UPC contribution to forward rapidity gap distribution in pPb collisions at the LHC

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(Dated: May 10, 2022)

In this letter, we consider strong and electromagnetic (ultraperipheral) mechanisms in proton-nucleus coherent diffraction at the LHC. We explicitly demonstrate the dominance of the latter and explain the CMS data on the forward rapidity gap distribution in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. In particular, we provide simple estimates, which give a good, semi-quantitative description of both magnitude and shape of the $\Delta \eta^F$ distribution in the Pomeron-proton topology. We also make predictions for the proton-oxygen run.

PACS numbers: 13.60.Hb,13.60.-r, 25.20.-x,25.75.-q
Keywords: Proton-nucleus relativistic scattering, diffraction dissociation, ultraperipheral collisions

Introduction and motivation. Diffraction in hadron scattering at high energies remains an active field of research. It is deeply connected to the nature of colorless exchanges with vacuum quantum numbers (Pomeron) in strong interactions and, more generally, small-$x$ phenomena in Quantum Chromodynamics (QCD), important for tuning event generators needed for interpretation of results of ultrarelativistic heavy-ion scattering, and also relevant for cosmic ray physics. In experiment diffractive events are characterized by large gaps in rapidity distributions of produced particles, which are defined as regions with no hadronic activity. To enhance sensitivity to such events and, in particular, to the so-called single diffractive dissociation, one can select events with the rapidity gaps in the most forward region of a detector; in proton-proton (pp) scattering such measurements have been performed at the Large Hadron Collider (LHC) at $\sqrt{s_{NN}} = 7$ TeV [1,2].

The CMS collaboration at the LHC for the first time measured the forward rapidity gap distribution in proton-Pb (pPb) collisions at $\sqrt{s_{NN}} = 8.16$ TeV [3]. It was found that for the Pomeron-proton topology, the EPOS-LHC, QGSJET II, and HIJUNG generators are at least a factor of five below the data. As a result, it was suggested that this discrepancy can be explained by a significant contribution of ultraperipheral photoproduction events mimicking the signature of diffractive processes.

Actually, this observation was already made in Ref. [1] in 2006, which showed that in coherent proton-nucleus (pA) diffraction, the electromagnetic (ultraperipheral) contribution dominates the cross section for heavy nuclei.

The purpose of this letter is to generalize the results of [1] for the CMS experimental conditions and, in particular, to make predictions for the distribution in the forward rapidity gap $\Delta \eta^F$. Our predictions for the $\Delta \eta^F$ distribution in the studied case of the Pomeron-proton topology agree both in magnitude and the shape with that measured by the CMS collaboration and, thus, confirm and quantify the essential role of ultraperipheral photoproduction in explanation of the CMS data.

We also make predictions for the case of proton-oxygen (pO) scattering.

Strong and electromagnetic mechanisms in pA coherent diffraction. The phenomenon of diffractive dissociation of protons in proton-nucleus scattering at high energies is a classic example of composite structure of hadronic projectiles, which can be conveniently described within the framework of cross section fluctuations [5–8]. In this approach, the cross section of pA coherent diffraction dissociation, $p + A \rightarrow X + A$, can be written in the following form

$$\sigma_{pA}^\text{diff}(s) = \int d^2\vec{b} \left[ \int d\sigma_p(\sigma)[\Gamma_A(\vec{b})]^2 - \int d\sigma_p(\sigma)\Gamma_A(\vec{b})^2 \right]$$

where $s$ is the total proton-nucleus energy squared per nucleon. Here $\Gamma_A(\vec{b})$ is nuclear scattering amplitude in representation of the impact parameter $\vec{b}$, which in the limit of high energies and large $A$ (heavy nucleus) is usually expressed in the eikonal form

$$\Gamma_A(\vec{b}) = 1 - e^{-\frac{\pi^2\Gamma_A(\vec{b})}{T_A(\vec{b})}}$$

where $T_A(\vec{b}) = \int d\vec{r} \rho_A(\vec{r})$ with $\rho_A(\vec{r})$ being the nuclear density normalized to the number of nucleons $A$. The $\Gamma_A(\vec{b})$ amplitude sums multiple interactions with target nucleons and captures the effect of nuclear shadowing leading to a dramatic suppression of the proton-nucleus cross section.

The distribution $\sigma_p(\sigma)$ describes cross section fluctuations of the proton and gives the probability for the proton to fluctuate into a hadronic configuration interacting with target nucleons with the cross section $\sigma$. In general, $\sigma_p(\sigma)$ should be modeled, see, e.g. [9, 8]. However, in the case of diffraction dissociation, the detailed information on the shape of $\sigma_p(\sigma)$ is not needed since one can use the general property that $\sigma_p(\sigma)$ is peaked around $\sigma_p = \langle \sigma \rangle \equiv \int d\sigma \sigma_p(\sigma)\sigma$. Thus, expanding Eq. (1) around $\langle \sigma \rangle$, one obtains [10]

$$\sigma_{pA}^\text{diff}(s) = \frac{\omega_{p}^{\sigma}(\sigma)^2}{4} \int d^2\vec{b} (T_A(\vec{b}))^2 e^{-\langle \sigma \rangle T_A(\vec{b})}$$

where $\omega_{p}^{\sigma}(\sigma)$ is the distribution of five below the data. As a result, it was suggested that this discrepancy can be explained by a significant contribution of ultraperipheral photoproduction events mimicking the signature of diffractive processes.
where $\omega_\sigma(s) = \langle \sigma^2 \rangle / \langle \sigma \rangle^2 - 1$ quantifies the dispersion of cross section fluctuations of the proton. At $\sqrt{s} = \sqrt{s_{NN}} = 8.16$ TeV, we use the COMPETE parametrization [10] giving $\langle \sigma \rangle = \sigma^{pp}_{\gamma p}(s) = 98.6$ mb and a simple interpolation from fixed-target to Tevatron and further to LHC energies giving $\omega_\sigma(s) = 0.092 \pm 0.015$ [3]. The spread in the values of $\omega_\sigma(s)$ reflects the theoretical uncertainty in modeling $P_\gamma(\sigma)$.

It was explained in [4] that a competing reaction mechanism leading to the same final state, $p + A \rightarrow p + \gamma + A \rightarrow X + A$, is provided by the electromagnetic contribution corresponding to ultraperipheral pA scattering. In this case, proton and Pb beams pass each other at large impact parameters and, hence, short-range strong interactions are suppressed. Instead, the relativistic heavy ion beam serves as an intensive source of quasi-real photons, which interact with the proton. In the equivalent photon (Weizsäcker-Williams) approximation, the corresponding cross section reads [11, 12]

$$\sigma^{e.m.}_{\gamma A}(s) = \int_{\omega_{\text{min}}}^{\omega_{\text{max}}} d\omega \omega N_{\gamma/A}(\omega) \sigma^{\text{tot}}_{\gamma p}(s_{\gamma p}),$$

(4)

where $N_{\gamma/A}(\omega)$ is the photon flux; $\omega$ is the photon energy; $\sigma^{\text{tot}}_{\gamma p}(s_{\gamma p})$ is the total photon-proton cross section and $s_{\gamma p}$ is the total invariant photon-proton energy squared. The integration limits can be estimated as follows. In the laboratory frame, the minimal photon energy corresponding to photo-excitation of the inelastic state is $\omega_{\text{min}} = (M^2_{\Delta} - m^2_p)/(4m_p\gamma_L(p))$, where $M_{\Delta}$ and $m_p$ are the masses of $\Delta(1232)$ and the proton, respectively, and $\gamma_L(p) = E_p/m_p$ is the Lorentz factor of the proton beam with energy $E_p$. The maximal photon energy is usually estimated as $\omega_{\text{max}} = \gamma_L(A)/R_A$, where $R_A$ is the nucleus effective radius and $\gamma_L(A) = E_A/m_p$ is the Lorentz factor of the nucleus beam with energy $E_A$.

For the photon flux, we use the approximate expression corresponding to the point-like (PL) source with the electric charge $Z$:

$$N_{\gamma/A}(\omega) = \frac{2Z^2\alpha_{\text{e.m.}}}{\pi} \left( \xi K_0(\xi) K_1(\xi) - \frac{\xi^2}{2} (K^2_1(\xi) - K^2_0(\xi)) \right),$$

(5)

where $\alpha_{\text{e.m.}}$ is the fine-structure constant; $K_{0,1}$ are modified Bessel functions of the second kind; $\xi = (\omega/\gamma_L(A))/b_{\text{min}}$ with $b_{\text{min}} = 1.15R_A$ and $R_A = 1.145A^{1/3}$ fm. With these parameters, Eq. (5) reproduces well a more accurate calculation of the photon flux taking into account the suppression of strong interactions at $|b| \leq b_{\text{min}}$ [13].

For the total photon-proton cross section, we use the Donnachie and Landshoff fit [14]

$$\sigma_{\gamma p}(s)/mb = 0.0677s_{\gamma p}^{0.0808} + 0.129s_{\gamma p}^{-0.4525},$$

(6)

where $s_{\gamma p} = 4\omega E_p + m^2_p$.

Employing the input specified above and using Eqs. (3) and (4), we obtain the following results for the strong and electromagnetic (ultraperipheral) contributions to the cross section of $pPb$ coherent diffraction at $\sqrt{s_{NN}} = 8.16$ TeV

$$\sigma_{\gamma p}^{\text{diff}}(s) = 7.4 \pm 1.2 \text{ mb},$$

$$\sigma_{\gamma p}^{e.m.}(s) = 450 \text{ mb}.$$

(7)

These values agree with those of Ref. [4] (the correct predictions for the electromagnetic contribution are given in the Erratum to that paper).

**Predictions for the strong and electromagnetic contributions differential in $\Delta \eta^F$.** In proton-nucleus coherent diffraction, the size of the rapidity gap between the intact nucleus and the diffractively-produced system $X$ is

$$\Delta \eta = -\ln \xi_X,$$

(8)

where $\xi_X = M_X^2/s$ is a variable commonly used in diffraction and $M_X$ is the mass of the state $X$. In the case of Pomeron-proton topology, the CMS collaboration has defined $\Delta \eta^F$ as the distance from $\eta = -3$ to the lower edge of the last non-empty $\eta$ bin $\mathbb{R}$. Since the elastically scattered proton corresponds to $\eta_A = -(1/2)\ln(4E_A^2/m_p^2) = \ln(2E_A/m_p) = -8.6$ (in the CMS coordinate system, the direction of the proton beam in $pPb$ collisions defines positive rapidity), we obtain

$$\Delta \eta^F = \Delta \eta - (8.6 - 3) = \Delta \eta - 5.6.$$

(9)

This is illustrated in Fig. 1. It should be compared to the definition of the ATLAS collaboration in the $pp$ case at $\sqrt{s_{NN}} = 7$ TeV, $\Delta \eta^F = \Delta \eta - 4$ [3].

Turning to Eq. (6) and recalling that the cross section of diffraction dissociation on the proton (nucleon) at the momentum transfer $t = 0$ is related to the dispersion of cross section fluctuations [2],

$$\frac{d\sigma_{pp}^{\text{diff}}(t = 0)}{dt} = \frac{1}{16\pi} \left( \langle \sigma^2 \rangle - \langle \sigma \rangle^2 \right) = \frac{\omega_\sigma(s)\langle \sigma \rangle^2}{16\pi},$$

(10)

Eq. (6) can be rewritten in the following form

$$\sigma_{\gamma p}^{\text{diff}}(s) = \frac{d\sigma_{pp}^{\text{diff}}(t = 0)}{dt} 4\pi \int d^2b \langle T_A(b) \rangle^2 e^{-\langle \sigma \rangle T_A(b)}.$$

(11)
Making the common assumption of an exponential momentum transfer $t$ dependence, $d\sigma_{pp}/dt = e^{-B(s)t}d\sigma_{pp}^{t=0}/dt$, we can express the proton-nucleus diffractive cross section as a product of the $t$-integrated proton-proton diffractive cross section $\sigma_{pp}^{diff}(s)$ and the nuclear factor,

$$\sigma_{pA}^{diff}(s) = \sigma_{pp}^{diff}(s)4\pi B(s) \int d^2b (T_A(b))^2 e^{-(s)T_A(b)} = 2.4 \sigma_{pp}^{diff}(s) . \quad (12)$$

In the second line of Eq. (12), we used that $B \approx B_{el} + 2\alpha_\gamma^p \ln(m_p^2/M_X^2) \approx 15 \text{ GeV}^{-2}$ for $40 \leq M_X \leq 300 \text{ GeV}$ at $\sqrt{s_{NN}} = 8.16 \text{ TeV}$. This estimate is based on the experimental results for the slope of the $t$ dependence of the elastic $pp$ cross section $B_{el} \approx 20 \text{ GeV}^{-2}$ and the general dependence of the slope of single diffractive dissociation on $M_X^2$ in Regge phenomenology with $\alpha_\gamma^p \approx 0.25 \text{ GeV}^{-2}$; the used range of $M_X$ corresponds to $1 \leq \Delta \eta^F \leq 5$.

Therefore, taking advantage of a simple connection between $\sigma_{pA}^{diff}(s)$ and $\sigma_{pp}^{diff}(s)$ and neglecting a weak dependence on $X$ of the slope $B(s)$ and the nuclear factor in Eq. (12), we can generalize Eq. (12) to the form differential in $\Delta \eta^F$,

$$\frac{d\sigma_{pA}^{diff}}{d\Delta \eta^F} = 2.4 \frac{d\sigma_{pp}^{diff}}{d\Delta \eta^F} . \quad (13)$$

Finally, without resorting to a particular model for $d\sigma_{pp}^{diff}/d\Delta \eta^F$, we use the ATLAS result $d\sigma_{pp}^{diff}/d\Delta \eta^F \approx 1 \text{ mb}$ [1] and thus arrive at the following estimate,

$$\frac{d\sigma_{pA}^{diff}}{d\Delta \eta^F} \approx 2.4 \text{ mb} . \quad (14)$$

This estimate semi-quantitatively agrees with predictions of EPOS-LHC, QGSJET II, and HIJUNG generators shown in Fig. 4 of Ref. [3].

Turning to Eq. (13), we notice that the photon energy required to excited the diffractive mass $M_X = \omega = (M_X^2 - m_p^2)/(4m_p\gamma_L(p)) \approx M_X^2/(4m_p\gamma_L(p))$ for sufficiently large $M_X$. Therefore,

$$d\omega/\omega = d\ln M_X = d\Delta \eta^F . \quad (15)$$

It allows us to rewrite Eq. (13) in the form differential in $\Delta \eta^F$,

$$\frac{d\sigma_{pA}^{diff, e.m.}}{d\Delta \eta^F} = N_{\gamma/A}(\omega(\Delta \eta^F))\sigma_{\gamma p}^{tot}(\omega) , \quad (16)$$

where the photon energy corresponds to the given $\Delta \eta^F$, i.e., to the given $M_X$, see Eqs. (8) and (9). The resulting values of $d\sigma_{pA}^{diff, e.m.}/d\Delta \eta^F$ as a function of $\Delta \eta^F$ in the $1 \leq \Delta \eta^F \leq 5$ interval are given in Table I.

![Fig. 2: The strong (“diff”), electromagnetic (“e.m.”), and total (“Total”) contributions to the cross section of proton-lead (pPb) coherent diffraction as a function of $\Delta \eta^F$.](image)

TABLE I: The contribution of the electromagnetic (ultraperipheral) mechanism to $pPb$ coherent diffraction, $d\sigma_{pA}^{e.m.}/d\Delta \eta^F$, as a function of the rapidity gap size $\Delta \eta^F$.

| $\Delta \eta^F$ (GeV) | $d\sigma_{pA}^{e.m.}/d\Delta \eta^F$, mb |
|-----------------------|---------------------------------------|
| 1                     | 13.9                                  |
| 2                     | 17.8                                  |
| 3                     | 21.1                                  |
| 4                     | 23.9                                  |
| 5                     | 26.3                                  |

Fig. 4 of [3] shows that our simple estimate reproduces rather well both the magnitude and the shape of the $\Delta \eta^F$ distribution. In particular, we demonstrate that the ultraperipheral mechanism is responsible for the increase of $d\sigma/d\Delta \eta^F$ with an increase of $\Delta \eta^F$.

It is important to note that our estimate of $d\sigma_{pA}^{e.m.}/d\Delta \eta^F$ is based on the assumption that it receives contributions from all $M_X$ comprising the total photon-proton cross section and, hence, should be considered as an upper limit. A more accurate account of the ultraperipheral contribution to $d\sigma/d\Delta \eta^F$ should include modeling of the mass spectrum in photon-proton scattering and the influence of the detector acceptance, which is beyond the scope of our work.

While the aim of this letter was to capture the bulk of physical effects explaining the CMS results in a semi-quantitative way, our calculations can be improved along several lines, in particular, in an estimate of the strong interaction mechanism of coherent diffraction. However, since it gives a subleading contribution, these refinements...
will not significantly affect the resulting total \( \Delta \eta^F \) distribution.

**Predictions for proton-oxygen run.** One can readily extend our predictions to proton-oxygen (pO) scattering at \( \sqrt{s_{NN}} = 9.19 \text{ TeV} \). In this case, \( \sigma^{\text{tot}}_{pp}(s) = 100.6 \text{ mb} \) and \( \omega_{\eta}(s) = 0.086 \pm 0.014 \), and we obtain (compare to Eq. (7))

\[
\begin{align*}
\sigma_{\text{pO}}^{\text{diff}}(s) & = 3.1 \pm 0.52 \text{ mb}, \\
\sigma_{\text{pO}}^{\text{e.m.}}(s) & = 5.0 \text{ mb}. 
\end{align*}
\]

One can see that the strong interaction and electromagnetic contributions have comparable magnitudes for oxygen because of a 100 times smaller photon flux compared to Pb. As a result, the electromagnetic contribution constitutes a 15–30\% correction to the \( \Delta \eta^F \) distribution. At the same time, this gives an opportunity to measure the cross section of soft pO diffraction, which is strongly suppressed by nuclear shadowing compared to the impulse approximation.

**Summary.** In summary, we showed that a straightforward extension of the results of Ref. [4] can explain the CMS data on the forward rapidity gap distribution in pPb collisions at \( \sqrt{s_{NN}} = 8.16 \text{ TeV} \). Notably, we explicitly demonstrated the dominance of the electromagnetic (ultraperipheral) mechanism in the Pomeron-proton topology, which provides a good, semi-quantitative description of both magnitude and shape of the measured \( \Delta \eta^F \) distribution.

**Acknowledgements.** The research of M.S was supported by the US Department of Energy Office of Science, Office of Nuclear Physics under Award No. DE-FG02-93ER40771. MS thanks Theory Division of CERN for hospitality while this work was done.

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[1] G. Aad et al. [ATLAS], Eur. Phys. J. C 72, 1926 (2012) [arXiv:1201.2808 [hep-ex]].

[2] V. Khachatryan et al. [CMS], Phys. Rev. D 92, no.1, 012003 (2015) [arXiv:1503.08689 [hep-ex]].

[3] [CMS], CMS-PAS-HIN-18-019.

[4] V. Guzey and M. Strikman, Phys. Lett. B 633, 245-252 (2006). Phys. Lett.B 663 456 (2008) [arXiv:hep-ph/0505088 [hep-ph]].

[5] M. L. Good and W. D. Walker, Phys. Rev. 120, 1857-1860 (1960)

[6] L. Frankfurt, G. A. Miller and M. Strikman, Phys. Rev. Lett. 71, 2859-2862 (1993) [arXiv:hep-ph/9309285 [hep-ph]].

[7] B. Blaettel, G. Baym, L. L. Frankfurt, H. Heiselberg and M. Strikman, Phys. Rev. D 47, 2761-2772 (1993)

[8] L. Frankfurt, V. Guzey, A. Stasto and M. Strikman, [arXiv:2203.12289 [hep-ph]].

[9] H. De Vries, C. W. De Jager and C. De Vries, Atom. Data Nucl. Data Tabl. 36, 495-536 (1987)

[10] P. A. Zyla et al. [Particle Data Group], PTEP 2020, no.8, 083C01 (2020)

[11] G. Baur, K. Hencken, D. Trautmann, S. Sadowsky and Y. Kharlov, Phys. Rept. 364, 359-450 (2002) [arXiv:hep-ph/0112211 [hep-ph]].

[12] A. J. Baltz, G. Baur, D. d’Enterria, L. Frankfurt, F. Gelis, V. Guzey, K. Hencken, Y. Kharlov, M. Klasen and S. R. Klein, et al. Phys. Rept. 458, 1-171 (2008) [arXiv:0706.3356 [nucl-ex]].

[13] V. Guzey and M. Zhalov, JHEP 02, 046 (2014) [arXiv:1307.6689 [hep-ph]].

[14] A. Donnachie and P. V. Landshoff, Phys. Lett. B 296, 227-232 (1992) [arXiv:hep-ph/9209205 [hep-ph]].