Trip the light fantastic: what DIS2022 should know about ultraperipheral collisions at high energy colliders

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Abstract. A brief review of ultraperihperal physics at major hadron and nuclear colliders is presented, with emphasis on topics which could be of interest to the DIS community

1 Introduction

The heavy ion programs at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, and the Large Hadron Collider (LHC) at CERN have been operating for more than 20 and 10 years, respectively. They collide both heavy ions (gold and lead) as well as offering symmetric (p+p) and asymmetric collisions involving protons, primarily as reference data to study nuclear effects. They have provided enormous insight into the dynamics of the hot and dense matter produced in these collisions, typically referred to as the quark-gluon plasma [1].

Some discoveries in heavy ion collisions typically involve establishing an expected scaling behavior, related to the intrinsic geometry of the colliding nucleons or nuclei [2], and then observing scaling violations, which can then be interpreted in terms of nuclear effects. The paradigmatic example of this is the phenomenon of "jet quenching" [3], where the yields of jets and dijets [4] are found to not scale as the number of binary nucleon-nucleon collisions. This is a robust expectation since, when scaled by the interaction luminostiy, the number of binary collisions provide the effective nucleonic luminosity.

Parton collectivity, another geometric effect, has also been a fertile area for major discoveries with heavy ions. In this case, observations have found that particles are not produced azimuthally symmetrically event-by-event. Instead they show clear correlations with a plane defined by the impact parameter between the colliding nuclei, which is lenticular due to the overlap of the highly-Lorentz-contracted spherical (or near spherical) nuclei. These correlations are characterized as Fourier coefficients of the angular distributions relative to the event plane angle. They are found to vary with the event centrality in such a way that calculations which assume particle production primarily following the nucleon positions, chosen randomly based on the known nuclear densities, and then near-ideal hydrodynamic evolution. Deviations from ideal hydro are found to be consistent with the presence of bulk and shear viscosity, typically at levels consistent with an upper bound that can be predicted using quantum mechanical or string-theory arguments.

However, while collectivity had long been observed in collisions involving large nuclei, proton-lead results at the LHC, followed by deuteron-gold results at RHIC, showed that similar collective effects are present in the much smaller systems. Non-zero Fourier coefficients,

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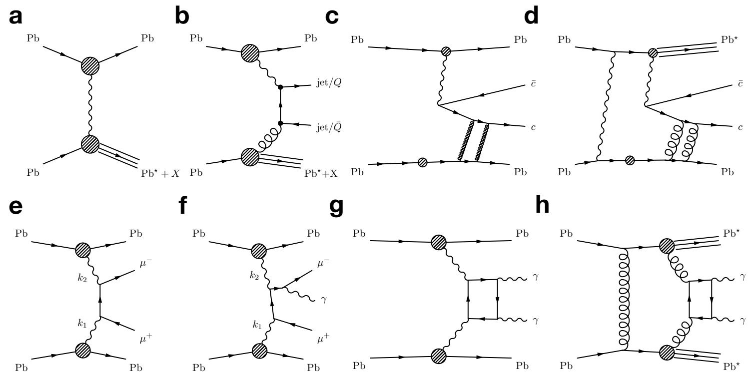

Figure 1. Feynman diagrams for many of the processes described in these proceedings: a) nuclear breakup, b) dijet production, c) vector meson production, d) vector meason production with breakup, e) dilepton production, f) dilepton production with additional final-state-radiation, g) light-by-light scattering, h) central exclusive production.

which show similar magnitudes and dependencies on particle p_T as seen for the larger systems. PHENIX has observed characteristic differences expected from colliding nuclei with A=1-3 (protons, deuterons and 3He) with Au, observing increased v_3 in the more "triangular" 3He system [5]. ATLAS has even observed this for heavy quarks, with a strong flow observed for decay muons from charm hadrons in 13 TeV pp collisions, but none from the decays of bottom hadrons [6]. In order to understand these results, one has to fascinating questions about the spatial structure of nucleons, and perhaps even short range correlations among nuclei. In particular we must finally understand the "shape" or "geometry" of a proton, something of great interest to scientists working at the upcoming electron-ion collider coming to Brookhaven Lab in the early 2030s in collaboration with Jefferson Lab. Studies of, e.g. deeply-virtual Compton scattering off of both nucleons and nuclei will help study TMDs and GPDs, parton distributions which both reflect geometric aspects [7].

2 Ultraperipheral collisions

Up to this point, the heavy ion collisions discussed have all involved impact parameters less than twice the nuclear radius ($b < 2R$), for which one expects strong interactions between the nucleons. From this vantage point, the nuclei will "miss" each other entirely at large impact parameters. However, stripped nuclei have strong electromagnetic (EM) fields, reflecting the proton charge distribution, which is strongly enhanced in the longitudinal direction by the Lorentz contraction along the beam direction. Magnetic field strengths for lead and gold are expected to reach upwards of 10^{15} T. So while high energy heavy ion collisions have already been proven to be powerful QCD laboratories, their surrounding EM fields make them equally powerful QED laboratories as well. This is the domain of "ultraperipheral collisions" (UPC) [8], which is the primary topic of these proceedings.

While full QED calculations involving nuclei have been carried out, the more typical approach to doing physics with the nuclear EM fields involves the equivalent photon approximation, based on the work of von Weiczsacker [9] and Williams [10] in the early 20th century, as well as work by Fermi [11]. This approximation assumes that the spectrum of photons is essentially the Fourier transform of the field of the contracted nuclear charge distribution. For a point charge, this gives a photon flux as a function of the longitudinal photon energy k and the radial distance b as $n(k,b) \propto (\alpha Z^2/kb^2) f(kb/\gamma)$, where α is the fine structure constant, and γ the Lorentz factor the beam. The function $f(x)$, where x is dimensionless, is dominated by $x^2 K_1^2(x)$. Based on this distribution, one can determine that the maximum energies reached scale as γ/R, where R is the nuclear radius. This is about 80 GeV at the LHC and 3 GeV at RHIC. Since there is no boost in the transverse direction, the typical transverse momentum scale does not depend on beam energy and is primaily $\hbar c/R$, so about 30 MeV. Finally, the Z^2 in the numerator implies that heavy nuclei provude particularly intense photon sources, and processes involving interactions of two photons scale as Z^4.

Ultraperipheral collisions provide two primary classes of events, which provide access to very different physics. Typical Feynman diagrams for them are shown in Fig 1. Photon-photon collisions are more accessible using ions than for protons due to the Z^4 enhancement, and allow detailed studies of QED. While the primary processes studied at RHIC and the LHC are dileptons (with final states involving electrons, muons and taus), two-photon final states (often called "light by light scattering") are also accessible via loop diagrams, and so with much lower rates. While resonance production, e.g. the f_2 meson, is also accessible, these have not been measured in heavy ions so far. Similarly, diquark final states are expected to be observed, but have not yet been specifically identified above the known background jets produced via central diffraction. Photonuclear processes, involving a photon emitted from one of the nuclei interacting strongly in the other nuclear wave function, have also been widely studied. If the process is diffractive in nature, exclusive vector mesons can appear in the final state, and these have been studied extensively at the LHC. However, the process can also be inelastic and involve soft scales, leading to production of hadrons primarily in the forward or backward direction, or hard scales, leading to jet production. Both of these processes are sensitive to the partonic structure of the nucleus (i.e. nPDFs), although exclusive vector meson production involves the exchange of two photons, and so is more complex theoretically. Either way, both processes are thought to be sensitive to the phenomenon of parton saturation, another topic of great interest for the electron-ion collider.

3 Higher order contributions

Although the Feynman diagrams for exclusive processes imply that the photon-emitting nuclei emerge intact, the leading order diagrams do not account for secondary photon exchanges. Secondary photon exchanges between the nuclei can lead to the breakup of one or both nuclei, e.g. via the excitation of the giant dipole resonance [12], where the protons and neutrons oscillate against each other and lead to the emission of one or more neutrons, and potentially other fragments. These are easily observed in the Zero Degree Calorimeters (ZDCs) installed in most heavy ion experiments to measure the spectator neutrons emerging from hadronic nuclear interactions, and show up as clear peaks in the ZDC energy spectrum, corresponding to 1-4 neutrons. Beyond that the peaks typically merge into a continuum. In many papers, the breakup patterns are charactersized by the ZDC "topology": no neutrons in either direction ("0n0n"), neutrons in one direction only ("Xn0n" or "0nXn"), and neutrons in both directions ("XnXn");

The expression for the nuclear photon fluxes show that the fluxes are largest closer to the nuclear barycenter, implying that there is a larger secondary breakup rate for smaller nuclear impact parameters. This further implies that selecting a particular ZDC neutron topology also selects a range of impact parameters between the nuclei. Calculations using the STARlight model, which convolves measured photoneutron cross sections with the EPA photon fluxes gives approximate ranges for 0n0n selecting $b > 40$ fm, $0nXn$ as $20 < b < 40$ fm, and finally $XnXn$ selecting $b < 20$ fm.

4 Physics with exclusive dileptons and photons

4.1 Photon luminosity with dimuons and dielectrons

Exclusive, non-resonant, dilepton production from $\gamma\gamma$ interactions, known as the Breit-Wheeler process for dielectron production [13] is one of the cleanest ways to study photon fluxes, particularly when performed with seletions on the ZDC, and it is also sensitive to the details of the QED showering process. However, it is also sensitive to background from dissociative processes, where a nucleon in the nucleus breaks up, but this can be controlled using the ZDCs. Distributions of acoplanarity ($\alpha = 1 - |\Delta\phi|/\pi$) are described quite well by STARlight [14] with Pythia8 QED showering, when it is required to have no signals in the ZDC. Conversely, when either one or two ZDC arms shows activity, it is required to include contributions from dissociative processes, e.g. modeled by LPair or SuperChic.

While the basic ideas underlying the calculations of the photon fluxes are shared between different groups, the handling of the nuclear charge distribution is handled somewhat differently between different calculations. Furthermore, some groups account for the linear (radial) polarization of the incoming photons, which has observable impact on the dilepton opening angles, but others do not. The STARlight generator convolves the photon fluxes from the two collidering nuclei, but performs radial cuts which exclude photon-photon collisions when either 1) when the two nuclei are close enough to have a hadronic interaction, or 2) if the production point is inside either nucleus. Although the latter selection achieves most of what it achieved in other calculations, e.g. SuperChic [15], through a consistent use of the nuclear form factor, it also excludes a region in which the dileptons could be produced and still remain exclusive, since the interactions of the leptons themselves are not strong enough to perturb the remaining nucleus. While SuperChic does not exclude this region, giving systematically higher cross sections, it has not yet implemented forward neutron production. However, there exist afterburners in the literature which could perhaps be used to restore this.

Detailed dilepton data has been release by ATLAS and CMS at the LHC for both muons and electrons, and by STAR at RHIC for dielectrons, and detailed comparisons to models have been performed. For both electrons [16] and muons [17] in ATLAS, STARlight is found to give a good description of the cross sections as a function of dilepton invariant mass, but underestimates the rates at larger pair rapidity. SuperChic 3.0 is found to describe better the shape of the rapidity distribution, but it systematically overestimates the cross sections, something which may be tamed using higher-order Coulomb corrections [18, 19]. ATLAS compares dimuon rates to STARlight after performing ZDC selections and gets qualitative agreement, but STARlight tends to overestimate the amount of secondary fragmentation, suggesting that it does not quite capture the impact parameter dependence of the breakup process. While CMS does not measure absolute cross sections, it has performed a measurement of the acoplanarity as a function of the ZDC topology, including some selections with only one neutron on each or both sides [20]. There, they observe a systematic broadening of the acoplanarity, which perhaps reflects an impact parameter dependence of the transverse distributions of the intial photons. Finally, STAR has measured the distribution of the angle ϕ, the opening angle between the vectors of the pair momentum sum and difference, observing a modulation characteristic of the linear polarization of the initial photons [21].

STAR and ATLAS [22] have also performed measurements of nearly back-to-back dileptons in events with substantial nuclear overlap. These events would be rejected by a typical UPC analysis, and are accompanied by a substantial background from heavy flavor decays at the LHC. However, such backgrounds are not present at RHIC. In both colliders, the acoplanarity or dilepton p_T distributions are found to be broader than expectations from UPC processes. The results have been found to be consistent with ab initio QED calculations, which deplete the cross section at low pair p_T due to QED interference effects.

4.2 Beyond the standard model physics with tau pairs

Recent results from ATLAS illustrate the potential for using UPC processes for probing physics beyond the standard model (BSM). The anomalous magnetic moment (g-2) of the tau lepton is sensitive to BSM physics since new particles modify the coupling of the tau to the incoming photon. This both affects the cross section for tau pair production and modifies the tau p_T distributions, as demonstrated by several theoretical frameworks utilized by the experimental measurements. As of this year, there are now first measurements from ATLAS and CMS, both based on single muon triggers but utilizing different number of tau lepton final states. In principle there are three decay modes accessible by the experiments: 1) the muon-electron decay mode, which has the lowest backgrounds, but also has low statistics, 2) the muon+1 track mode, and 3) the muon+3 track modes.

CMS [23] uses only the μ+3 track modes, and finds 77 ± 12 signal events in the 2015 Pb+Pb data with 404 μb^{-1}. They fit for a_τ using the predicted dependence of the cross section, and using an MC efficiency of 78%. This gives an extracted cross section of $4.8 \pm 0.6 \pm 0.5$ μb. Calculations of Beresford and Liu are then used to bound $(-8.8 < a_\tau < 5.6) \times 10^{-2}$ at 68% CL. There are high expectations of the data to be taken in LHC Runs 3 and 4, which should reduce the errors for this particular measurement by about a factor of 4-5. ATLAS [24] uses all three channels in the 2018 data with 1.44 nb^{-1}, requiring a 0n0n topology to suppress dissociative and hadronic backgrounds. They find 650 events and fit for a_τ using modifications to the $p_{T\mu}$ distributions, using $\mu\mu$ events to normalize the photon flux. The extracted cross section is found to be within 5% of expectations and a most probably value of $a_\tau = -0.04$ but with 95% CL limits within -0.058 and -0.012 as well as -0.006 and 0.025. These limits are similar in size to DELPHI data from 2004, and substantial improvements are expected using the Run 3 and 4 data

4.3 Light by light scattering

Light-by-light scattering had been predicted since the earliest days of QED but never observed directly until LHC measurements using the 2015 data. The production of two final state photons proceeds through box diagrams and so is also sensitive to a wide array of BSM processes. The signal process is a two-photon final state with no other activity in the detector, and with the two photons nearly back to back. However, electron pairs can mimic final state photons if the tracks are not observed. Also, there exist central exclusive production processes that are fundamentally gluon mediated, but which give large acoplanarity values. For both ATLAS [25–27] and CMS [28], the diphoton acoplanarity is used to define a signal region $\alpha < 0.01$. The electron pair background is addressed using data-driven methods, as is the CEP background, the latter including checks based on ZDC selections. The most recent ATLAS measurement uses the full Run 2 data set (2.2 nb^{-1}) and achieves a significance of over 8 sigma. Both ATLAS and CMS data have been utilized to establish upper limits on the production of axion-like particles that decay into two photons, and the limits from the heavy ion data are superior to all other approaches in the pertinent mass range. The two data sets are now in the process of being used for a combined extraction of cross sections, to improve the staistical signifcance, and to prepare for precision physics in the future.

5 Probing the nucleon and nucleus with exclusive vector mesons

Elastic photonuclear processes involve the interaction of a nuclear photon with a pomeron, either from a proton or a nucleus, whose transverse momentum reflects the internal spatial structure of the target. LHC and RHIC experiments have a broad range of results on vector mesons in A+A and p+A collisions, probing both the nucleon and nucleus. Cross sections are generally sensitive to the square of the gluon density, making them sensitive to shadowing and saturation physics. However, the presence or absence of forward fragments allow the separation into coherent and incoherent scattering. Coherent scattering is sensitive to the average spatial extent of the object, while incoherent is sensitive to fluctuations, e.g. due to "hot spots" [29]. A "hotspot" model used to describe dissociative (incoherent) data has been used to seed a hydrodynamic description of pp collisions and found improve the description of LHC pPb data [30]. Vector mesons in p+Pb probe the gluon densities in the proton. Measurements of ρ^0 production at CMS [31] and J/ψ production in ALICE [32] are consistent with measurements from DIS and LHCb (pp photoproduction), but do not yet have the statistical precision to distinguish models with and without saturation physics Coherent production of rho mesons from photo production in Pb+Pb and Xe+Xe from ALICE shows an enormous effect of shadowing relative to what is expected from coherent production [33]. ALICE [34] and STAR [35] have both observed "dips" associated with diffractive production of rho mesons off of nuclei, but only STAR has made the first published attempt to probe nuclear geometry with vector meson production, by measuring the t distribution from rho mesons and fitting it to a presumed nuclear density distribution. This is a process of great interest at the EIC. Just as with dileptons, STAR has utilized the angle between the momentum sum and difference vectors of pions from rho decay to study the interference induced by the fact that the rho final state could arise from pomeron emission from either nucleus [36]. These interference patterns are not seen in p+A, and are quite sensitive to the nuclear geometry and allow independent extraction of the nuclear geometry. Crucial to extracting information about nucleon PDFs and nuclear shadowing is to have a full NLO description of J/psi production in photo production, which involves incorporating nucleon GPDs [37]. Substantial recent progress on this has been made and compared to data, although comparison to ALICE [38] and LHCb [39] is revealing significant tension between the two experiments, perhaps related to event selection techniques to exclude incoherent processes.

6 Inelastic processes: jets and correlations

The processes discussed up to now were priarily elastic in nature, with no breakup of the targets (except as backgrounds). However, a substantial fraction of the cross section is inelastic multihadron production, including events with jets.

Jet production can be used to directly probe the gluon distribution in a nucleon or nucleus via the production of back to back dijets (or multi-jet final states). ATLAS [40] has used their ZDCs as a primary trigger by requiring activity only on one aide, enhancing the contributions from photoproduction, at the cost of rejecting events which have a secondary breakup process - a nontrivial fraction for this process. The jets themselves are utilized to define kinematic variables (H_T, x_A and z_γ) that map quite closely to well known kinematic quantities from deep inelastic scattering (Q^2, x and xy, respectively). Selections on z_γ, which reflects the initial photon energy, are performed to minimize acceptance effects. After that, triple differential cross sections can be measured and compared to Pythia8 calculations using CTEQ nPDFs, after reweighing the photon spectrum to agree with that found in STARlight. While the results are not yet finalized, due to some remaining issues with the final jet energy calibration, the results already demonstrate the potential of dijet photoproduction at the LHC to study nuclear PDFs over a wide kinematic range well before the EIC turns on.

CMS has performed a study of dijet correlations, to probe the polarization of gluons in the nucleus in a manner similar to the abovementioned STAR results [41]. They study the distribution of the same angle ϕ defined by the angular separation of sum and difference of the dijet transverse momentum vectors. After unfolding for experimental effects , CMS finds a substantial decorrelation of the dijets, relative to RAPGAP expectations. Models attempting to describe the data with final state radiation can only achieve this for low Q^2 while the effect persists out to 25 GeV^2.

Inelastic processes without a jet requirement probe momentum transfers similar to minimum bias events in pp, and were studied by ATLAS to see whether the collective effects in smaller systems, such as pp at the LHC and dAu at RHIC, are also observed. It should be noticed that results from reanalysis of HERA data (ZEUS and H1), as well as γp results from CMS, show no clear evidence of any collective behavior. ATLAS has performed a full two-particle correlation measurement, utilizing template fits based on lower multiplicity events to remove expected correlations from resonance decays and minijet production [42]. After template subtraction, a clear $\cos(2\Delta\phi)$ modulaiton is observed, and second and third-order Fourier coefficients have been extracted. The values of v_2 and v_3, integrated over p_T are found to have no multiplicity dependence, but with a lower magnitude than found in pp and pPb data. And while the statistical and systematic uncertainties are too large to make strong conclusions, they are qualitatively consistent with pp data. While this seems to indicate signs of collectivity in γPb collisions, it should be noted that calculations based on the color glass condensate are also able to describe the p_T dependence, and similar effects are also expected to be observed at the EIC.

7 Conclusions

Ultraperipheral collisions at high energy heavy ion colliders are truly offering a new physics program for these machines in $\gamma\gamma$, γA, and γp collisions. It is a program that operates "alongside" the hadronic (QGP) heavy ion programs, and offers a clean environment allowing precision measurements, even for modest integrated luminosities. The wide range of results shown at DIS2022, many of which were new for the conference, show amazing synergies between RHIC and the LHC, and between both and the EIC. In fact, one might even see this program as offering a preview of the EIC physics program, well before the new machine is even built. It will only strengthen the physics case, and help build the scientific community, and provide a wide range of baseline data to help accelerate the comissioning of the machine and its detector program.

References

[1] W. Busza, K. Rajagopal, W. van der Schee, Ann. Rev. Nucl. Part. Sci. **68**, 339 (2018), 1802.04801

[2] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Ann. Rev. Nucl. Part. Sci. **57**, 205 (2007), nucl-ex/0701025

[3] L. Cunqueiro, A.M. Sickles, Prog. Part. Nucl. Phys. **124**, 103940 (2022), 2110.14490

[4] (2022), 2205.00682

[5] PHENIX Collaboration, Nature Phys. **15**, 214 (2019), 1805.02973

[6] ATLAS Collaboration, Phys. Rev. Lett. **124**, 082301 (2020), 1909.01650

[7] R. Abdul Khalek et al. (2021), 2103.05419

[8] S. Klein, P. Steinberg, Ann. Rev. Nucl. Part. Sci. **70**, 323 (2020), 2005.01872
[9] C.F. von Weizsäcker, Z. Phys. **88**, 612 (1934)
[10] E.J. Williams, Kong. Dan. Vid. Sel. Mat. Fys. Med. **13N4**, 1 (1935)
[11] E. Fermi, Z. Phys. **29**, 315 (1924)
[12] A. Veyssiere, H. Beil, R. Bergere, P. Carlos, A. Lepretre, Nucl. Phys. A **159**, 561 (1970)
[13] S.J. Brodsky, T. Kinoshita, H. Terazawa, Phys. Rev. D **4**, 1532 (1971)
[14] S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, Comput. Phys. Commun. **212**, 258 (2017), 1607.03838
[15] L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, SciPost Phys. **11**, 064 (2021), 2104.13392
[16] ATLAS Collaboration (2022), 2207.12781
[17] ATLAS Collaboration, Phys. Rev. C **104**, 024906 (2021), 2011.12211
[18] A.J. Baltz, Phys. Rev. Lett. **100**, 062302 (2008), 0710.4944
[19] W. Zha, Z. Tang, JHEP **08**, 083 (2021), 2103.04605
[20] CMS Collaboration, Phys. Rev. Lett. **127**, 122001 (2021), 2011.05239
[21] STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021), 1910.12400
[22] ATLAS Collaboration (2022), 2206.12594
[23] CMS Collaboration (2022), 2206.05192
[24] ATLAS Collaboration (2022), 2204.13478
[25] ATLAS Collaboration, Nature Phys. **13**, 852 (2017), 1702.01625
[26] ATLAS Collaboration, Phys. Rev. Lett. **123**, 052001 (2019), 1904.03536
[27] ATLAS Collaboration, JHEP **11**, 050 (2021), 2008.05355
[28] CMS Collaboration, Phys. Lett. B **797**, 134826 (2019), 1810.04602
[29] H. Mäntysaari, B. Schenke, Phys. Rev. Lett. **117**, 052301 (2016), 1603.04349
[30] H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B **772**, 681 (2017), 1705.03177
[31] CMS Collaboration, Eur. Phys. J. C **79**, 702 (2019), 1902.01339
[32] ALICE Collaboration, Eur. Phys. J. C **79**, 402 (2019), 1809.03235
[33] ALICE Collaboration, Phys. Lett. B **820**, 136481 (2021), 2101.02581
[34] ALICE Collaboration, JHEP **06**, 035 (2020), 2002.10897
[35] STAR Collaboration, Phys. Rev. C **96**, 054904 (2017), 1702.07705
[36] STAR Collaboration (2022), 2204.01625
[37] K.J. Eskola, C.A. Flett, V. Guzey, T. Löytäinen, H. Paukkunen (2022), 2203.11613
[38] ALICE Collaboration, Eur. Phys. J. C **81**, 712 (2021), 2101.04577
[39] LHCb Collaboration, JHEP **07**, 117 (2022), 2107.03223
[40] ATLAS Collaboration, *Photo-nuclear jet production in ultra-peripheral Pb+Pb collisions at* $\sqrt{s_{NN}} = 5.02$ *TeV with the ATLAS detector* (2022)
[41] CMS Collaboration (2022), 2205.00045
[42] ATLAS Collaboration, Phys. Rev. C **104**, 014903 (2021), 2101.10771