Probing small x parton densities in ultraperipheral AA and pA collisions at the LHC

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We calculate photoproduction rates for several hard processes in ultraperipheral proton-lead and lead-lead collisions at the LHC with $\sqrt{s_{NN}} = 8.8$ and 5.5 TeV respectively which could be triggered in the large LHC detectors. We use ATLAS as an example. The lead ion is treated as a source of (coherently produced) photons with energies and intensities greater than those of equivalent ep collisions at HERA. We find very large rates for both inclusive and diffractive production which will extend the HERA x range by nearly an order of magnitude for similar virtualities. We demonstrate that it is possible to reach the kinematic regime where nonlinear effects are larger than at HERA.

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Studies of small x deep inelastic scattering at HERA substantially improved our understanding of strong interactions at high energies. Among the key observations at HERA were the rapid growth of the small x structure functions over a wide range of virtualities, Q^2, and the significant probability for hard diffraction consistent with approximate scaling and a logarithmic Q^2 dependence ("leading twist" dominance). HERA also established a new class of hard exclusive processes – high Q^2 vector meson production – described by the QCD factorization theorem and related to generalized parton distributions in nucleons.

The importance of nonlinear QCD dynamics at small x is one of the focal points of theoretical activity (see *e.g.* Ref. [1]). Analyses suggest that the strength of the interactions, especially when a hard probe directly couples to gluons, approaches the maximum possible strength – the black disk limit – for $Q^2 \leq 4$ GeV^2. These values are relatively small, with an even smaller Q^2 for coupling to quarks, $Q^2 \sim 1$ GeV^2, making it difficult to separate perturbative from nonperturbative effects at small x and Q^2. Possible new directions for further experimental investigation of this regime include higher energies, nuclear beams and studies of the longitudinal virtual photon cross section, σ_L. The latter two options were discussed for HERA [2, 3]. Unfortunately, it now seems that HERA will stop operating in two years with no further measurements along these lines except perhaps of σ_L. One might therefore expect that experimental investigations in this direction would end during the next decade.

The purpose of this letter is to demonstrate that several of the crucial directions of HERA research can be continued and extended by studies of ultraperipheral heavy ion collisions (UPCs) at the LHC using the current detectors. UPCs are interactions of two heavy nuclei (or a proton and a nucleus) in which a nucleus emits a quasi-real photon that interacts with the other nucleus (or proton). These collisions have the distinct feature that the photon-emitting nucleus either does not break up or only emits a few neutrons through Coulomb excitation, leaving a substantial rapidity gap in the same direction. These kinematics can be readily identified by the hermetic LHC detectors, ATLAS and CMS. In this paper we consider the feasibility of studies in two of the directions pioneered at HERA: parton densities and hard diffraction. The third, quarkonium production, was discussed previously [4–6]. It was shown that pA and AA scattering can extend the energy range of HERA, characterized by $\sqrt{s_{\gamma N}}$, by about a factor of 10 and, in particular, investigate the onset of color opacity for quarkonium photoproduction. UPC rates for hard photoproduction at the LHC were previously presented for $Q\overline{Q}$ [7–9] and for dijets and γ+jet [10]. However, it was heretofore unclear whether the x-range relevant for heavy ion collisions at the LHC, $10^{-4} < x < 10^{-3}$, could access high gluon densities at small x and moderate Q^2. This is the first study to more fully address the kinematic range available at the LHC using current detectors and planned luminosities.

Though we can only study reactions initiated by a quasi-real photon, this is not a disadvantage in the study of new phenomena relative to HERA. Indeed, nonlinear effects should set in earlier in the gluon sec-

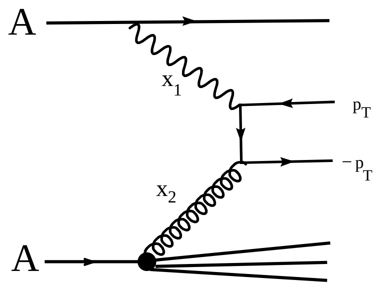

FIG. 1: Diagram of dijet production by photon-gluon fusion where the photon carries momentum fraction x_1 while the gluon carries momentum fraction x_2.

tor, more easily accessed through photon-gluon interactions than inclusive electron-hadron scattering. In the following discussion, we assume that DGLAP evolution of the parton densities holds in the region we explore. For definiteness, we discuss measurements of the nucleus (proton) inclusive parton distribution functions (PDFs) and diffractive PDFs, even though it appears that part of the accessible kinematics is within the domain where the DGLAP approximation is likely to break down. In principle, the nuclear (proton) PDFs (though not the diffractive PDFs) could be studied in pp and pA collisions. However, PDF studies in the p_T range we explore are impossible in hadronic interactions due to the large background from *e.g.* multiple jet production. Photon-nucleus interactions are thus much cleaner than proton-nucleus interactions. In addition, the LHC pA program is likely to begin several years after the start of the heavy ion program.

In our study, we calculate dijet and heavy flavor production to leading order (LO) in nucleus-nucleus collisions, as in Ref. [9, 10]. Based on HERA studies, we use a 5 GeV p_T cutoff for the applicability of perturbative QCD to jet production. We also assume the ATLAS detector coverage and performance as discussed below. We use the MRST LO nucleon PDFs [11] to estimate the counting rates since, while nuclear shadowing is theoretically important, it is expected to be less than factor of two for gluons in the p_T range we discuss. We calculate inclusive rates as a function of gluon x and jet p_T to compare with HERA.

The coherent diffractive processes we study are characterized by gaps in the directions of both nuclei and two jet production near the edge of the rapidity interval where hadrons are produced, as is the case for direct photon-nucleus/nucleon interactions. The diffractive rate is intimately related to the phenomenon of nuclear shadowing and the onset of the black disk limit where coherent diffraction would be 50% of the total cross section. In our numerical studies, we used the only nuclear diffractive PDFs currently available [12], based on the leading twist description of hard diffraction in ep scattering and using a quasi-eikonal approximation to model diffraction off more than 3 nucleons.

In our calculations, we focus on small x kinematics where a photon interacts predominantly with a gluon via photon-gluon fusion. Since the direct mechanism dominates in this kinematics, we ignore the partonic constituents of the photon. We define x_1 as the momentum fraction carried by the photon while x_2 is the momentum fraction carried by the gluon from the nucleus (both per nucleon) or proton (see Fig. 1). The average jet rapidity is $y \sim -0.5 \ln(x_1/x_2)$. The photon x_1 is related to the jet p_T by $x_1 x_2 \sim 4p_T^2/s_{NN}$.

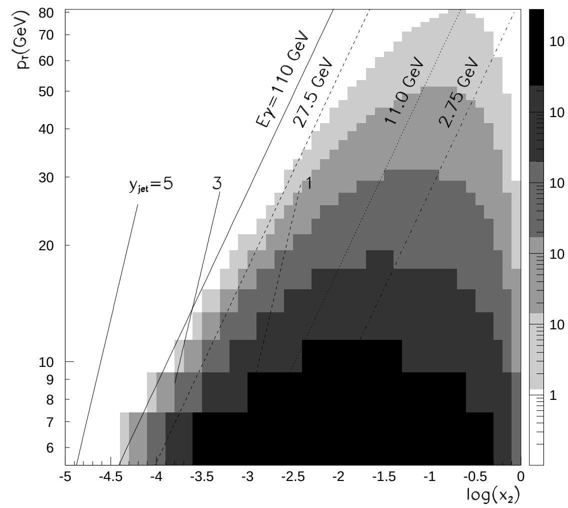

FIG. 2: The expected inclusive dijet photoproduction rate for a one month LHC Pb+Pb run at 0.42×10^{27}cm^{-2}s^{-1}. Rates are in counts per bin of $\pm 0.25 x_2$ and ± 1 GeV in p_T.

Event rates were calculated in bins of ± 1 GeV in p_T and $\pm 0.25 x_2$ in x_2 for a nominal one month run, 10^6 s. We take an average luminosity of 0.42×10^{27}cm^{-2}s^{-1} for Pb+Pb collisions [13] and 7.4×10^{29}cm^{-2}s^{-1} for pPb collisions [14]. Figure 2 shows that the x dependence of the gluon density at *e.g.* $p_T \sim 6$ GeV can be studied two orders of magnitude below $x \sim 10^{-2}$ to search for the onset of nonlinear effects at small x. This onset is detectable by the reduction of the predicted rate increase with decreasing x.

UPC data can be recorded exploiting the full live time available as long as an acceptable trigger can be found. The PHENIX collaboration at RHIC found that a loose UPC trigger in Au+Au runs yielded a trigger rate of $< 0.5\% \, \sigma_{\rm inel}$ ($10-20$ Hz at the LHC) [15]. The PHENIX UPC J/ψ trigger required a single high p_T electron, a rapidity gap and a leading neutron tag.

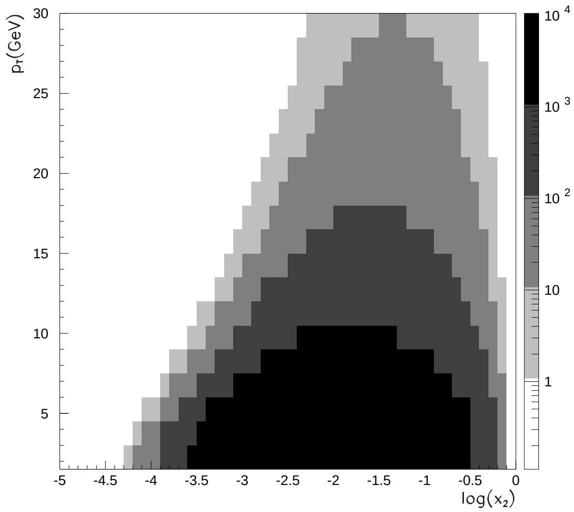

FIG. 3: The rate for inclusive $b\bar{b}$ photoproduction. Here the p_T bins are ± 0.75 GeV.

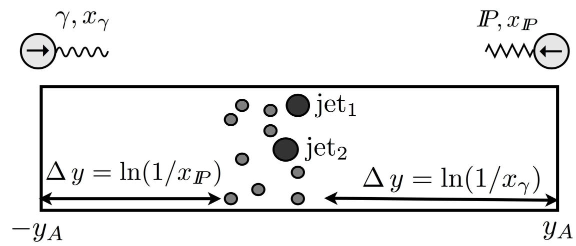

FIG. 4: A schematic lego plot of a diffractive photoproduction event showing the gap between the photon-emitter nucleus and the produced dijet system on the right-hand side and the additional gap between the Pomeron-emitter nucleus and the dijet system on the left-hand side. The dijet is accompanied by fewer soft hadrons than in inclusive photoproduction where the nucleus that emits the parton breaks up.

In our case, there is always a high p_T jet as well as the potential for a heavy flavor tag using soft leptons or a secondary vertex, well within the calorimeter and tracking acceptance of ATLAS, for example. Because the ATLAS calorimeter extends ± 4.9 units in η, it should be possible to veto on activity with $E_T \geq 2$ GeV within $2.9 < |\eta| < 4.9$ along the direction of the ion emitting the exchanged photon. The target lead ion will always emit an evaporation neutron which can be tagged with the ATLAS Zero Degree Calorimeters except in the case of coherent diffractive photoproduction. Furthermore, the neutron multiplicity is correlated with centrality in photon-nucleus collisions and hence can be used to select central collisions where high gluon density effects are maximized.

In Fig. 2 we present the counting rate per x_2 and p_T bin accumulated in a one month LHC Pb+Pb run. In addition to the rates, we show contours of constant photon energy. Photon energies of a few GeV up to ~ 100 GeV dominate the rates. Under normal conditions, these photons will collide with nuclei at energies of 2.75 TeV/nucleon. Contours of constant average jet rapidity are also shown in Fig. 2. It is significant that jet production is predominantly in the region $|y_{\rm jet}| \leq 3$ and therefore well matched to the calorimeter coverages of ATLAS and CMS at the LHC. The rapidity gap distinguishes these photoproduced jets from those produced in the more abundant nuclear collisions.

The ATLAS experiment was designed to study jet production at $p_T > 10$ GeV. It is not yet clear what lower p_T limit will apply to photoproduction where neither the "underlying event" nor multiple event pileup are present to degrade the measurement. The counting rate per bin, $100-1000$ for $p_T \geq 10-20$ GeV, should be high enough for meaningful statistics.

Figure 3 shows the corresponding $b\bar{b}$ photoproduction yield. The b's can be detected via a detached vertex using the ATLAS pixel tracker or via a soft lepton tag. We also calculated gamma-jet production but, since the rates are several orders of magnitude smaller than the dijet rates, they are not shown.

We have also calculated diffractive $b\bar{b}$ and dijet photoproduction employing the leading twist analysis of the diffractive PDFs in Ref. [12]. This analysis suggests that even at $p_T \sim 5-10$ GeV, diffractive nuclear interactions at $x_2 \leq 10^{-3}$ will be rather close to the black disk limit where more than 20% of events are diffractive. Accordingly, the diffractive rates are large over most of the x_2 range and the fraction of the total cross section due to diffractive processes should be measurable to less than 10% for almost all bins (see rates in Figs. 2 and 3). There is, however, a potential problem specific to diffractive events: determining which nucleus emitted the photon and which the "Pomeron". Such an event is shown schematically in Fig. 4. One can generally identify the photon source by comparing the invariant mass of the entire produced system, the dijet and the accompanying soft hadrons, the diffractive mass, to that of the dijet alone. For most events the diffractive mass is much larger than the dijet mass and the gap between the dijet and the photon-emitting nucleus is larger than that on the Pomeron-emitter side, making identification of the photon source possible. In the rare cases where the diffractive and dijet masses are similar, fewer accompanying hadrons are produced in a limited rapidity range and the gaps on both sides of the produced system are nearly the same and the identification of the photon source is not possible. In this case, the x range is more restricted.

Measurements of diffractive jet production present a triggering challenge for ATLAS since essentially the only activity in the event is a pair of soft jets at midrapidity. The target nucleus does not break up as in the non-diffractive case. Therefore, we have also calculated photoproduction cross sections including the exchange of low energy photons. These low energy photons are plentiful since the strength parameter, $Z^2\alpha$, is of order unity in heavy ion collisions. The calculation proceeds as in Ref. [16]. The fraction of events with additional photon exchanges which break up both beam nuclei is strictly a function of primary photon energy and is $\sim 20-40\%$ over most of our kinematic range.

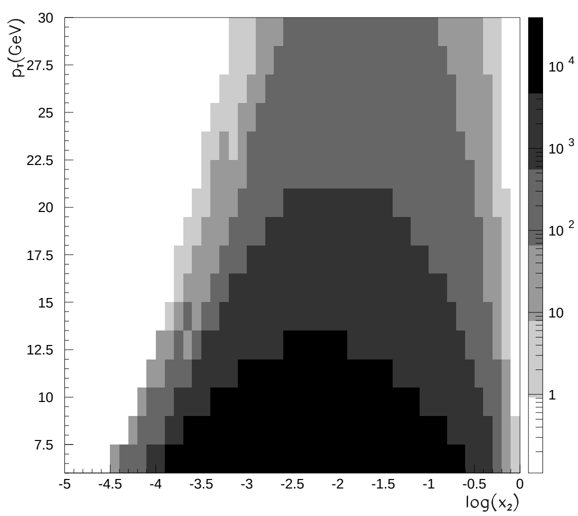

FIG. 5: The expected inclusive $b\bar{b}$ photoproduction rate in a one month LHC pPb run at $7.4\times10^{29}\text{cm}^{-2}\text{s}^{-1}$.

The LHC can also run with asymmetric species so that pPb collisions are likely to be a part of the heavy ion program. Under these conditions, the LHC will extend to higher energy, albeit at large Q^2, the proton structure measurements carried out at HERA. Figure 5 shows the $b\bar{b}$ photoproduction rates for collisions of photons emitted by the lead nucleus with gluons from the proton beam. The $b\bar{b}$ photoproduction rate is considerably higher than in Pb+Pb, primarily due to the increased energy of the proton beam relative to the lead beam. The $c\bar{c}$ rate is at least a factor of four larger. Heavy quark production is optimal in pA since the strong interaction contribution due to screened Pomeron exchange becomes important in dijet production [17]. The diffractive rates should also be a significant fraction of the total rate, $\geq 10\%$, allowing study of the diffractive proton PDFs at smaller x than at HERA. If the 420 m tagging proton stations [18] are implemented, proton dissociation events are likely to be suppressed more effectively than at HERA. The mass resolution of the diffractive system is also likely to improve.

Our calculations have assumed that the linear DGLAP approximation is valid. However, at the lowest values of x_2 and p_T we study, DGLAP evolution may break down. The validity of the DGLAP approximation at a given x and Q^2 can be characterized by the ratio of the first nonlinear evolution term to the DGLAP linear term, $C\alpha_s(Q^2)xg(x,Q^2)/Q^2R_T^2$, where R_T is the radius of the target. The coefficient C is a factor of 9/4 larger for processes dominated by direct coupling to gluons relative to quark couplings. The highest HERA Q^2 bin where nonlinear effects may be present is $Q^2\sim 4$ GeV^2. At this Q^2, $F_2(x,Q^2)$ measurements are available down to $x=10^{-4}$. On the other hand, UPC measurements at the LHC can reach $x\sim5\times10^{-5}$ for our minimum p_T of 5 GeV. To quantify how much further UPCs are into the nonlinear regime than are ep collisions at HERA, we form the double ratio [2],

$$\frac{(9/4)0.7\,A^{1/3}\alpha_s(p_T^2)xg(x\sim5\times10^{-5},p_T^2)/p_T^2}{\alpha_s(Q^2)xg(x\sim10^{-4},Q^2)/Q^2}\sim 3\,. \tag{1}$$

The factor of 0.7 is the ratio $(r_N/R_A)^2$ multiplied by a factor of 1.5 for photons going through the center of the nucleus. To calculate Eq. (1), we used recent leading-order parton density fits and neglected leading-twist nuclear shadowing, a small correction for $p_T\geq5$ GeV. Note that by comparing the ratios at the same values of x and Q^2, Eq. (1) becomes $(9/4)0.7\,A^{1/3}\sim 9$ for lead beams. We can form a similar ratio of UPCs at the LHC to eA collisions at the proposed eRHIC collider where the lowest x is $\sim10^{-3}$ for $Q^2\sim4$ GeV^2, finding a relative ratio of ~1.5. The increase in the importance of the nonlinear regime for UPCs at the LHC relative to ep and eA collisions are due to the direct gluon coupling and a much larger x range as well as the use of nuclear beams (relative to ep collisions).

We thus demonstrate that UPCs probe the nuclear PDFs at $p_T\geq5$ GeV over an x range a factor of ten greater than at HERA as well as determine the nuclear diffractive PDFs in much of the same x range. An LHC pA run will also extend the HERA x range of the inclusive and diffractive gluon PDFs in the proton a factor of ten. All together UPC studies will greatly extend the program of the small x studies at HERA and provide a very valuable input for modeling initial stage of heavy ion collisions at LHC.

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