

# ULTRA-PERIPHERAL VECTOR MESON PHOTOPRODUCTION IN HEAVY-ION COLLISIONS IN CMS\*

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In this document, an introduction to ultra-peripheral collisions (UPCs) is given. The recent results on UPCs obtained by the Compact Muon Solenoid Collaboration are presented. They are also shown in conjunction with theoretical predictions. Finally, the analysis of ultra-peripheral  $\Upsilon$  photoproduction in the new PbPb data collected at the end of 2018 by the CMS is discussed. This analysis is still in progress.

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## 1. Introduction

Hadronic collisions at the Large Hadron Collider (LHC) are a very powerful source of  $\gamma$ -hadron and  $\gamma$ - $\gamma$  interactions. Protons and ions possess an electric charge and, when colliding in the LHC, are surrounded by high-energy, quasi-real photons, which can interact with another photon or with a parton inside the second hadron in a process called photoproduction. This process can be observed in a clean way during ultra-peripheral collisions (UPC), where the impact parameter  $b$  for the two hadrons is larger than the sum of their radii,  $R_A + R_B$  (see figure 1 (a)). A variety of final-state particles can be produced in these processes. For example, the ultra-peripheral exclusive vector meson (VM) photoproduction has received great theoretical interest [1, 2]. In this process, both hadrons ( $h$ ) stay intact after the collision, and there is a VM in the final state,  $\gamma h \rightarrow \text{VM} + h$  (see figure 1 (b)). The VM interacts with the hadron by the exchange of the Pomeron carrying vacuum quantum numbers.

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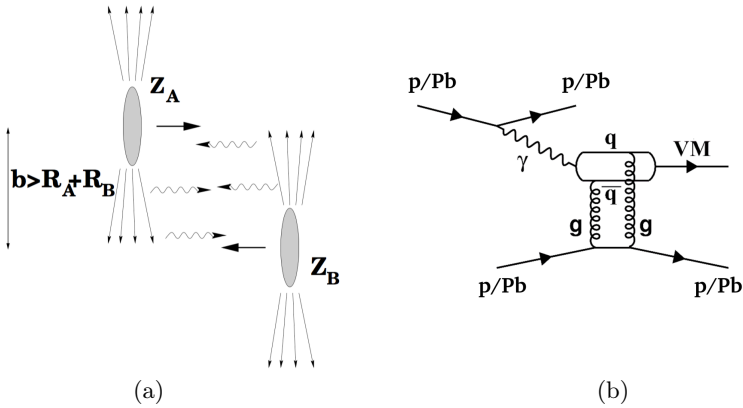


Fig. 1. Panel (a) the UPC: the impact parameter  $b$  for the two hadrons is larger than the sum of their radii  $R_A + R_B$ . Panel (b) Feynman diagram of the ultra-peripheral exclusive VM photoproduction. Both hadrons stay intact after the collision.

## 2. Exclusive $\rho(770)^0$ photoproduction in $pPb$ data

During  $pPb$  collisions, the large electric charge of the lead nucleus enhances photon–proton interactions. Since these interactions are asymmetrical, it is possible to determine photon direction unambiguously — an advantage that is not present in the case of symmetric  $PbPb$  or  $pp$  collisions. This feature enables determination of the center-of-mass energy,  $W_{\gamma p}$ . In exclusive VM photoproduction, the dependence of the cross section on the squared four-momentum transfer at the proton vertex ( $t$ ) has been considered as a very promising way to find the onset of gluon saturation [6]. Furthermore, the Fourier transform of the  $t$  distribution is related to the two-dimensional, spatial distribution of the partons transverse to the beam direction.

In the presented analysis [4], the exclusive photoproduction of  $\rho(770)^0$  meson in ultra-peripheral  $pPb$  collisions is measured in the  $\pi^+\pi^-$  decay channel. The data have been collected by the Compact Muon Solenoid (CMS) detector in 2013. A full description of CMS and its subdetectors is given in Ref. [3]. The center-of-mass energy per nucleon pair was  $\sqrt{s_{NN}} = 5.02$  TeV, and the integrated luminosity of the analyzed sample was  $L = 7.4 \mu b^{-1}$  for  $pPb$  and  $L = 9.6 \mu b^{-1}$  for  $Pb p$ , where  $pPb$  and  $Pb p$  mean opposite directions of beams in the LHC. The STARLIGHT Monte Carlo event generator [5] has been used for simulations of the exclusive resonant and nonresonant  $\pi^+\pi^-$  production, exclusive  $\rho(1700)$  events, acceptance and efficiency studies and for photon flux calculation.

The event selection consists of a number of requirements: events with an energy deposition in any tower in Hadronic Forward (HF) calorimeter below 3.0 GeV (consistent with only noise in HF) are selected to reject hadronic interactions. It is required that there are exactly two tracks with a pseudorapidity less than 2.0, and their transverse momenta greater than 0.4 and 0.2 GeV. Additional requirements to ensure exclusivity consist of a selection of events with energy deposited in CASTOR to be below 9 GeV, and for Zero Degree Calorimeter (ZDC) to be below 500 GeV on the positive side and below 2000 GeV on the negative side. The lack of symmetry for the ZDC requirement is due to the difference in radiation damage between them. For detailed selection requirements with numbers of events after each step, see Table 1 in [4]. The final signal extraction is done in two steps, by fitting background distributions to  $p_T^{\pi^+\pi^-}$  and  $M^{\pi^+\pi^-}$  distributions as shown in figure 2.

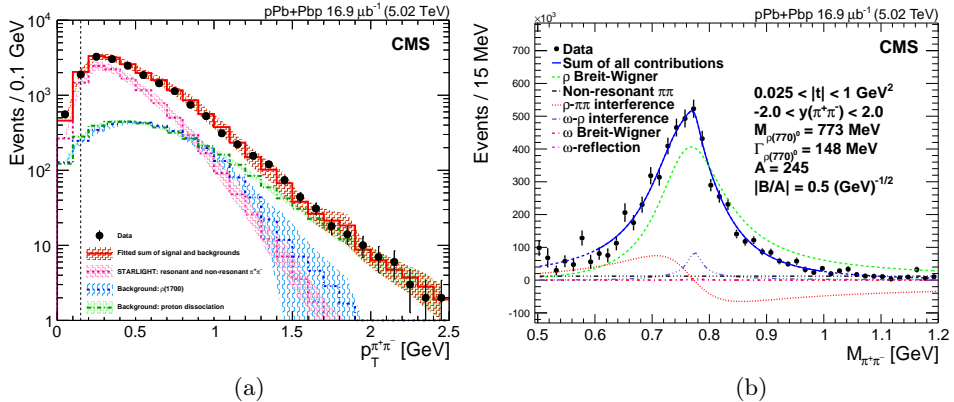


Fig. 2. Panel (a) shows the distribution of the  $\pi^+\pi^-$  transverse momentum together with fits to signal and background components. Panel (b) shows the unfolded  $\pi^+\pi^-$  invariant mass distribution in the  $\pi^+\pi^-$  rapidity interval  $|y^{\pi^+\pi^-}| < 2.0$  [4].

In figure 3, the photon–proton cross section,  $\sigma(\gamma p \rightarrow \rho(770)^0 p)$ , for four bins in  $W_{\gamma p}$  is shown. The total obtained cross section for  $29 < W_{\gamma p} < 213$  GeV is found to be  $11.0 \pm 1.4(\text{stat.}) \pm 1.0(\text{syst.}) \mu\text{b}$ . Figure 3 shows also results from fixed-target and HERA results (for details, see [4]). The CMS results are consistent with those from the ZEUS Collaborations at HERA, which shows that ion–proton collisions can be used similarly to electron–proton collisions.

Thanks to the large integrated luminosity, the energy dependence ( $d\sigma/dt$ ) for the four bins in  $W_{\gamma p}$  are provided for the first time. Figure 4 from a recent theoretical publication [6] compares the CMS results with different theoretical models. The location of the diffractive dips in exclusive UPC VMs in

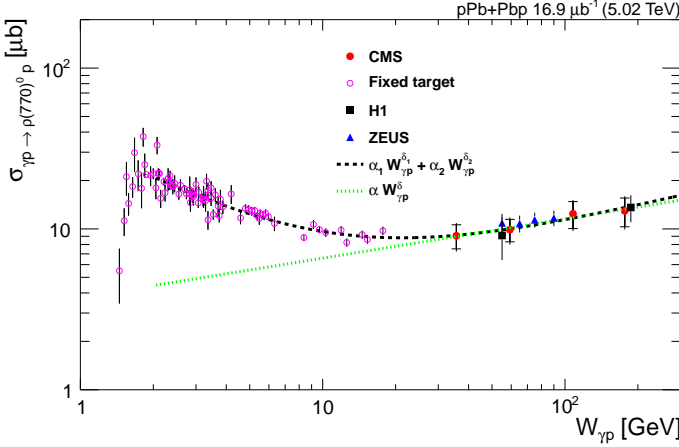


Fig. 3. Exclusive  $\rho(770)^0$  photoproduction cross section is shown as a function of  $W_{\gamma p}$ . The fit of the CMS and HERA data yields  $\delta = 0.24 \pm 0.13(\text{stat.}) \pm 0.04(\text{syst.})$  [4].

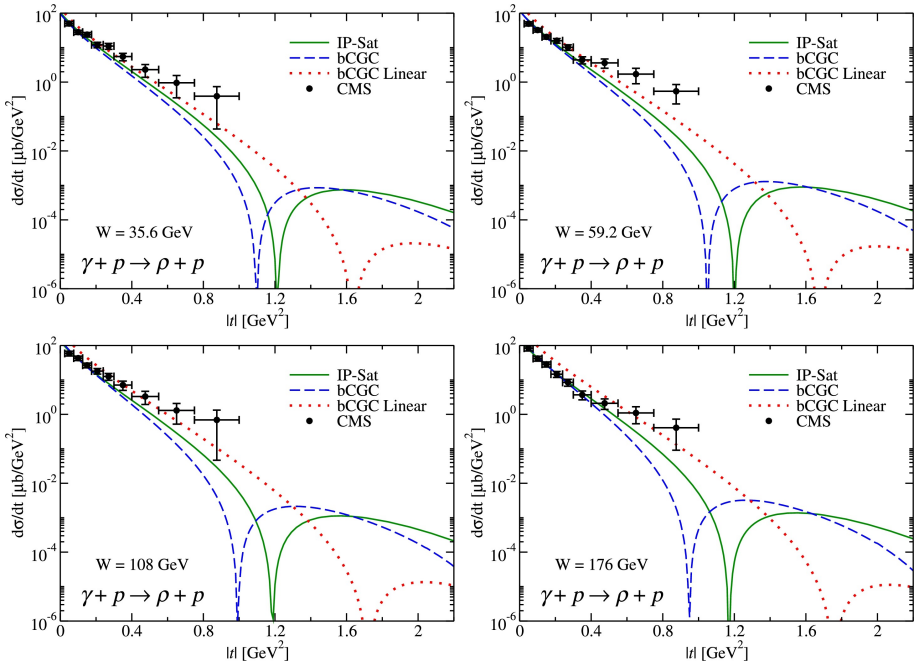


Fig. 4. Differential cross sections for exclusive  $\rho(770)^0$  photoproduction as a function of  $|t|$ . The four panels present different corresponding center-of-mass energies,  $W_{\gamma p}$ , from the lowest value of 35.6 GeV on the top-left to the highest, 176 GeV on the bottom-right [6].

gamma–proton interactions is sensitive to the gluon saturation effect, which makes these measurements very promising. As can be seen, for the highest energy point,  $W_{\gamma p} = 176$  GeV (lower-right panel in figure 4), the data for low  $|t|$  values are not well-described by the bCGS model with only linear contribution. This can be a first indication that the model of the spatial distribution of gluons in protons will have to be reevaluated for the purpose of the study of the gluon saturation effects.

### 3. Exclusive $\Upsilon$ photoproduction in Run 2 PbPb data

The initial state of the nuclei is described by the Parton Distribution Functions (PDFs), describing the probability of finding a parton (gluons and quarks) with a longitudinal momentum fraction of the hadron  $x$  at the energy transfer to the hadron  $Q^2$ . As can be seen in figure 5 (a), the nuclear gluon PDFs for lead are poorly known, especially in the low- $x$  ( $x < 10^{-2}$ ) region. It can be probed with exclusive  $J/\psi$  and  $\Upsilon$  photoproduction measurements [1, 2]. CMS and ALICE have performed this analysis for the  $J/\psi$  meson at  $\sqrt{s_{NN}} = 2.76$  TeV with PbPb data [8, 9] (see figure 5 (b)). An analogous analysis with the  $\Upsilon$  meson decaying to  $\mu^+\mu^-$ , at a higher center-of-mass energy of  $\sqrt{s_{NN}} = 5.02$  TeV with 2018 Run 2 PbPb data is still in progress. The PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV took place during Run 2 in 2015

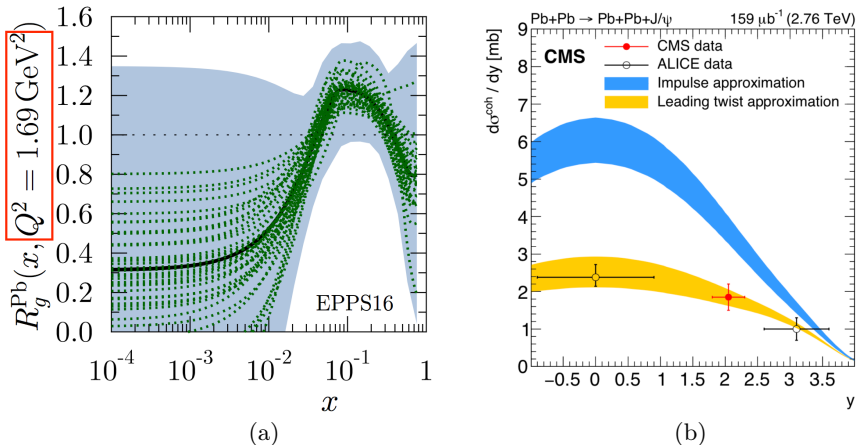


Fig. 5. (Color online) Panel (a) shows the EPPS16 nuclear gluon modifications for lead nucleus. The dotted green lines show all the contributions to the uncertainties. The largest uncertainty occurs at  $x < 10^{-2}$  because of lack of data in this region [7]. Panel (b) shows the cross section as a function of dimuon rapidity for coherent  $J/\psi$  photoproduction in ultra-peripheral PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, measured by CMS [8] and ALICE [9]. The data are consistent with the leading twist approximation calculations, which include nuclear gluon shadowing.

and 2018. In the latter year, the CMS collected 3 times more data than in 2015, about  $1.7 \text{ nb}^{-1}$ . This allows to perform the measurement for  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(3S)$ . The event selection consists in the requirement that there is no energy deposited in the forward calorimeters and that there are exactly two muons with kinematic requirements in an otherwise empty detector. Example event displays passing those requirements are shown in figure 6.

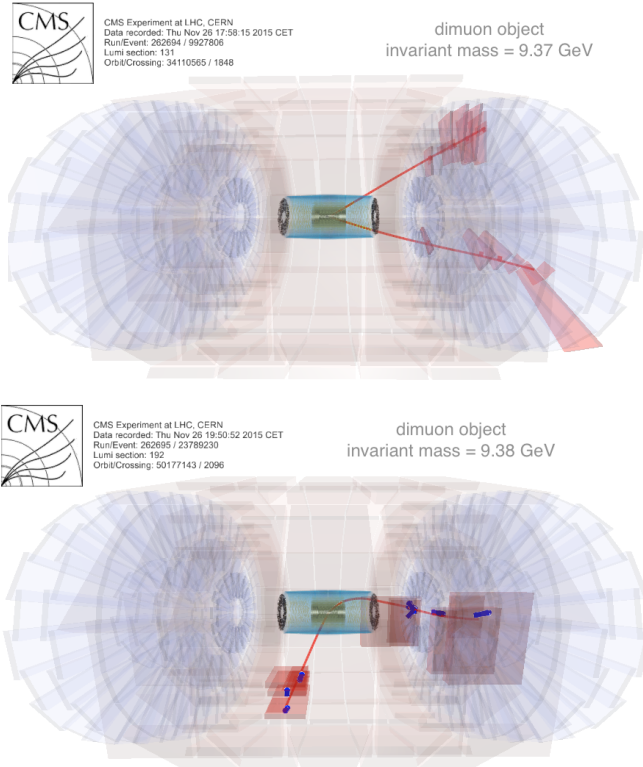


Fig. 6. The event displays show two of the candidate events for ultra-peripheral, exclusive  $\Upsilon$  photoproduction. In an otherwise empty detector, there are two muons going into forward (panel (a)) and central (panel (b)) direction. The reconstructed invariant mass of the dimuon objects is consistent with the  $\Upsilon(1S)$  mass. Events were recorded by CMS during the Run 2 PbPb collisions at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ .

#### 4. Conclusions

The CMS detector, due to its good coverage in the forward region and excellent muon subdetectors, is perfect for the UPC studies. The ultra-peripheral VM photoproduction process is a very useful tool for measuring the properties of protons and nuclei. The cross sections obtained by CMS are

in agreement with the power law dependence of  $W_{\gamma p}$  observed at HERA, indicating that ion–proton interactions can supplement electron–proton data. UPC studies allow to set constraints on a variety of theoretical models, in particular, the UPC photoproduction  $\Upsilon(nS)$ , which probes the kinematic range of  $x < 10^{-2}$  with few experimental results. The ongoing analysis of the Run 2 PbPb data could be the first measurement of this process. Future measurements with more data on exclusive VM photoproduction will be very useful to improve our understanding of the QCD dynamics at high energies.

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