PROCEEDINGS OF SCIENCE

Search for monopole production in ultraperipheral Pb+Pb collisions with the ATLAS detector

Krzysztof Cieśla* on behalf of the ATLAS Collaboration

AGH University of Kraków, al. Adama Mickiewicza 30, Kraków, Poland

E-mail: krzysztof.marcin.ciesla@cern.ch

In ultraperipheral Pb+Pb collisions, intense electromagnetic fields may enable the generation of magnetic monopole pairs via the Schwinger mechanism. Due to their high ionization and unique trajectories in a solenoidal magnetic field, monopoles are expected to leave numerous clusters in the innermost ATLAS pixel detector without associated reconstructed charged-particle tracks or calorimeter activity. This document presents a search for monopole-pair production in ultraperipheral Pb+Pb collisions in the monopole mass range of 20-150 GeV, based on 5.36 TeV data recorded in 2023 by the ATLAS experiment at the Large Hadron Collider. Semiclassical free particle approximation model and a recent search limits obtained by the MoEDAL Collaboration are compared with the ATLAS results.

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*Speaker

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1. Introduction

The relativistic heavy-ion collisions at the Large Hadron Collider [1] (LHC) provide a wide range of unique measurement opportunities. A significant part of the LHC heavy-ion programme consists of measuring ultraperipheral collisions (UPC) where ions do not collide directly, but interact via their electromagnetic fields. Such collisions are an intense source of quasi-real photons, with each photon flux scaling with Z^2 (where Z is the charge of the nucleus, $Z_{\mathrm{Pb}} = 81$). The UPC events can be used to study many photon-induced processes such as exclusive dilepton production ($\gamma\gamma \to l^+l^-$) [2–4] or light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) [5], as well as beyond the Standard Model searches, e.g. τ-lepton anomalous magnetic moment [4], axion-like particles [5] or magnetic monopole ($M\bar{M}$) production [6].

The primary mechanism via which magnetic monopoles can be produced in UPC collisions is the Schwinger mechanism [7]. In this formalism, electrically charged particles could be produced in a strong electric field by tunnelling through the Coulomb barrier and if magnetic monopoles exist, electromagnetic duality implies that they would also be produced by the same mechanism in a sufficiently strong magnetic field. With this mechanism, the $M\bar{M}$ production cross-section can be calculated non-perturbatively using semiclassical techniques, such as free-particle approximation (FPA) [8].

The first search for $M\bar{M}$ production in Pb+Pb collisions was performed by the MoEDAL experiment during the 5.02 TeV heavy-ion run at the LHC in November 2018 [9]. MoEDAL trapping detectors were exposed to 235 μb^{-1} of Pb+Pb collisions, which allowed the exclusion of production of monopoles in UPC with Dirac charges between $1gD$ and $3gD$ and masses up to 75 GeV. The search presented here [6] uses 262 μb^{-1} of 5.36 TeV of Pb+Pb collision data collected in 2023 by the ATLAS experiment. The magnetic monopoles considered in this search have magnetic charge equal to one Dirac charge and masses between 20 GeV and 150 GeV.

2. ATLAS experiment

The ATLAS experiment [10, 11] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each, and includes a system of precision tracking chambers and fast detectors for triggering. The luminosity is measured mainly by the LUCID–2 detector which is located close to the beampipe. A two-level trigger system is used to select events [12]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 3 kHz on average, depending on the data-taking conditions. A software suite [13] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The zero-degree calorimeter (ZDC) consists of four longitudinal compartments on each side of the interaction point (IP), each with one nuclear interaction length of tungsten absorber plates interleaved with a row of 1.5 mm-diameter quartz rods. Light produced by Cherenkov radiation from shower products is transported up to the top of the detector, guided through a trapezoidal prism light guide and into a photomultiplier tube assembly. The detectors are located 140 m from the nominal IP in both directions, covering $|\eta| > 8.3$. They detect neutral particles such as neutrons emitted from interacting nuclei. The ZDC thresholds were set to select events with even a single neutron reaching the ZDC.

3. Analysis strategy

The magnetic monopoles considered in this search have relatively low masses, below 150 GeV, and have often low energy. They deposit their energies in the innermost part of the ATLAS detector, primarily in the pixel detector, via emission of δ-electrons. In addition, their trajectories in a solenoidal magnetic field differ considerably from that of electrically charged particles: parabolic trajectory in $r - z$ and no bending in $r - \varphi$ planes. This leads to events with multiple pixel clusters and no reconstructed charged-particle tracks.

The events of interest are selected by the first-level trigger system, requiring the $XnXn$ event topology (presence of neutrons on both ZDC sides), mainly due to limitations in triggering on monopole production, and additionally at the high-level trigger, a presence of at least 100 pixel clusters is required. To suppress collision background, signal events are required to have at most one reconstructed charged-particle track (with transverse momentum $p_T > 0.1$ GeV, $|\eta| < 2.5$, and a transverse impact parameter of $|d_0| < 1$ mm), and at most one topological cluster of calorimeter-cell energy deposits (with transverse energy $E_T > 0.1$ GeV and $|\eta| < 4.9$). Events are also required to have at least 150 pixel clusters $n_{PixCl} > 150$, with at least 50 of them originating from the innermost pixel layer. Additional requirements are applied to suppress pixel detector noise.

The dominant background considered in the search is beam-induced background (BIB), caused by beam particle losses in the LHC ring upstream of the ATLAS experiment. To reduce it a "back-to-back" topology of the signal process is being used via the T variable, related to transverse thrust [14], and is defined as:

$$T = \frac{1}{n_{PixCl}} \sum_{i=1}^{n_{PixCl}} |\hat{r}_i \cdot \hat{n}|,$$

where $\hat{r}_i$ is a direction of given pixel cluster in the transverse plane with respect to the origin of ATLAS coordinate system, and $\hat{n}$ is the direction which maximises the T value. For background events this value is just above $2/\pi$, while for the simulated signal it is close to unity. Therefore, a requirement of $T > 0.95$ is used to define the signal region (SR).

Monte Carlo (MC) simulated signal samples were produced using a semiclassical approach based on the FPA model. The semiclassical approximation breaks down for sufficiently light mono-

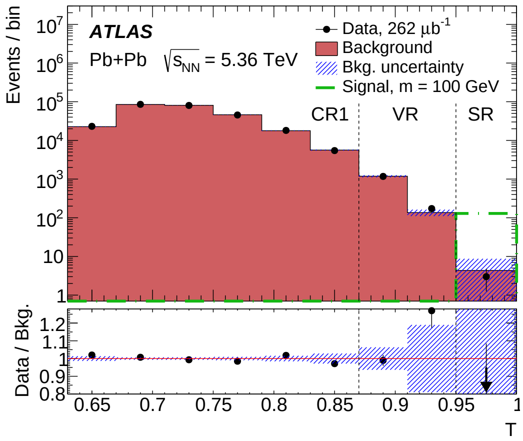

Figure 1: T distribution for data in CR1, the VR, and the SR. Data (markers) are shown together with the estimated background (filled histograms). The distributions for background use events from CR2 scaled as described in the text. The lower panel shows the ratio of data and the estimated background. The shaded bands represent the statistical uncertainty of the background. The green dotted-dashed line shows the representative signal contribution for a monopole of mass 100 GeV, and the arrow in the ratio plot is for the point that is outside the range. [6]

poles, $m < 20$ GeV for 5.36 TeV Pb+Pb collisions, so monopole mass hypotheses below 20 GeV are not considered. Signal MC event yields are also corrected for the trigger requirements in the data.

4. Background estimate

The background is estimated using a fully data-driven method. The first control region (CR1) is defined by requiring $T \leq 0.87$, and it is observed that the characteristics of these events agree with those of BIB events. Due to the asymmetric nature of BIB events, a second control region (CR2) is defined from events having a $Xn0n$ topology (presence of neutrons only on one ZDC side). The same selection criteria as to the signal events were applied to the events in CR2, except for the T requirement, and a different topocluster selection: one to three topoclusters, with at least one topocluster being out-of-time (reconstructed time more than 10 ns before the bunch-crossing time). This allows to enrich the CR2 sample with BIB events and consequently reduce its signal contamination. Events in CR2 are used to extrapolate the background contribution from CR1 to SR by fitting the distribution:

$$N_{bkg}^{SR} = \frac{N^{CR1}}{N_{T<0.87}^{CR2}} N_{T>0.95}^{CR2}.$$

To cross-check this procedure, a validation region (VR) is defined by requiring $0.87 < T \leq 0.95$.

Figure 1 shows the T distribution in the CR1, the VR and the SR, and the background contribution in the SR is estimated to be 4 ± 4 events.

5. Systematic uncertainties

The systematic uncertainties considered are related to the modeling of the detector response to the monopole, the overall noise level in the pixel detector and calorimeters, potential mismodeling of the $XnXn$ selection, the background uncertainty, and the luminosity uncertainty. The largest uncertainties are attributed to the $XnXn$ selection modeling (20%) and the detector material modeling (up 20% for highest masses), with the remaining sources ranging between less-than-one to a few percent. The total systematic uncertainty varies between 21% (lowest) and 38% (highest masses).

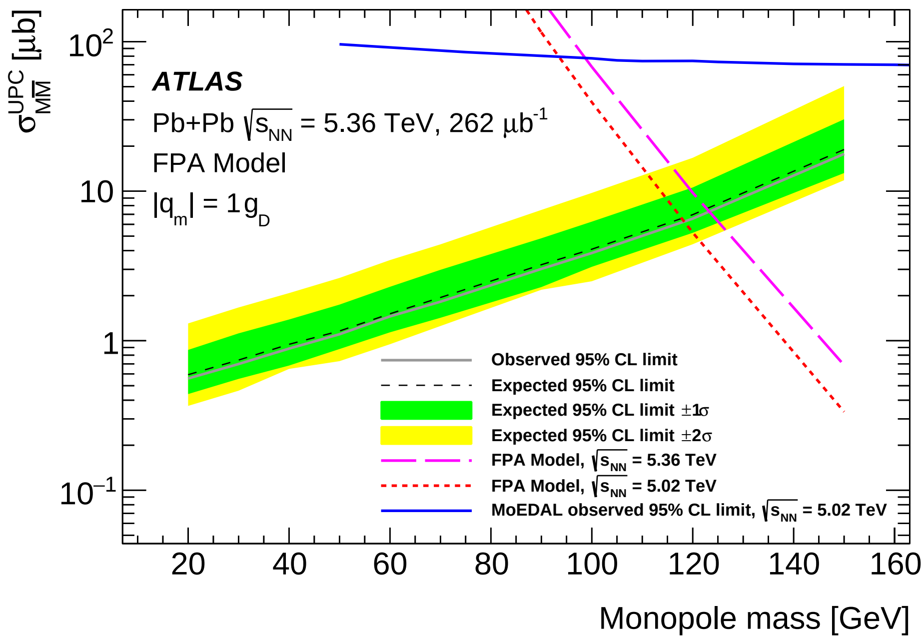

Figure 2: Expected and observed upper limits on the monopole pair-production cross-section in Pb+Pb UPC at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV for $|q_m|$ = 1gD and assuming the FPA model. The gray solid line (black dashed line) represents observed (expected) limits, whereas the darker and lighter shaded bands around the expected limits represent the $\pm1\sigma$ and $\pm2\sigma$ intervals, respectively. The FPA model predictions (dashed lines) and the observed limits by MoEDAL for $|q_m|$ = 1gD at a lower centre-of-mass energy of $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV (blue line) are compared to limits obtained by ATLAS. [6]

6. Results

Three events were found in the SR, which is consistent with the background estimate of 4 ± 4 events. The exclusion limits are set at 95% confidence level (CL) using the CL_s method [15] and are shown in Figure 2. The limits are calculated using the pseudo-experiment approach, with 20,000 “toys” per mass point. The results exclude magnetic monopoles with magnetic charge equal to one Dirac charge and masses below 120 GeV. The FPA model predictions [8] and the limits observed by MoEDAL [9] are compared to the ATLAS results.

7. Summary

This document presents the search for magnetic monopole production with mass range between 20 GeV and 150 GeV in ultraperipheral collisions using 262 $\mu\mathrm{b}^{-1}$ of Pb+Pb data at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV, collected by the ATLAS experiment in 2023. This search uses a novel method of detecting low-mass magnetic monopoles in UPC collisions. The method is complementary to the one used by the MoEDAL experiment. The derived upper limits on monopole pair-production cross-sections are more stringent than the recently reported limits from MoEDAL. Magnetic monopoles with magnetic charge equal to one Dirac charge and masses below 120 GeV are excluded.

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