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EXPLORING ULTRAPERIPHERAL HEAVY ION COLLISIONS IN CMS RUN III [1]

Ultraperipheral collisions (UPCs) of heavy ions are a useful probe to study nuclear parton distribution functions (nPDFs) and, in particular, to characterize nuclear matter at Bjorken $x < 10^{-3}$ and low squared momentum transfer Q^2 (shadowing/saturation regime). In order to fully exploit these collisions, dedicated triggers on such event topologies were developed for the heavy ion data-taking period in 2023 by the CMS experiment. These triggers relied on the possibility of using the Zero Degree Calorimeter (ZDC) as a level-1 (L1) trigger detector for the first time. As a result, they allowed for an improved selection performance in addition to existing UPC triggers (as well as minimum-bias hadronic triggers), and enabled the study of hard processes (jets and heavy flavor hadrons) in photon-photon ($\gamma\gamma$) and photon-nucleus (γN) scatterings [1].

Keywords: UPC, heavy ion, RUN3, nuclear breakdown.

1. Introduction

Presented at the "New Trends in High Energy and Low-x Physics" conference in Sfantu Gheorghe, Romania, this article delves into the advancements and potential of Ultraperipheral Collisions (UPCs) within the CMS (Compact Muon Solenoid) experiment during Run III at the LHC.

2. Physics of UPCs

UPCs represent a frontier in electromagnetic interaction studies, occurring when relativistic heavy ions collide at large impact parameters, thereby preventing direct hadronic interactions. This setup allows the LHC to probe photonuclear and photon-photon interactions at unprecedented energy levels, offering insights into several phenomena.

• ***Nuclear Shadowing and Structure Analysis:*** UPCs enable a detailed study of nuclear shadowing, enhancing our understanding of nuclear structure and interactions beyond the Standard Model.

• ***Photonuclear and Photon-Photon Interactions:*** UPCs allow for the study of exclusive and coherent photoproduction of vector mesons, light-by-light scattering, and dilepton production, revealing rare and complex nuclear interactions.

These Feynman diagrams illustrate the variety of photon-induced processes studied in UPCs (Fig. 1). For example, incoherent and coherent photoproduction (diagrams (b) and (d) provide insights into nuclear structure, while light-by-light scattering (diagram (g)) tests the quantum electrodynamics (QED) predictions at high energy.

3. CMS Run III and ZDC Configurations

The CMS Run III is investigating UPC events at the LHC with new technological advancements. Enhanced photon detection, such as the Zero Degree Calorimeter (ZDC), will extract higher-energy photons without requiring increases in LHC energy, broadening research possibilities in high-energy physics (Fig. 2).

Key points:

• ***Photon Kinematics***: The flux of photons is proportional to Z^2. The transverse momentum p_T is

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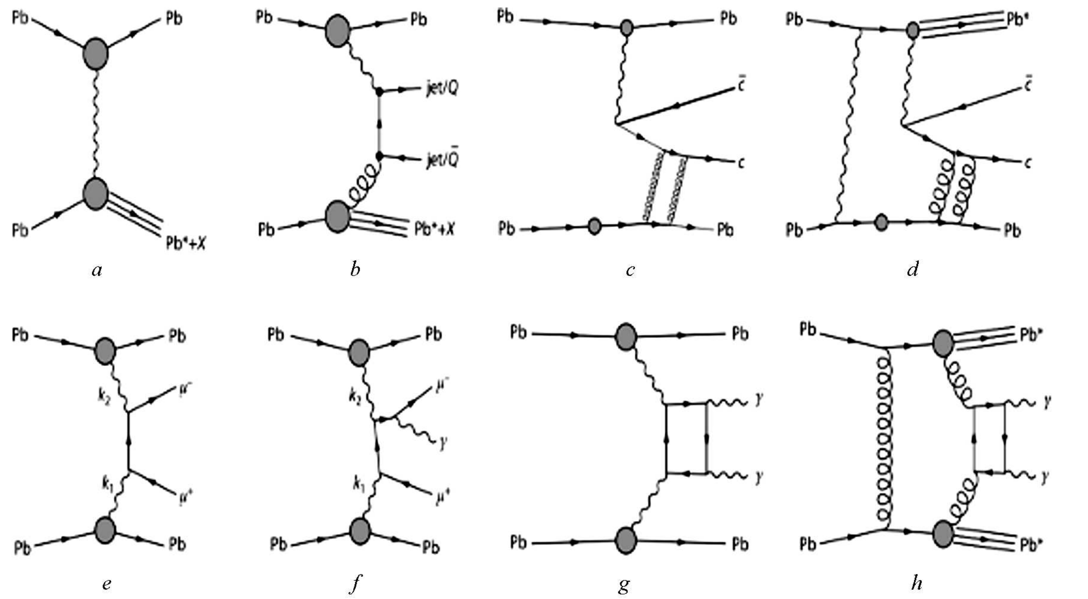


Fig. 1. Feynman diagrams for various processes in UPCs. Each diagram represents different interactions that can occur: Generic photonuclear interaction with nuclear breakup target (*a*). Incoherent photoproduction (*b*). Exclusive photoproduction of a vector meson (*c*). Coherent photoproduction of a vector meson (*d*). Dilepton production (*e*). Dilepton production with higher-order processes (*f*). Light-by-light scattering with no nuclear breakup (*g*). Central exclusive diphoton production with double breakup (*h*) [2]

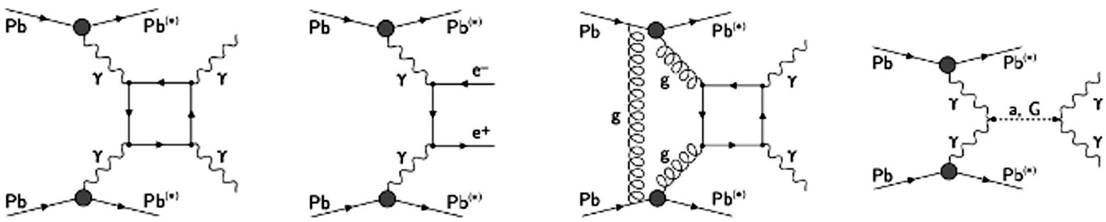


Fig. 2. Ultraperipheral collisions at the LHC, where the impact parameter b exceeds the sum of the radii of the nuclei $R_A + R_B$ [2]

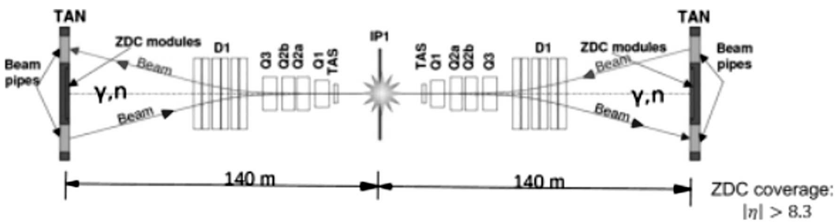


Fig. 3. Diagram of the ATLAS experiment setup including the Zero Degree Calorimeter (ZDC) for detecting γN events in ultraperipheral collisions [2]

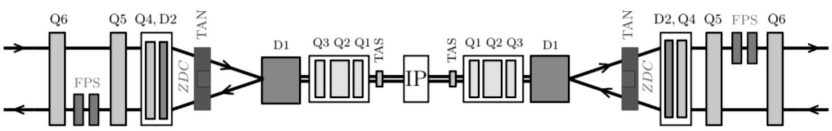


Fig. 4. Diagram of the CMS experiment setup including the Zero Degree Calorimeter (ZDC) for detecting γN events in ultraperipheral collisions [2]

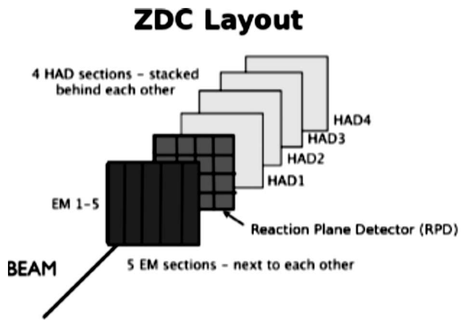


Fig. 5. ZDC detector composed of three sections: EM, RPD, and HAD [3]

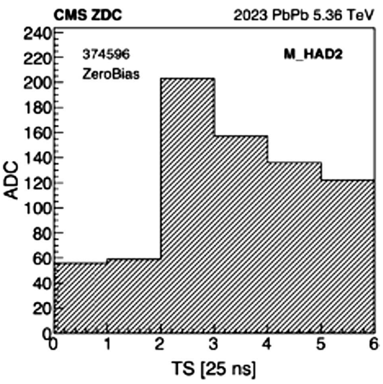


Fig. 6. ZDC Out of Time Pileup Subtraction: ADC counts in the ZDC second hadronic layer on the minus side as a function of the time slice (TS) in 25 ns intervals for a zero-bias sample [3]

less than $\hbar/R_A \approx 30$ MeV, while the energy $E_{\max}$ can reach $\mathcal{O}(100)$ GeV at the LHC.

• ***Effective Photon-Photon and Photon-Nucleus Collider***: When running on PbPb, the LHC effectively operates as a $\gamma\gamma$ and γN collider, allowing access to high-energy photon-nuclear collisions to test nuclear matter effects in the absence of final-state effects (similar to proton-Pb collisions).

3.1. ZDC in ATLAS and CMS

In the LHC, two Zero Degree Calorimeters (ZDC) are installed in both the ATLAS (Fig. 3) and CMS(Fig. 4) experiments to enable the detection of photons in ultraperipheral collisions. These detectors provide essential data for studying high-energy photon-nuclear and photon-photon interactions.

3.2. Nuclear Breakup Detection

The ZDC is used to detect neutrons produced in the nuclear breakup process in UPCs. Neutron energy is measured by summing up energy in the electromag-

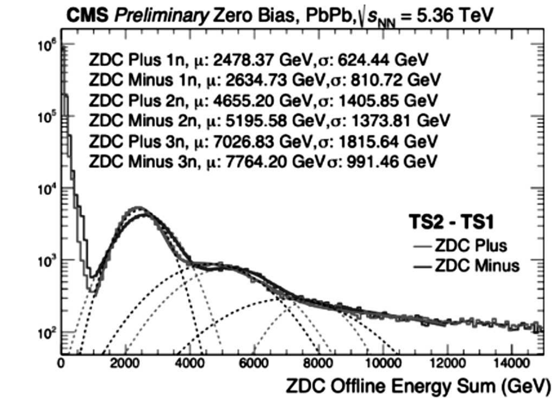
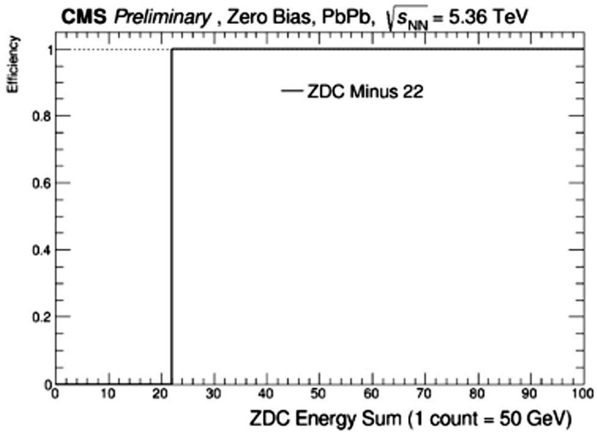
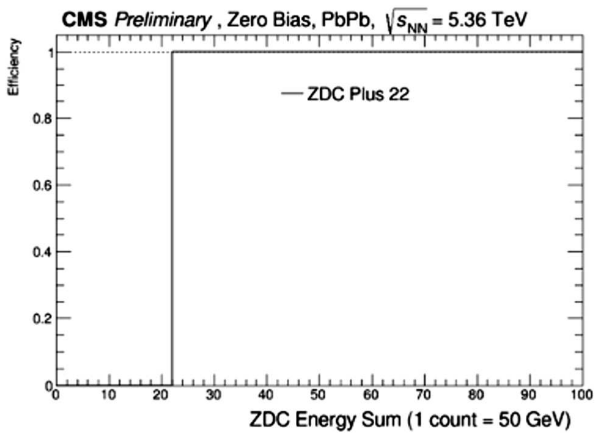


Fig. 7. ZDC offline energy sums for a sample of 3 million zero-bias events with fits to the 1n, 2n, and 3n peaks. For out-of-time pileup, a TS2–TS1 subtraction is applied [3]



a



b

Fig. 8. Turn-on curve for ZDC 1n triggered events as a function of the ZDC online energy sum for ZDC minus (*a*) and ZDC plus (*b*) with a threshold of 22 counts [3]

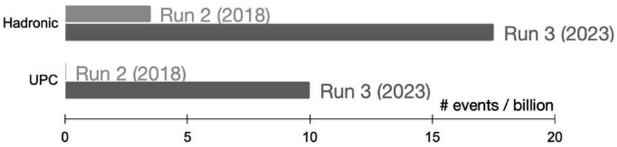


Fig. 9. Comparison of collected UPC dijet and hadronic events in Run 3 (2023) vs. Run 2 (2018) [3]

netic (EM) and hadronic (HAD) sections. The Reaction Plane Detector (RPD) is not used here (Fig. 5).

3.3. Out of Time Pileup Subtraction

During the 2023 run, the "out-of-time" contamination from the ZDC signal was managed using pile-up subtraction(Fig. 6). The probability of two hadronic collisions in two subsequent time slices (TSs) in 50 ns intervals is negligible. However, this subtraction helps remove noise and addresses contamination from EM pileup.

Two approaches were used:
• Offline Approach:**TS2–TS1.
• Online Approach:**TS2–0.4*TS1 (a more conservative method used in trigger mode).

3.4. Offline Energy Sums

The ZDC offline energy sums were analyzed in a sample of 3 million zero-bias events (Fig. 7). No additional offline selection was made.

3.5. Turn-On Curve as a Function of Online Sums

The turn-on curve for ZDC 1n triggered events is analyzed as a function of the ZDC online energy sum (Fig. 8).

4. Comparison of UPC Events in Run3 vs. Run2

The number of collected UPC dijet and hadronic events per billion in Run 3 (2023) shows a significant increase compared to Run 2 (2018), due to the new L1 trigger strategy (Fig. 9).

5. Applications of UPCs in High-Energy Physics

1. ***Vector Meson Production:*** UPC events facilitate the exclusive photoproduction of vector mesons, like J/psi in PbPb collisions, allowing the detailed study of photon interactions with heavy nuclei.

2. ***Photon Flux and Tau-Lepton Studies:*** UPCs enable improved photon flux analysis, particularly focusing on the properties and interactions of tau leptons.

3. ***Axion-Like Particle Probing:*** By exploring UPCs, there is a unique opportunity to probe axion-like particle interactions, pushing the boundaries of Standard Model physics.

6. Summary

The LHC's high-luminosity upgrades (HL-LHC) are designed to enhance detection capabilities, particularly for rare photon-induced processes. CMS and ATLAS will implement advanced triggering systems, increasing the efficiency of capturing exclusive photon-photon and photon-nucleus interactions. Ultraperipheral collisions hold significant potential in high-energy physics, providing insights into photon-induced processes and the study of phenomena beyond the Standard Model. With ongoing and planned upgrades, the LHC is positioned to achieve unprecedented results in UPC research, paving the way for new discoveries.

1. S.R. Klein, P. Steinberg. Photonuclear and two-photon interactions at high-energy nuclear colliders. *Ann. Rev. Nucl. Part. Sci.* **70**, 323 (2020).
2. https://indico.cern.ch/event/1353482/contributions/6085488/attachments/2921079/5127201/NewTrendPresentation.pdf.
3. https://cds.cern.ch/record/2887066/files/DP2024_002.pdf

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ДОСЛІДЖЕННЯ УЛЬТРАПЕРИФЕРІЙНИХ ЗІТКНЕНЬ ВАЖКИХ ІОНІВ НА ДЕТЕКТОРІ CMS УСТАНОВКИ CERN LHC RUN 3

Ультрапериферійні зіткнення (UPCs) важких іонів – зручний метод для вивчення функцій розподілу партонів у ядрі (nPDFs) і, зокрема, для того, щоб характеризувати ядерну матерію при змінній Бйоркена $x < 10^{-3}$ та малому квадраті переданого імпульсу Q^2 (режим затінення/насичення). Для повного використання цих зіткнень були створені спеціальні тригери для фіксації таких подій у період збору даних про важкі йони в експериментах 2023 року з використанням детектора CMS. Ці тригери вперше були основані на можливості використання калориметра нульового градуса (ZDC) як тригерного детектора рівня 1 (L1). Як наслідок, вони дозволили покращити продуктивність відбору подій на додаток до існуючих тригерів UPC (а також гадронних тригерів з мінімальним зміщенням) і дозволили досліджувати жорсткі процеси (струмені та важкі гадрони) у фотон-фотонному ($\gamma\gamma$) та фотон-ядерному (γN) розсіюванні [1].

Ключові слова: UPC, важкий іон, ядерний розпад.