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Photon-proton and photon-nucleus measurements in CMS

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Abstract
The CMS measurements of exclusive photoproduction of Υ in pPb and J/ψ in PbPb collisions, that probe the low-x gluon density in the proton and the lead nucleus respectively, are discussed.

Keywords
Ultra-peripheral collisions; Υ; J/ψ ; Photoproduction

1 Introduction

The exclusive photoproduction of quarkonia in γ-proton and γ-nucleus interactions from ultraperipheral proton-nucleus and nucleus-nucleus collisions at high-energies [1], where one of the incoming hadrons emits a photon that interacts with the "target" proton/nucleus via a colour-singlet gluon exchange and materializes into a Υ or J/ψ meson, provides a powerful tool to directly probe the gluon density inside the proton/nucleus [2].

The central feature of the CMS detector is a superconducting solenoid that provides a magnetic field of 3.8 T, required to bend the charged particle's trajectory and measure its momentum accurately. Within the solenoid volume are a silicon pixel and strip tracker, electromagnetic calorimeter (ECAL), hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid over the range $|\eta| < 2.4$. Two Hadron Forward (HF) calorimeters cover $2.9 < |\eta| < 5.2$, and two zero degree calorimeters (ZDC) are sensitive to neutrons and photons with $|\eta| > 8.3$. The beam scintillator counters (BSCs) are plastic scintillators that partially cover the face of the HF calorimeters over the range $3.9 < |\eta| < 4.4$. A more detailed description of the CMS detector can be found in Ref. [3].

2 Exclusive photoproduction of Υ in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

In Ultra-Peripheral Collisions (UPCs), the interactions are mainly photon-induced and strong interactions are largely suppressed. Since the photon flux scales with the square of the charge (Z^2) of the emitting particle, UPC are strongly enhanced for Pb compared to proton. In exclusive quarkonia photoproduction processes, the photon emitted by one of the accelerated charges (electron, proton or ion) fluctuates into $q\bar{q}$ bound pair (vector meson) and interacts with the other "target" proton or ion through a color-singlet gluon exchange. The corresponding photoproduction cross-section is thereby proportional to the square of the gluon density inside the "target".

Exclusive Υ photoproduction was first observed at HERA [4–6] and has recently been studied at the LHC by the LHCb experiment [7] in pp UPCs at $\sqrt{s} = 7$ and 8 TeV. CMS has carried out a similar measurement in p-Pb collisions, including the Υ(1S) cross section as a function of the photon-proton center-of-mass energy, $W_{\gamma \mathrm{p}}$, in the interval 91–826 GeV, corresponding to the Υ rapidity, y $< |2.2|$, and Bjorken-x values of the order $x \sim 10^{-4}$ to $x \sim 1.3 \cdot 10^{-2}$. The differential cross-section for Υ(nS) states as a function of transverse momentum squared, p_{T}^2, has been measured, where $p_{\mathrm{T}}^2 \approx |t|$ is the four-momentum transfer at the proton vertex. At low values of $|t|$, the cross-section can be parameterized as $e^{-b|t|}$, where b provides also information on the transverse density profile of the proton.

The measurement of exclusive Υ photoproduction in ultra-peripheral p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV has been presented in [8] corresponding to an integrated luminosity of $L_{\mathrm{int}} = 32.6$ nb^{-1} collected by the CMS experiment. The STARLIGHT [9] MC event generator was used to simulate exclusive

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Υ(nS) photoproduction events, Fig. 1 (left), and the elastic QED background, Fig. 1 (right). The Υ(nS) states are studied in their dimuon decay channel. The UPC events were selected with a dedicated trigger, which requires at least one muon in each event and at least one to six tracks. In order to reduce the muon inefficiencies at low p_{T} , muons with $p_{\mathrm{T}} > 3.3$ GeV and pseudo-rapidity $|\eta| < 2.2$ are selected. Dimuons are selected in the invariant mass range 9.1–10.6 GeV. Exclusive Υ candidates are selected by requiring only one vertex and no extra charged particles with $p_{\mathrm{T}} > 0.1$ GeV in the event. The p_{T} of the dimuon is restricted from 0.1 to 1 GeV, to reduce the contamination from elastic QED and inelastic background contributions.

The dominant background contribution to the exclusive Υ signal originates from QED, $\gamma\gamma \rightarrow \mu^+\mu^-$, which was estimated by STARLIGHT. The absolute prediction of QED was checked by comparing the data between invariant mass regions 8–9.12 and 10.64–12 GeV for dimuon $p_{\mathrm{T}} < 0.15$ GeV to the simulation. The contribution of non-exclusive background (inclusive Υ, Drell-Yan and proton dissociation) was estimated by a data-driven method by loosening the exclusivity cuts. A background template is build with events with more than 2 tracks. This template was normalized to the exclusive sample in the region of dimuon $p_T > 1.5$ GeV to estimate the data-driven background. A small additional background originates from exclusive $\gamma\mathrm{Pb} \rightarrow \Upsilon\ \mathrm{Pb}$ events. The fraction of these events in the total number of exclusive Υ events was estimated using a reweighted STARLIGHT Υ MC sample. These backgrounds were subtracted from data to extract the exclusive signal. The background subtracted $|t|$ and y distributions were used to measure the b parameter, and to estimate the exclusive Υ photoproduction cross-section as a function of $W_{\gamma p}$, respectively. The distributions were first unfolded in the region $0.01 < |t| < 1$ GeV^2, $|y| < 2.2$, and muon $p_{\mathrm{T}}^{\mu} > 3.3$ GeV, using the iterative Bayesian unfolding technique, and were further extrapolated to transverse momenta of zero using acceptance correction factors.

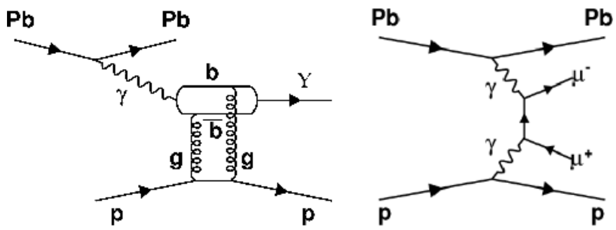

Fig. 1: Diagrams representing exclusive Υ photoproduction (left), and exclusive dimuon QED continuum (right) in pPb collisions [8].

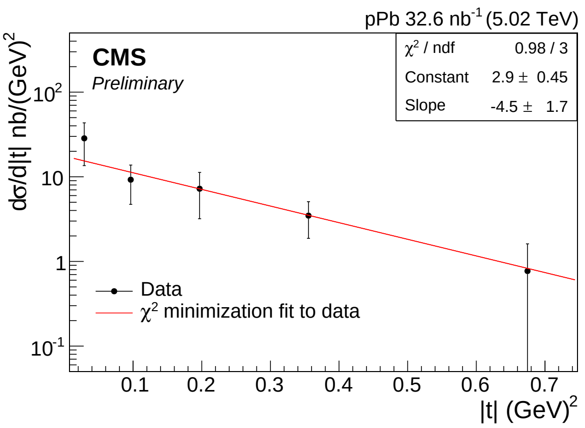

Fig. 2: Differential Υ(nS) photoproduction cross section as a function of $|t|$. The solid line represents the result of a fit with an exponential function $Ne^{-b|t|}$ [8].

The differential $d\sigma/dt$ cross section is shown in Fig. 2 and extracted for the combined three Υ(nS) states according to the following formula:

$$\frac{\mathrm{d}\sigma_{\Upsilon}}{\mathrm{d}|t|} = \frac{N^{\Upsilon(\mathrm{nS})}}{\mathcal{L} \times \Delta|t|}\ , \tag{1}$$

where $|t|$ is approximated by the dimuon transverse momentum squared p_{T}^2, $N^{\Upsilon(\mathrm{nS})}$ denotes the yield of background-subtracted, unfolded and acceptance-corrected signal events in each $|t|$ bin, $\mathcal{L}$ is the integrated luminosity, and $\Delta|t|$ is the width of each $|t|$ bin. The cross section is fitted with an exponential function $N\ e^{-b|t|}$ in the region $0.01 < |t| < 1.0$ GeV^2, using an unbinned χ^2 minimization method. A value of $b = 4.5 \pm 1.7$ (stat) $\pm$ 0.6 (syst) GeV^{-2} is extracted from the fit. This result is in agreement with the value $b = 4.3^{+2.0}_{-1.3}$ (stat) measured by the ZEUS experiment [10] for the photon-proton center-of-mass energy $60 < W_{\gamma\mathrm{p}} < 220$ GeV, and with the predictions based on pQCD models [11].

The differential Υ(1S) photoproduction cross section, $\mathrm{d}\sigma/\mathrm{d}y$, is extracted in four bins of dimuon rapidity according to:

$$\frac{d\sigma_{\Upsilon(1\mathrm{S})}}{dy} = \frac{f_{\Upsilon(1\mathrm{S})}}{\mathcal{B}(1+f_{\mathrm{FD}})} \frac{N^{\Upsilon(\mathrm{nS})}}{\mathcal{L} \times \Delta y} , \tag{2}$$

where $N^{\Upsilon(\mathrm{nS})}$ denotes the background-subtracted, unfolded and acceptance-corrected number of signal events in each rapidity bin. The factor $f_{\Upsilon(1\mathrm{S})}$ describes the ratio of $\Upsilon(1\mathrm{S})$ to $\Upsilon(\mathrm{nS})$ events, f_{FD} is the feed-down contribution to the $\Upsilon(1\mathrm{S})$ events originating from the $\Upsilon(2\mathrm{S}) \to \Upsilon(1\mathrm{S}) + X$ decays (where $X = \pi^+\pi^-$ or $\pi^0\pi^0$), $\mathcal{B} = (2.48 \pm 0.05)\%$ is the branching ratio for muonic $\Upsilon(1S)$ decays, and Δy is the width of the y bin. The $f_{\Upsilon(1\mathrm{S})}$ fraction is used from the results of the inclusive Υ analysis [12] at CMS. The feed-down contribution of $\Upsilon(2\mathrm{S})$ decaying to $\Upsilon(1S) + \pi^+\pi^-$ and $\Upsilon(1S) + \pi^0\pi^0$ was estimated as 15% from STARLIGHT. The contribution of feed-down from exclusive χ_b states was neglected, as these double-pomeron processes are expected to be comparatively much suppressed in proton-nucleus collisions [13, 14].

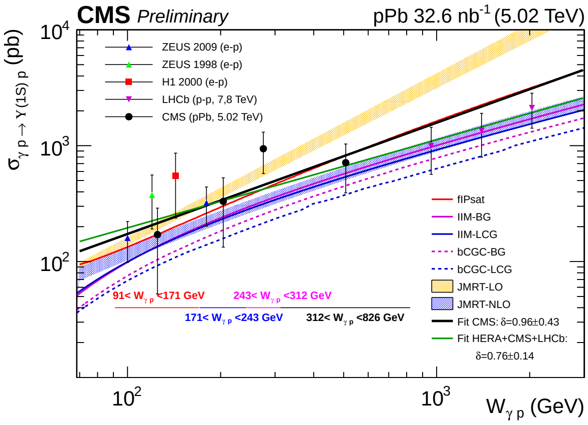

Fig. 3: Cross section for exclusive $\Upsilon(1\mathrm{S})$ photoproduction, $\gamma\mathrm{p} \to \Upsilon(1S)\mathrm{p}$ as a function of photon-proton center-of-mass energy, $W_{\gamma p}$ [8].

The exclusive $\Upsilon(1\mathrm{S})$ photoproduction cross section as a function of $W_{\gamma p}$ shown in Fig. 3, is obtained by using,

$$\sigma_{\gamma p \to \Upsilon(1S)p}(W^2_{\gamma p}) = \frac{1}{\Phi} \frac{d\sigma_{\Upsilon(1S)}}{dy}, \tag{3}$$

where Φ is the photon flux evaluated at the mean of the rapidity bin, estimated from STARLIGHT. The CMS data are plotted together with the previous measurements from H1 [4], ZEUS [5, 6] and LHCb [7] data. It is also compared with different theoretical predictions of the JMRT model [11], factorized IPsat model [15, 16], IIM [17, 18] and bCGC model [19]. As $\sigma(W_{\gamma p})$ is proportional to the square of the gluon PDF of the proton and the gluon distribution at low Bjorken x is well described by a power law, the cross section will also follow a power law. Any deviation from such trend would indicate a different behavior of the gluon density function. We fit a power law $A \times (W/400)^{\delta}$ with CMS data alone that gives $\delta = 0.96 \pm 0.43$ and $A = 655 \pm 196$, and is shown by the black solid line. The extracted δ value is comparable to the value $\delta = 1.2 \pm 0.8$, obtained by ZEUS [5]. Our data are compatible with a power-law dependence of $\sigma(W_{\gamma p})$ and disfavor a faster increase with energy as predicted by LO pQCD approaches.

3 Coherent photoproduction of J/ψ in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

CMS has also carried out a measurement of the coherent J/ψ photoproduction in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [20], in a data sample corresponding to an integrated luminosity of $L_{\mathrm{int}} = 159\ \mu b^{-1}$. In PbPb UPC events, vector mesons are produced in γPb interactions off one of the nuclei and thus, the gluon distribution inside the Pb ion can be probed for low values of Bjorken x, of the order of $x \sim 10^{-5}$ to $x \sim 2 \cdot 10^{-2}$. The STAR and PHENIX collaborations at RHIC have studied ρ^0 and J/ψ photoproduction in ultra-peripheral AuAu collisions at $\sqrt{s_{NN}}$ = 200 GeV [21, 22]. The measurement of coherent photoproduction of the J/ψ meson has been performed at the LHC by the ALICE collaboration [23] in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The results provided by the ALICE collaboration have been used to compute the nuclear suppression factor, and it provides the evidence that the nuclear gluon density is below that expected for a simple superposition of protons and neutrons in the nucleus [23].

The exclusive J/ψ photoproduction can be classified as coherent if the photon interacts with the whole nucleus, leaving the nucleus intact. In incoherent interactions, the photon interacts with a single nucleon, and the nucleus breaks apart. The STARLIGHT [9] MC event generator was used to simulate coherent and incoherent J/ψ photoproduction events and the elastic QED background. The J/ψ candidates are reconstructed through the dimuon decay channel in the rapidity interval $1.8 < |y| < 2.3$. The UPC events were selected with a dedicated trigger, which requires an energy deposit consistent with at least one neutron in either of the ZDCs; a low signal in at least one of the BSC+ or BSC- scintillators; the presence of at least one single muon without a p_{T} threshold requirement, and at least one track in the pixel detector. The coherent J/ψ cross section is measured for the case when the J/ψ mesons are accompanied by at least one neutron on one side of the interaction point and no neutron activity on the other side ($\mathrm{X_n0_n}$), to reject the non-UPC events. In addition to the ZDC requirements, the exclusive J/ψ events are selected by requiring exactly two muon tracks within the phase space region $1.2 < |\eta| < 2.4$ and $1.2 < p_{\mathrm{T}} < 1.8$ GeV and no activity above noise threshold, 3.85 GeV, in the HF detectors. Dimuon candidates with $p_{\mathrm{T}} < 1.0$ GeV within the rapidity interval $1.8 < |y| < 2.3$ and with invariant mass between 2.6–3.5 GeV are considered.

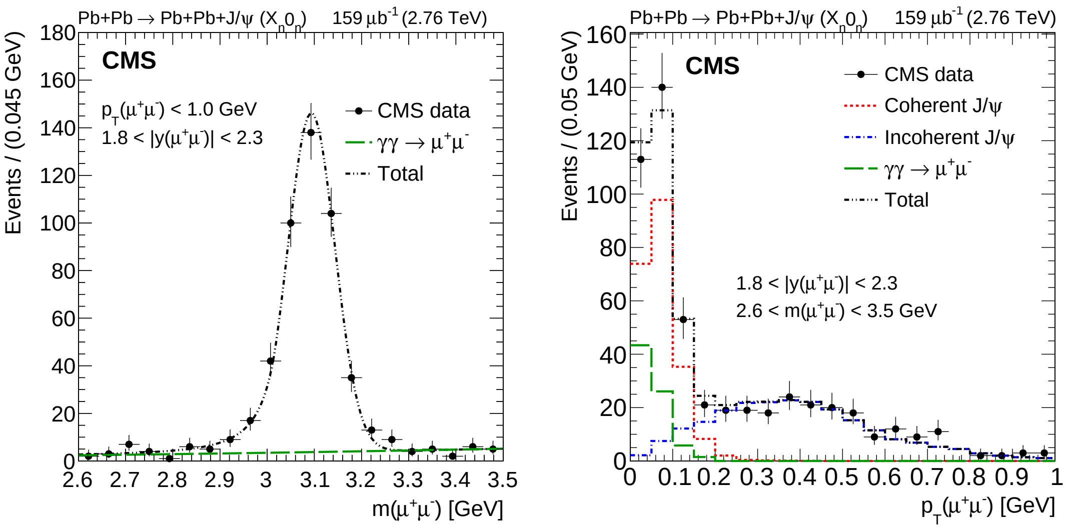

Fig. 4: Results from the simultaneous fit to the dimuon invariant mass (left) and p_{T} (right) for the $\mathrm{X_n0_n}$ break-up mode, after all selections are applied [20].

The dimuon invariant mass (Fig. 4, left) and p_{T} (Fig. 4, right) distributions satisfying the selection criteria are simultaneously fitted in order to extract the yield of coherent J/ψ , incoherent J/ψ , and $\gamma\gamma \to \mu^+\mu^-$ events. The fit uses a maximum likelihood algorithm that takes unbinned projections of the data in invariant mass and p_{T} as inputs. The shapes of the p_{T} distributions for these three processes are determined from a STARLIGHT simulation. The fit yields 207 ± 18 (stat) for the coherent J/ψ candidates, 75 ± 13 (stat) for the incoherent J/ψ candidates, and 75 ± 13 (stat) for $\gamma\gamma$ events with dimuon $p_{\mathrm{T}} < 0.15$ GeV in the rapidity interval $1.8 < |y| < 2.3$.

The coherent J/ψ photoproduction cross-section in the $\mathrm{X_n0_n}$ break-up mode is given by the following formula,

$$\frac{d\sigma^{coh}_{X_n0_n}}{dy} = \frac{N^{coh}_{X_n0_n}}{\mathcal{B}(1+f_{\mathrm{FD}})\mathcal{L} \times \Delta y (A\epsilon)^{J/\psi}} \tag{4}$$

where $\mathcal{B} = 5.96 \pm 0.03$ (syst)% is the branching fraction of J/ψ to dimuons, $\mathrm{N}^{coh}_{X_n0_n}$ is the coherent J/ψ yield for $p_{\mathrm{T}} < 0.15$ GeV, $\mathcal{L} = 159 \pm 8$ (syst) $\mu\mathrm{b}^{-1}$ is the integrated luminosity, Δ y = 1 is the rapidity bin width, and $(A\epsilon)^{J/\psi}$ = 5.9 ± 0.5 (syst)% is the combined acceptance times efficiency correction factor.

The coherent J/ψ yield is given by,

$$N^{coh}_{X_n0_n} = \frac{N_{yield}}{1 + f_{FD}} \tag{5}$$

where N_{yield} is the coherent J/ψ yield as extracted from the fit, and f_{FD} is the fraction of J/ψ mesons coming from coherent ψ(2S) $\to$ J/ψ + anything, estimated from STARLIGHT to be 0.018 ± 0.011 (theo). The resulting J/ψ yield is, $N^{coh}_{X_n0_n} = 203 \pm 18$ (stat). Thus, the coherent J/ψ photoproduction cross section for prompt J/ψ mesons in the X_n0_n break-up mode is $d\sigma^{coh}_{X_n0_n} = 0.36 \pm$ 0.04 (stat) ± 0.04 (syst) mb. The $d\sigma^{coh}_{X_n0_n}$ cross-section was measured for the X_n0_n break-up mode, and is scaled to the total cross-section by correcting it with a scale factor 5.1 ± 0.5 (theo), estimated with STARLIGHT [9]. After applying this scaling factor we obtain the total coherent J/ψ photoproduction cross section $d\sigma^{coh} = 1.82$ ± 0.22 (stat) ± 0.20 (syst) ± 0.19 (theo) mb.

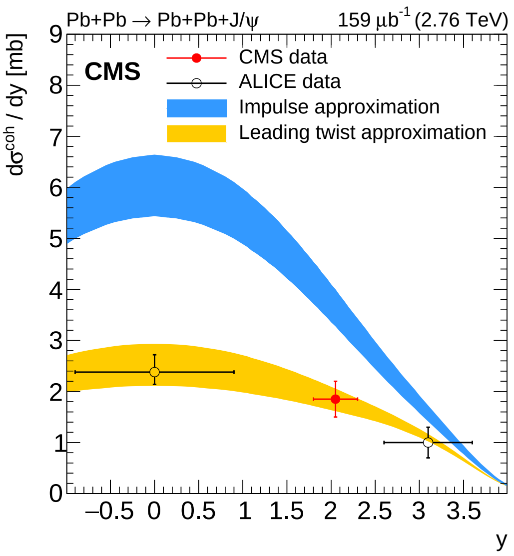

Fig. 5: Differential cross section as a function of rapidity for coherent J/ψ photoproduction [20].

The coherent J/ψ photoproduction cross section is shown in Fig. 5, compared to recent ALICE measurements [23] and to the theoretical predictions by Guzey *et al.* [24, 25] based on the impulse and leading twist approximations. The data from ALICE and CMS show a steady decrease with rapidity. The leading twist approximation prediction obtained from Ref. [25] is in good agreement with the data, while an impulse approximation model prediction is strongly disfavored, indicating that nuclear effects expected to be present at low x and Q^2 values are needed to describe the data. The prediction given by the leading twist approximation, which includes nuclear gluon shadowing, is consistent with the data.

4 Conclusions

Exclusive photoproduction of Υ in pPb at 5.02 TeV and J/ψ in PbPb at 2.76 TeV collisions have been measured by the CMS experiment at the LHC. Both measurements provide new constraints on the poorly-known gluon density at low x in the proton and the lead nucleus respectively.

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