Constraining nuclear parton distributions with heavy ion collisions at the HL-LHC with the CMS experiment

The CMS Collaboration

Abstract

Recent measurements in heavy ion collisions by the CERN LHC Collaborations have been used to assess nuclear effects and provide valuable data for nuclear parton distribution analyses. In this note, performance studies for measurements with the CMS detector at the High-Luminosity LHC (HL-LHC) are presented. These include the coherent $\Upsilon(1S)$ photoproduction in ultraperipheral lead-lead collisions, corresponding to a total integrated luminosity of 10 nb$^{-1}$ at a nucleon-nucleon (NN) center-of-mass energy ($\sqrt{s_{\text{NN}}}$) of 5.5 TeV. This note also presents the performance studies at the HL-LHC for analyses of inclusive Z boson, dijet, and top quark pair production in proton-lead collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV for an integrated luminosity of 2 pb$^{-1}$. 
1 Introduction

This note contains a series of performance studies that illustrate the physics potential using heavy ion data that will be recorded with the CMS experiment in the High-Luminosity LHC (HL-LHC) era in the near future [1]. For the HL-LHC phase, which is planned to operate from 2026, the LHC experiments have requested an integrated luminosity of about $10–13 \text{ nb}^{-1}$ and $2 \text{ pb}^{-1}$ using lead-lead (PbPb) and proton-lead (pPb) data at nucleon-nucleon (NN) center-of-mass energies ($\sqrt{s_{\text{NN}}}$) of 5.5 and 8.8 TeV, respectively.

Based on these scenarios, performance studies for future measurements of coherent $\Upsilon(1S)$ photoproduction in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ are presented. Performance results are also presented for analyses in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$, namely, studies of the inclusive $Z$ boson production, differential cross sections of top quark pair ($t\bar{t}$) production, and the pseudorapidity distributions of dijets. Altogether, these studies show the potential of having large sample sizes to substantially reduce the statistical uncertainty in the measurements that will be carried out as discussed in this note, while opening up new opportunities to study nuclear parton distribution functions (nPDFs) and quantum chromodynamics (QCD) phenomena and its associated nuclear effects (nuclear gluon shadowing, among others).

2 Impact of detector upgrades

The CMS detector [1] will be substantially upgraded in order to fully exploit the physics potential offered by the increase in luminosity at the HL-LHC [2, 3], and to cope with the demanding operational conditions at the HL-LHC [4–8]. The upgrade of the first level hardware trigger (L1) will allow for an increase of L1 rate and latency to about 750 kHz and 12.5 $\mu$s, respectively, and the high-level software trigger (HLT) is expected to reduce the rate by about a factor of 100 to 7.5 kHz. The entire pixel and strip tracker detectors will be replaced to increase the granularity, reduce the material budget in the tracking volume, improve the radiation hardness, and extend the geometrical coverage and provide efficient tracking up to pseudorapidities of about $|\eta| = 4$. The muon system will be enhanced by upgrading the electronics of the existing cathode strip chambers (CSC), resistive plate chambers (RPC) and drift tubes (DT). New muon detectors based on improved RPC and gas electron multiplier (GEM) technologies will be installed to add redundancy, increase the geometrical coverage up to about $|\eta| = 2.8$, and improve the trigger and reconstruction performance in the forward region. The barrel electromagnetic calorimeter (ECAL) will feature the upgraded front-end electronics that will be able to exploit the information from single crystals at the L1 trigger level, to accommodate trigger latency and bandwidth requirements, and to provide 160 MHz sampling allowing high precision timing capability for photons. The hadronic calorimeter (HCAL), consisting in the barrel region of brass absorber plates and plastic scintillator layers, will be read out by silicon photomultipliers (SiPMs). The endcap electromagnetic and hadron calorimeters will be replaced with a new combined sampling calorimeter (HGCal) that will provide highly-segmented spatial information in both transverse and longitudinal directions, as well as high-precision timing information. Finally, the addition of a new timing detector for minimum ionizing particles (MTD) in both barrel and endcap region is envisaged to provide capability for 4-dimensional reconstruction of interaction vertices that will allow to significantly offset the CMS performance degradation due to high PU rates.

A detailed overview of the CMS detector upgrade program is presented in Ref. [4–8], while the expected performance of the reconstruction algorithms and pile-up mitigation with the CMS detector is summarized in Ref. [9].
In the following sections, physics performance studies for both PbPb and pPb collisions, based on the existing data and Monte Carlo (MC) simulations, are presented.

3 Coherent quarkonia photoproduction in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.5$ TeV

The data from ultra-peripheral collisions at the LHC have the potential to provide new constraints to the gluon PDFs in protons and nuclei. Photon-induced interactions can be studied in ultra-peripheral heavy ion collisions [10]. Both the ALICE and CMS Collaborations have recently carried out measurements on coherent photoproduction of $\rho^0$ mesons [11], $J/\psi$ [12–14] and $\psi(2S)$ [15] for the $\gamma +$ Pb $\rightarrow$ VM + Pb process, with "VM" denoting a vector meson. CMS has also results on the exclusive photoproduction of $\rho^0$ [16] and $\Upsilon(1S)$ [17] for the $\gamma +$ p $\rightarrow$ VM + p process. LHCb has also recent results in the exclusive photoproduction of $J/\psi$, $\psi(2S)$ and $\Upsilon$ in pp collisions [18, 19].

It was first suggested by [20, 21] that the photoproduction cross section of vector mesons is proportional to the squared gluon density at the scale $Q = m_V/2$ at leading order QCD. By comparing results of the photoproduction cross section in both $\gamma +$ Pb and $\gamma +$ p interactions it is possible to extract information about the nuclear gluon density at various Bjorken-x values for a given VM. Ref. [22] illustrates how this can be done by calculating the nuclear suppression factor ($R_{Pb}(x)$) which is defined as the root squared of the ratio between the photoproduction cross section measured in $\gamma +$ Pb ($\sigma_{\gamma Pb}$) to the corresponding one in the Impulse Approximation (IA):

$$R_{Pb}(x) = \sqrt{\left(\frac{\sigma_{\gamma Pb}(x)}{\sigma_{IA}(x)}\right)}, \quad \text{where} \quad x = \frac{m_V}{\sqrt{s_{NN}}} \exp(-y). \quad (1)$$

The Impulse Approximation is computed using data from the photoproduction of the vector meson in $\gamma +$ p scaled by the integral over the squared Pb form factor as described in [22]. The impulse approximation calculation neglects all nuclear effects such as the expected modification of the gluon density in the lead nuclei compared to that of the proton. A recent CMS study of coherent $J/\psi$ photoproduction has followed this procedure to estimate the nuclear gluon shadowing as reported in [14].

The high luminosities envisaged for the HL-LHC will significantly extend the Bjorken-x values that can be explored using coherent vector meson photoproduction. Although the gluon shadowing is smaller for $\Upsilon(1S)$ than that for $J/\psi$, having measurements from $\Upsilon(1S)$ photoproduction will serve as important tests to theoretical models that can describe the $J/\psi$ data from existing results by the ALICE and CMS collaborations.

We have used the calculations provided by V. Guzey et al. as described in [23] which takes into account nuclear gluon shadowing corrections [24]. We assume that the CMS experiment will have an improved level of detector and triggering performance during the HL-LHC operation by increasing the combined acceptance and efficiency from about 60% to 80% [17].

Physics performance projections for the nuclear suppression factor for $\Upsilon(1S)$ photoproduction are shown in Fig. 1. The error bars represent the statistical uncertainties, and the boxes the systematic ones.

For rapidity values different than zero there is a two-fold ambiguity in the photon direction of the $\gamma +$ Pb system (either Pb can serve as photon emitter or photon target). To overcome...
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this uncertainty we follow the prescription discussed in [23] that suggests studying the dependence of the vector meson photoproduction cross section on the associated production of forward or backward neutrons (break-up modes) to disentangle the two photon directions. In particular, this would require measuring coherent vector meson photoproduction in the configuration where the $Y(1S)$ is accompanied by at least one neutron in either the forward or backward direction from the interaction point using zero degree calorimeters (ZDC), and in the configuration where both ZDCs record no neutrons.

For a given rapidity interval different than zero there will be two solutions, one corresponding to low Bjorken-$x$ and another one for high Bjorken-$x$ values. Since such a procedure has not been reported in any measurements so far, although there are qualitatively evidence from existing CMS measurements [14] that this method is sound, we are not providing projections for the most forward/backward rapidity intervals that can be studied with the CMS detector where both the theoretical and systematic uncertainties are the largest. At the same time, this is the rapidity interval where measurements corresponding to Bjorken-$x$ below $10^{-4}$ for $Y(1S)$ photoproduction can be explored.

For the measurements with a rapidity value different than zero, the statistical uncertainty is larger for the lowest $x$ solution as shown in Fig. 1. The statistical uncertainty at mid-rapidity is negligible, corresponding to the middle point of the nuclear suppression factor as a function of Bjorken-$x$ as shown in Fig. 1.

This analysis assumes that there will be no significant improvement in the theoretical descriptions of relevant physics effects (photon flux uncertainty). Projected uncertainties on luminosity (4%), reference cross section in photon-proton interactions (5%) and photon flux (5%) result in $\sim 8\%$ systematic uncertainty on the ratio $\sigma_{\gamma Pb}(x)/\sigma_{IA}(x)$ and $\sim 4\%$ uncertainty on the nuclear suppression factor $R_{Pb}(x)$ are reported. Systematic uncertainties in the identification and isolation efficiencies for muons are expected to be reduced to around 0.5%.

The uncertainty in the integrated luminosity of the data sample could easily be reduced from 5% down to 4% in PbPb by a better understanding of the calibration and fit models employed in its determination, and making use of the finer granularity and improved electronics of the upgraded detectors. A luminosity uncertainty in the 3.2–3.5% range has recently been reported for pPb collisions in Run 2 [25].

4 Projections for inclusive Z boson production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

The differential cross section of Z boson production as a function of its rapidity in the center-of-mass frame has also been studied. The integrated luminosity of 2 pb$^{-1}$ at $\sqrt{s_{NN}} = 8.16$ TeV has been considered. The MCFM program is used to generate the Z boson signal [27]. We have used the calculations from the CT14 proton PDF [28] and the EPPS16 nPDF for the lead ions [29]; the latter are used as central values for our projections.

The extrapolation assumes that the CMS experiment will have a similar level of detector and triggering performance during the HL-LHC operation as it provided during the LHC Run 2 period, which is quite a cautious assumption for pPb running. The acceptance and efficiency corrections are estimated using Run 2 simulation, while systematic uncertainties are reduced by a factor 3 with respect to the previous Z boson measurements in pPb collisions $\sqrt{s_{NN}} = 5.02$ TeV [30]. Figure 2 shows the results for the projected Z boson differential cross sections.
Figure 1: Projections for gluon shadowing factor measured with $\Upsilon(1S)$ photoproduction in ultraperipheral PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.5$ TeV. The error bars represent the statistical uncertainties, and the boxes the systematic ones. The projected data is compared to the central value of the EPS09 global fit [26]. The most dominant uncertainties are those of EPS09 (not shown).

5 Projections for $\bar{t}t$ differential cross sections in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

In proton-nucleus collisions, the top quark is a novel and theoretically precise probe of the nuclear gluon density at high virtualities $Q^2 \approx m_t^2$ (where $m_t$ is the top quark mass [31]) in the less explored high Bjorken-$x$ region ($x \gtrsim 2m_t/\sqrt{s_{\text{NN}}} \approx 0.05$ at leading order in QCD). The first observation of the inclusive $t\bar{t}$ production ($\sigma(t\bar{t})$) in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV [32] has been performed using $174 \pm 6$ nb$^{-1}$ [25]. The measured cross section of $\sigma(t\bar{t}) = 45 \pm 8$ nb is consistent with predictions from perturbative QCD as well as with the expectations from scaled pp data. However, the total uncertainty of about 17% is not sufficient for imposing any constraints on current nPDF parameterizations: the PDF uncertainty in the theoretical prediction of $\sigma(pPb \rightarrow t\bar{t} + X) = 59.0 \pm 5.3$ (PDF) $^{+2.1}_{-1.6}$ (scale) nb [32] is approximately 8%, corresponding to a 90% confidence level (CL). The prospects of measuring $\sigma_{t\bar{t}}$ differentially have recently been studied in Refs. [33, 34]. A simple feasibility study of the $\sigma_{t\bar{t}}$ measurement is therefore carried out as a function of the reconstructed lepton $p_T$ and rapidity, based on existing simulated events [32] of the Run 2 CMS detector.

Events are selected fulfilling the same requirements (“visible phase space”) established in Ref. [32]. The baseline selection includes exactly one charged electron (e) or muon ($\mu$) with $p_T > 30$ GeV and $|\eta| < 2.1$, and at least four jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are required, the latter reconstructed based on the anti-$k_T$ clustering algorithm [35] using a distance parameter of 0.4. The QCD multijet background is retained from the nonisolated control region obtained with the pPb data sample of $174$ nb$^{-1}$ [32], whereas the signal ($m_t = 172.5$ GeV) is simulated at next-to-leading order with POWHEG (v2) [36–38] using PYTHIA (v8.205) [39] to simulate parton showering and hadronization. The existing MC samples [32] make use of PYTHIA (v6.424) [40] for simulating $W$+jets and Drell–Yan (DY) production of charged-lepton pairs with invariant mass larger than 30 GeV. The expectation of signal and background processes is scaled to 2 pb$^{-1}$.

The $\sigma_{t\bar{t}}$ measurement is performed fitting the mass, $m_{jj'}$, of the non b-tagged jets that are closest
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Figure 2: Projections for Z boson differential cross section in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV as a function of the Z boson rapidity in the center-of-mass (CM) frame. The expectations from CT14 PDF and EPPS16 nPDF are also shown.
in the $\eta$-$\phi$ plane according to the $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ criterion, where $\Delta \eta$ and $\Delta \phi$ are their separations in pseudorapidity and azimuthal angle. This dijet system is expected to be primarily found in $W \rightarrow q\ell\nu$ decays, and hence expected to be of resonant and combinatorial nature for most of the $t\bar{t}$ signal and background events, respectively. The fit is combined from different event categories depending on the flavor of the charged lepton and the b-tagging multiplicity. Figures 3 shows the dijet invariant mass and a proxy of the top quark mass, $m_{\text{top}}$, defined as the invariant mass of the $t \rightarrow j j b$ candidate formed by pairing the W candidate with a b-tagged jet [32].

To separate the signal from background contributions, and hence optimizing for the conjectured pPb data sample, we make use of the $s_P$Plot technique [41]. The $m_{jj'}$ (“discriminating”) variable, used to extract the signal and background yields, does not correlate with the lepton kinematic (“control”) variables, rendering it particularly suited to the $s_P$Plot technique. Figure 4 displays the differential $\sigma_{tt}$ in the visible phase space as a function of the charged lepton $p_T$ and rapidity at reconstruction (“detector”) level. The relative statistical uncertainty in both variables is found to be at the level of 4–5% in each bin, and it is expected to be the dominant uncertainty. Despite the fact that most sources of systematic uncertainty are expected to cancel out in the normalized measurement of the differential $\sigma_{tt}$, a kinematic-independent systematic uncertainty of 5% is taken into account. The latter is considered as a conservative estimate, given the extrapolation—as described above—assumes similar future performance to Run 2, and it is partly motivated from Ref. [42]. No unfolding of the detector- to particle-level [43] dis-
tributions is performed, although the physics reach should not be compromised significantly because of the high purity/stability of the response matrices.

The bottom panel of Figure 4 displays the ratio between the pseudo-data used in the study and the POWHEG+PYTHIA prediction employing the EPPS16 nPDFs. The comparison between the projected and the overall nPDF uncertainty is also shown. To that end, the nPDF uncertainty is scaled from 90 to 68% CL, and is computed using the prescription described in Ref. [44]: In the Hessian representation, a central PDF is given along with error sets, each of which corresponds to an eigenvector of the covariance matrix in parameter space.

Figure 4: The top panels represent the differential $t\bar{t}$ production cross section in the visible phase space as a function of the charged lepton $p_T$ (left) and rapidity (right) at reconstruction level. The statistical uncertainty in the pseudo-data, represented by the inner error bars, is estimated through the application of the $e$Plot technique [41]. The outer error bars represent the total uncertainty, assuming a conservative 5% systematic uncertainty envelope. The uncertainty in the POWHEG+PYTHIA [36–39] prediction is shown as a band corresponding to the 68% CL variation envelope of the EPPS16 [29] nPDF eigenvalues. The bottom panels represent the relative uncertainties in the pseudo-data and theory predictions.

6 Projections for dijet pseudorapidity distributions in pPb collisions

Theoretical calculations and recent experimental data have shown that dijet pseudorapidity distributions are sensitive to nuclear modifications of the gluon nPDFs [45, 46]. The expected luminosities for pPb collisions at $\sqrt{s_{NN}} = 8.8$ TeV during the HL-LHC phase will allow for an extension of the current measurements from pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [46] by one bin to lower $\eta_{dijet}$ values.

The projected results for the ratio of the dijet pseudorapidity distributions between pPb and pp data, and the associated statistical and systematic uncertainties, are shown in Fig. 5.

The central values used in the projections are based on the existing data and smoothed by a third-order polynomial fit. The statistical uncertainty is scaled to a total integrated luminosity of 2 pb$^{-1}$. While the systematic uncertainties are reduced based on an assumption of a 50%
reduction in the uncertainty in jet energy scale, consistent with other projections of jet measurements in heavy ion collisions. This result is a consequence of the large increase in available data, since the absolute jet energy scale is derived using a data-driven method based on photon- and Z-jet events. This technique is currently limited by the small total number of such events at large $\eta$. Hence, an improvement in the derivation of the jet energy scale corrections and its associated systematic uncertainty in that region can be expected with the higher luminosities.

7 Summary

We have presented a series of performance studies for future measurements in both PbPb and pPb collisions for the High-Luminosity LHC project, putting special emphasis on a selected number of physics analyses that can serve to get insights into nuclear effects and nuclear parton distribution functions with the projected larger sample sizes that are envisaged.
References


[16] CMS Collaboration, “Exclusive $\rho(770)^0$ photoproduction in ultraperipheral pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the CMS experiment”, CMS Physics Analysis Summary CMS-PAS-FSQ-16-007, 2018.


