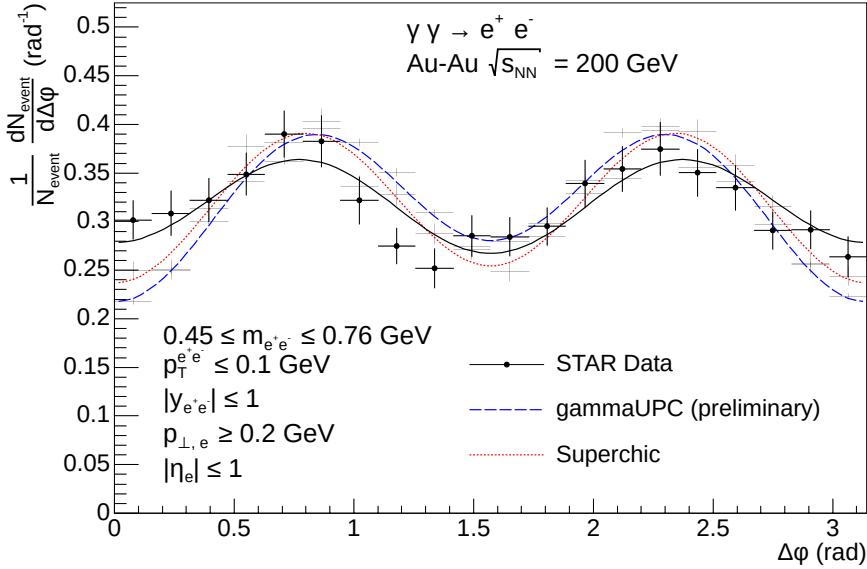
In UPCs, the electric field associated with a charge accelerated at high energies vibrates in a single, straight-line direction. This implies that its associated quasireal photon flux, in the equivalent photon approximation (EPA) [12, 13], is linearly polarized. One particularly clean way to probe the polarization of photons in UPCs is studying the azimuthal angle distribution of dileptons produced in  $\gamma\gamma \rightarrow \ell^+\ell^-$  processes [14]. The differential cross section with respect to the angle  $\Delta\varphi$  between  $\mathbf{q}_\perp = \mathbf{k}_{1\perp} + \mathbf{k}_{2\perp}$  and  $\mathbf{P}_\perp = \frac{\mathbf{k}_{1\perp} - \mathbf{k}_{2\perp}}{2}$ , where  $\mathbf{k}_{1\perp}$  and  $\mathbf{k}_{2\perp}$  are the transverse momentum of produced leptons, can be decomposed into three terms:

$$\frac{d\sigma}{d\Delta\varphi} \propto A + B \cos(2\Delta\varphi) + C \cos(4\Delta\varphi), \quad (1)$$

where  $A$ ,  $B$ , and  $C$  are coefficients ( $\text{GeV}^{-2}$  units) that can be derived from convolutions of the photon transverse-momentum distribution (TMD) [15] (cf. Eqs. (4–6) therein). So far, the combination of gamma-UPC with MG5\_AMC or HELAC-ONIA operates within the collinear factorization approach, and the azimuthal modulation represented by Eq. (1), properly accounted for by TMD factorization, is absent. In order to restore the full transverse-momentum dependencies of the photon fluxes, our gamma-UPC setup incorporates small extra transverse momentum  $k_\perp$  and azimuthal angle  $\varphi$  “smearings” of the initial photons in events generated within the collinear factorization MC setup.

<sup>1</sup>Code downloadable from: <http://cern.ch/hshao/gammaupc.html>

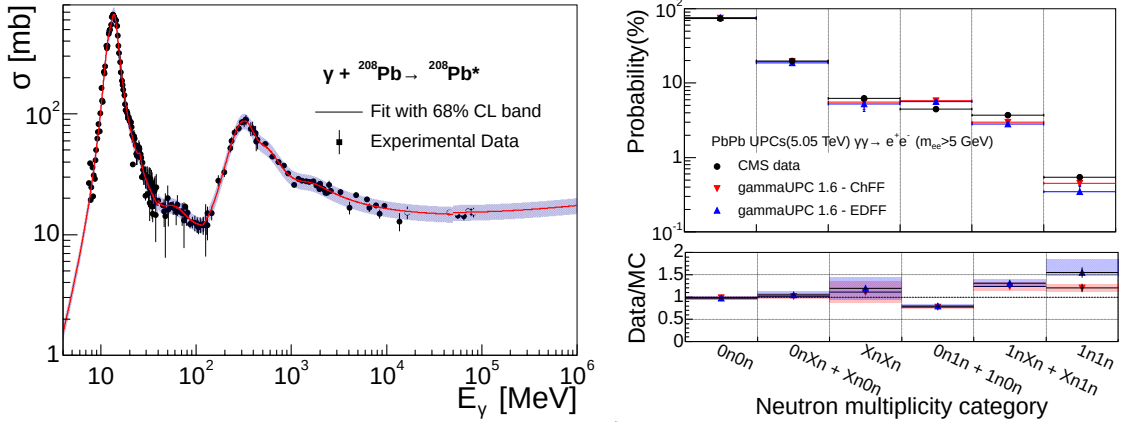
The implementation of the  $k_{\perp}$  smearing alone has been described in Ref. [10]. In these proceedings, we report the new implementation of the simultaneous  $k_{\perp}$  and  $\varphi$  smearing in the gamma-UPC framework. The photon TMD coefficients given by Eq. (1) have been incorporated into our setup through a smearing of the initial and final states performed by running a `python` script on the MC output Les Houches (LHE) file that modifies the kinematics of external particles in each event. This implementation has been tested by simulating  $\gamma\gamma \rightarrow e^+e^-$  events in Au-Au UPCs at  $\sqrt{s_{NN}} = 200$  GeV within the fiducial cuts corresponding to the measurement of the STAR collaboration [16]:  $m_{e^+e^-} \in [0.45, 2.6]$  GeV,  $p_T^{e^+e^-} \leq 0.1$  GeV,  $|y_{e^+e^-}| \leq 1$ ,  $p_{\perp,e} \geq 0.2$  GeV, and  $|\eta_e| \leq 1$ . Our preliminary result (blue dashed curve) is shown in Figure 1 compared to the azimuthal modulation measured in the experimental data (black symbols), and to the alternative prediction from the SUPERCHIC model (red dotted curve) [17]. Within uncertainties, both MC predictions can reproduce the modulation observed in data, thereby confirming the linearly polarized nature of the incoming photons.



**Figure 1:** Normalized dielectron  $dN/d\Delta\varphi$  distributions for  $\gamma\gamma \rightarrow e^+e^-$  events in Au-Au UPCs at  $\sqrt{s_{NN}} = 200$  GeV, with the kinematics cuts listed. The STAR data (points) [16] are compared to our predictions (blue dashed curve) and that of SUPERCHIC (red dotted curve).

### 3. Coulomb excitation and neutron emission in UPCs with Pb ions

The second improvement implemented into the gamma-UPC code is the calculation of the photoexcitation probability of the nuclei in UPCs, due to soft Coulomb photon exchanges between them taking place simultaneously with the hard  $\gamma\gamma$  reaction, and their subsequent deexcitation via neutron emission [4]. The neutron(s) emitted from the excited nuclei in UPCs can be detected in very forward (zero-degree) calorimeters, and thereby are commonly used by the experiments to trigger on photon-photon interactions. The most straightforward way to implement such processes is by adding a probability to emit  $X$  and  $Y$  neutrons by the photoexcited nuclei A and B (separated by



**Figure 2:** Left: Experimental Pb photoabsorption cross sections as a function of photon energy,  $\sigma_{\gamma\text{Pb}\rightarrow\text{Pb}^*}(E_\gamma)$ , fitted to our parametrization (red curve with violet band uncertainties). Right: Probability for different neutron emission categories in the  $\gamma\gamma \rightarrow e^+e^-$  process measured by CMS in PbPb UPCs at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV [27] compared to our predictions with ChFF and EDFF  $\gamma$  fluxes (the bottom panel shows the data/gamma-UPC ratio).

an impact parameter separation  $|\mathbf{b}_1 - \mathbf{b}_2|$ ,  $P_{X_n Y_n}(|\mathbf{b}_1 - \mathbf{b}_2|)$ , that multiplies the no-inelastic hadronic interaction probability,  $P_{\text{no inel}}(|\mathbf{b}_1 - \mathbf{b}_2|)$ , inside the convolution integral of the two photon fluxes:

$$\frac{d^2 N_{\gamma_1/Z_1, \gamma_2/Z_2}^{(\text{AB}, X_n Y_n)}}{dE_{\gamma_1} dE_{\gamma_2}} = \int d^2 \mathbf{b}_1 d^2 \mathbf{b}_2 P_{X_n Y_n}(|\mathbf{b}_1 - \mathbf{b}_2|) P_{\text{no inel}}(|\mathbf{b}_1 - \mathbf{b}_2|) N_{\gamma_1/Z_1}(E_{\gamma_1}, \mathbf{b}_1) N_{\gamma_2/Z_2}(E_{\gamma_2}, \mathbf{b}_2).$$

The probability term is determined from the experimentally measured values of photoabsorption cross sections followed by neutron emission,  $\sigma(\gamma\text{Pb} \rightarrow \text{Pb}^* \rightarrow \text{Pb} + X_n)$  with  $X \geq 1$ . We have fit the individual cross sections measured in photon-lead interactions for various neutron multiplicities (1n, 2n, 3n, 4n,  $\dots$ , and their sum), as a function of the incoming photon energy  $E_\gamma$  from threshold (a few MeV) up to 16.4 GeV [18–23]. Beyond this energy, since few data points are available [24], we follow the approach used by other MC generators, such as nOON [25] and SUPERCHIC [17], and use a Regge-based parameterization of the total photoabsorption cross sections of the proton at high energy [26], scaled by the nuclear mass number  $A = 208$  times a shadowing factor of 0.65 so that the resulting fit matches the high energy Pb photodissociation data [24]. Figure 2 (left) shows the collected experimental photoabsorption cross sections (black points) with our fit results and assigned uncertainties (red curve with violet band).

With the corresponding neutron deexcitation probabilities implemented in gamma-UPC as explained above, we can now compare our predictions to the experimental data measured in PbPb UPCs at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The results are shown in Figure 2 (right) for various neutron emission probabilities (0n0n, 1n1n, XnXn and combinations, where  $X \geq 1$  here) in the  $\gamma\gamma \rightarrow e^+e^-$  ( $m_{e^+e^-} > 5$  GeV) process, obtained using two different  $\gamma$  fluxes (based on the charged (ChFF) and electric dipole (EDFF) form factors) compared to the corresponding CMS data [27]. Our ChFF-based results (within the assigned theoretical uncertainties) reproduce well the experimental data as indicated by a data/gamma-UPC ratio around unity (red symbols in the bottom panel).

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