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Conference Report

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Exclusive Photoproduction of Upsilon and lepton pairs in Pb-Pb at 5.5 TeV

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Abstract

Electromagnetic interactions of heavy-ions give access to a unique programme of photon-induced studies in the QCD and QED sectors of the Standard Model. On the one hand, exclusive photoproduction of bottomonium ($\gamma\,A\;\rightarrow\;\Upsilon\,A$, where the nucleus A remains intact) offers a useful means to constrain the small-x nuclear gluon density. On the other, two-photon exclusive dilepton production ($\gamma\,\gamma\;\rightarrow\;l^+\,l^-$) allows us to study QED at field-strengths close or above the Schwinger limit ($E_{\rm crit}\approx 1.5\times 10^{16}$ V/cm). We present full simulation studies of exclusively photo-produced Υ and high-mass dileptons in Pb-Pb collisions at the LHC.

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1 Introduction

All charges accelerated at very high energies generate electromagnetic fields which, in the equivalent photon approximation [1], can be considered as (quasi-real) photon beams. A significant fraction of the p-p [2] and Pb-Pb [3] collisions at the LHC will involve photon interactions at TeV energies giving access to a unique programme of γ-induced studies. In the heavy-ion running mode, the strong electromagnetic field due to the coherent action of the $Z = 82$ TeV-energy proton charges generates a flux of photons with energies and intensities much larger than those of equivalent e-p collisions at HERA. Lead beams at 2.75 TeV have Lorentz factors $\gamma = 2930$ leading to maximum photon energies $\omega_{max} \approx \gamma/R \sim 80$ GeV. These photons can then collide either with the other incoming 2.75 TeV/nucleon nucleus at center-of-mass energies up to $W^{max}_{\gamma Pb} \approx 1$ TeV/nucleon, or they can interact with another similarly radiated photon leading to photon-photon collisions at $W^{max}_{\gamma\gamma} \approx 160$ GeV.

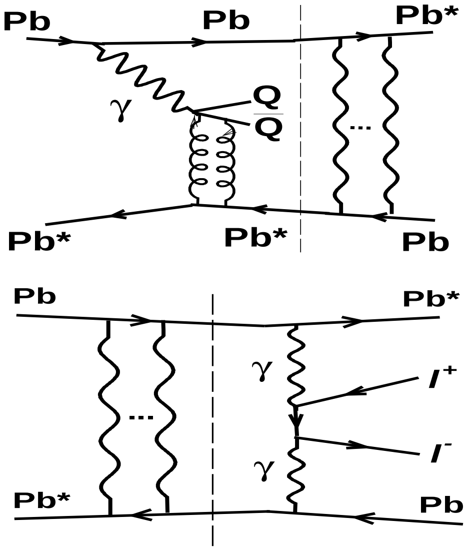

Figure 1: Diagrams for exclusive photo-production of (i) diffractive quarkonium in γA collisions (top), and (ii) dileptons in two-photon interactions (bottom) in ultra-peripheral Pb-Pb at the LHC. The dashed vertical lines separate soft Pb-Pb photon exchanges from the "harder" γ-induced interaction.

We discuss here the possibilities of the CMS experiment to study (i) the low-x regime of the nuclear parton distribution functions (PDFs) via exclusive quarkonium photoproduction (Fig. 1, top), and (ii) QED in the "non-perturbative" (high-field) regime via high-mass exclusive dilepton production (Fig. 1, bottom) in ultraperipheral collisions (UPCs) of lead ions.

2 Low-x nuclear PDFs via Υ photoproduction in Pb-Pb at the LHC

The gluon density, $xG(x,Q^2)$, at small fractional momenta $x = p_{parton}/p_{proton} \lesssim 0.01$ and low, yet perturbative, Q^2 is a subject of intensive experimental and theoretical activity [4]. On the one hand, DGLAP analyses based on DIS e-p data cannot reliably determine xG as it is only indirectly constrained by the $\log(Q^2)$ dependence of the *quark* distributions (F_2 scaling violations). On the other, there are well funded theoretical arguments [5] that support the inapplicability of DGLAP- or BFKL-type evolution equations at low enough values of x, due to the increasing importance of gluon-gluon fusion processes, unaccounted for in such linear-QCD approaches. Alternatively, the low-x "parton saturation" regime can be well described theoretically within the Color-Glass-Condensate [6] or "black-disk limit" [7] framework.

Our knowledge of the low-x gluon distribution in the *nucleus* is even more scarce [8]. Nuclear DIS data only cover the range above $x \approx 10^{-2}$ (Fig. 2), and gluon saturation effects are expected to be much larger in nuclei than in the proton due to their larger transverse parton density. Exclusive $Q\bar{Q}$ photoproduction offers an attractive opportunity to constrain the low-x gluon density at moderate virtualities, since in such processes the gluon couples *directly* to the c or b quarks (see Fig. 1, top) and the cross section is proportional to the gluon density *squared* (see [9] and refs. therein). The mass of the $Q\bar{Q}$ vector meson introduces a relatively large scale, amenable to a perturbative QCD (pQCD) treatment.

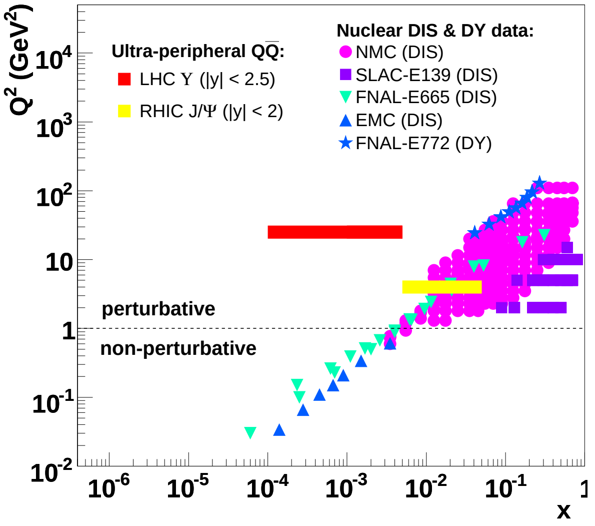

Figure 2: Kinematic (x, Q^2) plane probed in e-,γ-A collisions: existing nuclear DIS data compared to ultraperipheral $Q\bar{Q}$ photoproduction ranges.

At the LHC, $\gamma A \rightarrow J/\psi(\Upsilon)A$ processes, probe the gluon distribution at values (Fig. 2) as low as $x = M_V^2/W_{\gamma A}^2 \approx 10^{-2}(10^{-4})$. Gluon saturation effects are expected to reveal themselves through strong suppression of hard exclusive diffraction yields relative to the leading-twist approximation [7]. While this suppression may be beyond the kinematics achievable for J/ψ photoproduction in UPCs at RHIC ($x \approx 0.01$ and $Q^2_{\rm eff} \approx M_V^2/4 \approx 3$ GeV^2) [10], it could be important in UPCs at the LHC [3].

Table 1: Cross sections predicted by the STARLIGHT model [11] for exclusive heavy-quarkonium photoproduction in ultraperipheral Pb-Pb interactions at 5.5 TeV accompanied by neutron emission in single (Xn) or double ($Xn|Xn$) Pb breakup (top diagram in Fig. 1). (σ_{Xn} includes $\sigma_{Xn|Xn}$).

Process	σ_{tot}	σ_{Xn}	$\sigma_{Xn\|Xn}$
γPb$\rightarrow J/\psi$Pb	32 mb	8.7 mb	2.5 mb
γPb$\rightarrow \Upsilon(1S)$Pb	173 μb	78 μb	25 μb

Table 1 lists the expected cross sections for J/ψ and Υ photoproduction in Pb-Pb UPCs at the LHC, as given by the STARLIGHT Monte Carlo [11]. The STARLIGHT model satisfactorily reproduces the existing UPC J/ψ [10] and low- [12] and high-mass [10] dielectron data at RHIC energies. The predicted total cross section for $\Upsilon(1S)$ photoproduction is of the order of 150 μb in agreement with other calculations [13]. Inclusion of leading-twist shadowing effects in the nuclear PDFs reduces the yield by up to a factor of two, σ_Υ = 78 μb [13]. Even larger reductions are expected in calculations including gluon-saturation (CGC) effects [14, 15].

The cross-sections are given also for the case where one or both nuclei are mutually Coulomb-excited – indicated by the soft γ's exchanged in the diagrams of Fig. 1. In the case of Υ photoproduction about 50% of the UPCs induce Giant-Dipole-Resonance (GDR) oscillations of the interacting nuclei which will subsequently deexcite via neutron emission. The presence of very forward neutrons detectable in Zero-Degree-Calorimeters (ZDCs) [16], in a significant fraction of UPC events provides a crucial tool to trigger on those collisions. In Section 4 we present the expected $\Upsilon \rightarrow e^+e^-, \mu^+\mu^-$ reconstruction performances and yields for Pb-Pb at 5.5 TeV in CMS.

3 High-field QED via exclusive lepton-pair production

In proton-proton collisions, exclusive dilepton production $pp \rightarrow p\,l^+l^-p$ has been proposed [17] as a standard beam luminosity calibration process at the LHC, thanks to its precisely known (nearly [18]) pure QED cross section. Experimentally, such a process can be tagged with rapidity-gaps ("exclusivity") conditions [19] or via forward protons [2], and has a clear signature in the exclusive back-to-back dileptons ($|\Delta\phi(l^+l^-)| > 2.9$) measured in CMS (or ATLAS) within $|\eta| < 2.5$.

Exclusive dileptons are also easily accessible in electromagnetic Pb-Pb collisions (bottom diagram of Fig. 1) since the continuum cross sections – thanks to the Z^4 photon flux enhancement factor – are much larger than in p-p. As a matter of fact, the huge Z^4 enhancement factor of equivalent photon fluxes in the ion running mode at the LHC, results in QED fields of the same order of magnitude or above the so-called Schwinger limit, $E_{\rm crit} = m^2c^3/(e\hbar) \approx 1.5\times 10^{16}$ V/cm, which sets the threshold for the generation of real e^+e^- pairs out of the vacuum by an (strong enough) electromagnetic field. Under such conditions, $Z\alpha_{em} \approx 0.6$, the l^+l^- production probabilities are close to one and the lowest order perturbative calculations of the cross sections violate unitarity. Detailed calculations involving higher order processes, such as the exchange of multiple photons and the production of multiple pairs as shown in Fig. 3(b-d), have been carried out in the recent years [20]. Testing of QED in the non-perturbative regime will be thus possible via the measurement of exclusive dileptons in ultraperipheral nucleus-nucleus collisions at the LHC.

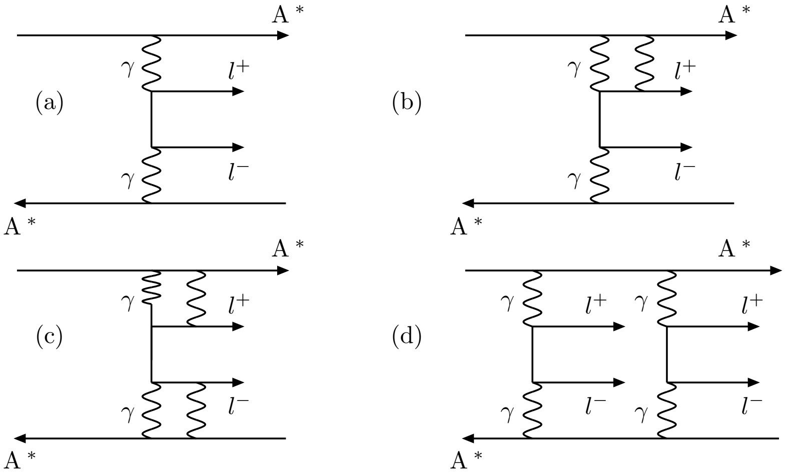

Figure 3: Feynman diagrams for l^+l^- production in high-energy UPCs: (a) lowest order, (b) next to lowest order three-photon exchange, (c) four-photon exchange, (d) double l^+l^- pair production.

Table 2 lists the expected cross sections for the lepton pair continuum in two ranges of invariant-mass ranges as predicted by STARLIGHT. The dilepton continuum yields are 2 to 3 orders of magnitude larger than those due to the exclusive quarkonia decays. However, the single leptons from the continuum are much more forward-peaked than those from J/ψ or Υ and fall much more often outside the CMS acceptance. The fraction of the continuum cross sections accompanied by nuclear breakup with neutron emission is expected to be the same as in the case of quarkonia photoproduction, i.e. of the order of $\sim 50\%$ for moderately high mass dileptons. Exclusive dilepton production in STARLIGHT is calculated combining the two equivalent (Weizsäcker-Williams) photon fluxes from each ion with the Breit-Wheeler formula for $\gamma\gamma \to l^+l^-$ (the leading order diagram of Fig. 3). The level of agreement is good with other calculations [20] when the pair invariant mass is not too low. If strong QED fields are accounted for, multiple pairs are also produced at lower masses. In the next section we present the expected exclusive lepton pair contributions around the Υ mass in the CMS detector.

Table 2: Cross sections for dilepton production in two-photon collisions from ultraperipheral Pb-Pb interactions at 5.5 TeV (bottom diagram in Fig. 1) according to STARLIGHT [11] for two different invariant mass regions.

Process	$\gamma\gamma \to e^+e^-$	$\gamma\gamma \to \mu^+\mu^-$
$\sigma(M > 1.5$ GeV/$c^2)$	139 mb	45 mb
$\sigma(M > 6.0$ GeV/$c^2)$	2.8 mb	1.2 mb

4 Expected UPC dilepton results in CMS

In [21] we present the possibilities of the CMS detector to carry out the measurement of exclusive $\Upsilon \to l^+l^-$ and continuum l^+l^- pairs produced in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV, tagged with forward neutron detection in the ZDCs [16]. The CMS electromagnetic calorimeter ECAL and the muon spectrometers, covering the pseudorapidity ranges $|\eta| < 3.$ and $|\eta| < 2.5$ respectively, are used to measure the final leptons. Two dedicated UPC level-1 triggers have been defined which require respectively hits above ~2.5 GeV in the ECAL and muon chambers, no activity in one of the hadron-forward (HF) calorimeters (i.e. no particle produced above threshold

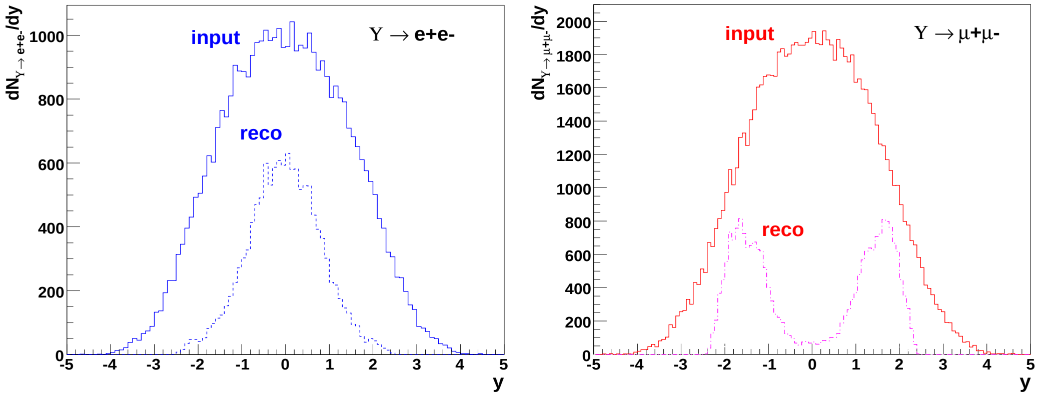

Figure 4: Generated and reconstructed rapidity spectra of the UPCs Υ measured in the e^+e^- (left) and $\mu^+\mu^-$ (right) channels in CMS.

within $3 < |\eta| < 5$ as expected in "exclusive" events) and a neutron signal in one or both of the ZDCs. Signals are generated with the STARLIGHT Monte Carlo according to the cross sections quoted in Tables 1 and 2. The geometrical acceptance, detector response and resolutions, and reconstruction efficiency losses, have been determined for the dimuon and dielectron channels. In the case of the Υ signal, the rapidity distributions in both analyses are complementary, with the dimuons peaked around $|y| = 2$ and the dielectrons at $|y| < 1$ (see Fig. 4). The p_T resolution (not shown here) is good enough to separate the coherent (peaked at very low $p_\mathrm{T} \approx M_V/\gamma \approx 30$ MeV/c) from the incoherent ($p_T \gtrsim 0.3$ GeV/c) [22] components.

Figure 5 shows the reconstructed $dN/dM_{l^+l^-}$ around the Υ mass (only the ground-state, $\Upsilon(1S)$, of the bottomonium family was generated). In the real data, any residual combinatorial background can be removed by directly subtracting the like-sign (l^+l^+ or l^-l^-) from the unlike-sign pairs. The signal over continuum is around unity for both decay modes. The combined reconstructed mass spectra are fitted to a Gaussian (for the Υ peak) plus an exponential for the underlying lepton pair contribution. The reconstructed bottomonium peak positions and widths are: $M_{\mu^+\mu^-} = 9.52$ GeV/c^2($\sigma_{\mu^+\mu^-} = 0.090$ GeV/c^2) and $M_{e^+e^-} = 9.34$ GeV/c^2($\sigma_{e^+e^-} = 0.154$ GeV/c^2), very close to the nominal $M_\Upsilon = 9.46$ GeV/c^2mass. In the dimuon channel, the good mass resolution of our measurement would allow for a clean separation of the Υ' (10.02 GeV/c^2) and Υ'' (10.36 GeV/c^2) which are also vector mesons and can be photoproduced (but were not included in the current simulation).

The total Υ production yields are obtained from an integration within 3σ of the corresponding peak maxima. The final Υ acceptance and efficiencies are $\varepsilon_{\mathrm{rec}} \times \mathcal{A} \times \varepsilon_{\mathrm{yield-extract}} = 21\%$ for the e^+e^- analysis and 19% for the $\mu^+\mu^-$ one. The total expected number of Υ events, normalised to the nominal PbPb integrated luminosity of $\int \mathcal{L}$ dt = 0.5 nb^{-1}, are 220 ± 15 (stat) and 180 ± 14 (stat) in the e^+e^- and $\mu^+\mu^-$ channels, respectively, with a $\sim 10\%$ systematic uncertainty. With such a statistics, detailed p_T,y studies can be carried out, that will help constrain the low-x gluon density in the nucleus.

In the dilepton continuum sector, the same analysis would yield a few thousand e^+e^- and $\mu^+\mu^-$ pairs in the mass range above $M_{l^+l^-} \approx 6$ MeV/c^2 that will allow us to test the predictions of QED models including non-perturbative corrections.

5 Summary

Exclusive quarkonia and dilepton production in ultra-peripheral Pb-Pb collisions at 5.5 TeV provide useful tools to carry out various studies of the QCD and QED sectors of the Standard Model. High-energy Υ photoproduction provides a particularly useful means to constrain the poorly known low-x gluon distribution of the nucleus in a "clean" environment. Exclusive dileptons allow us to test QED in the non-perturbative (high field-strength) regime. We have presented the perspectives of the CMS experiment in 5.5 TeV Pb-Pb collisions at the LHC. In the absence of strong non-linear QCD effects, around 400 photo-produced Υ will be reconstructed in the CMS acceptance with nominal integrated luminosities. The same analysis cuts would yield a few thousand e^+e^- and $\mu^+\mu^-$ pairs in the mass range above $M_{l^+l^-} \approx 6$ MeV/c^2.

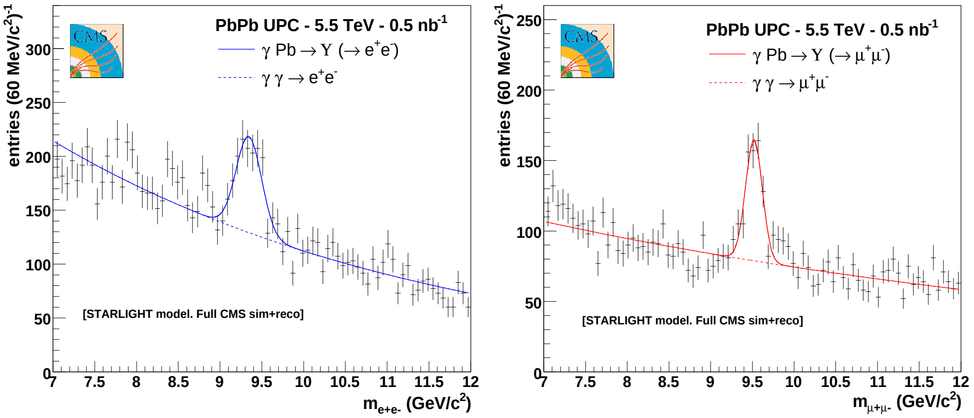

Figure 5: Expected e^+e^- (top) and $\mu^+\mu^-$ (bottom) invariant mass distributions from γPb$\rightarrow\Upsilon$Pb (followed by $\Upsilon\rightarrow l^+l^-$) and $\gamma\gamma\rightarrow l^+l^-$ continuum in UPC Pb-Pb at $\sqrt{s_{NN}}$ = 5.5 TeV.

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