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Search for magnetic monopole pair production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV with the ATLAS detector at the LHC

The ATLAS Collaboration

This Letter presents a search for highly ionizing magnetic monopoles in 262 μb^{-1} of ultraperipheral Pb+Pb collision data at $\sqrt{s_{\text{NN}}} = 5.36$ TeV collected by the ATLAS detector at the LHC. A new methodology that exploits the properties of clusters of hits reconstructed in the innermost silicon detector layers is introduced to study highly ionizing particles in heavy-ion data. No significant excess above the background, which is estimated using a data-driven technique, is observed. Using a nonperturbative semiclassical model, upper limits at 95% confidence level are set on the cross-section for pair production of monopoles with a single Dirac magnetic charge in the mass range of 20–150 GeV. The search significantly improves on the previous cross-section limits for production of low-mass monopoles in ultraperipheral Pb+Pb collisions.

Magnetic monopoles are hypothetical particles that carry isolated magnetic charge. The existence of a magnetically charged particle would restore symmetry to Maxwell's equations and explain why electric charge is quantized in nature, as shown by Dirac [1]. Dirac's argument predicts the magnetic charge of a monopole to be $q_{\mathrm{m}} = N g_{\mathrm{D}}$, where N is an integer number, $g_{\mathrm{D}} = e/(2\alpha) \approx 68.5e$ is the Dirac elementary charge in cgs Gaussian units, α is the fine-structure constant, and e is the elementary electric charge. Magnetic monopoles would manifest as highly ionizing particles, with unique trajectories in a magnetic field [2].

While monopoles appearing in grand unification theories typically have masses of the order of the unification scale ($m \approx 10^{16}$ GeV) [3] , some extensions of the Standard Model predict composite monopoles with masses near the TeV scale [4]. This improves the prospects for monopole production at existing colliders.

In ultrarelativistic heavy-ion collisions, the ion beams are accompanied by large electromagnetic (EM) fields (or equivalently, large photon fluxes). For photons emitted coherently by the entire nucleus, the flux is enhanced by a factor of Z^2 (where Z is the charge of the nucleus), as compared with beams of protons. At impact parameters b larger than twice the nuclear radius, $b > 2R_{\mathrm{A}}$, photon-induced reactions become the dominant interaction mechanism. These events, referred to as ultraperipheral collisions (UPC), have been used to study photon–nucleus (photonuclear) and photon–photon ($\gamma\gamma$) collisions [5]. These events typically have features such as rapidity gaps and lower particle multiplicity, or exclusive final states with no extra particle production, that make them qualitatively different from nuclear collisions where hadronic interactions occur [6]. The interaction of strong magnetic fields in UPC can also give rise to the production of magnetic monopole-antimonopole pairs ($M\bar{M}$). Using a simplified (leading order, LO) approach, the process corresponds to a $\gamma\gamma$ fusion reaction, $\gamma\gamma \to M\bar{M}$ [7].

The initial-photon energy spectra in UPC have a typical power-law behavior (E^{-1}) up to energies of the order of $E_{\max} \approx \gamma_{\mathrm{L}}/R_{\mathrm{A}}$ (where γ_{L} is the relativistic Lorentz factor of the ion). For Pb+Pb collisions at the Large Hadron Collider (LHC) at a nucleon–nucleon (NN) center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV, $E_{\max} \approx 85$ GeV, which implies that the UPC production cross-section for a final state with invariant mass m_X is suppressed for $m_X > 170$ GeV.

Most searches for the direct production of magnetic monopoles at particle colliders have focused on collisions of elementary particles such as electrons or quarks, assuming pair production of spin-0 or spin-$\frac{1}{2}$ point-like monopoles via the Drell–Yan mechanism or $\gamma\gamma$ fusion process [8–44]. However, due to the large coupling constant, $1/(4\alpha) \approx 34$ [45], perturbative treatments in terms of Feynman diagrams are generally not well defined. Indeed, it has been argued that the production of composite monopoles from elementary-particle collisions is suppressed by a factor of $\mathrm{e}^{-4/\alpha} \approx 10^{-236}$ [46].

Magnetic monopoles could be produced in strong magnetic fields by a magnetic analogue of the Schwinger mechanism [47]. In this case, the $M\bar{M}$ production cross-section can be computed nonperturbatively using semiclassical techniques such as the free-particle approximation (FPA) [48]. In the FPA model the formula for the total cross-section for magnetic monopole production in Pb+Pb UPC [48–50] is

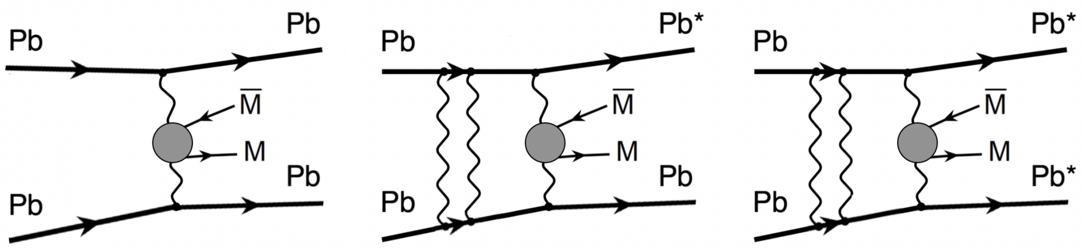
$$\sigma_{\mathrm{FPA}} = \frac{\omega}{m} \frac{2(q_{\mathrm{m}}B)^4 R_{\mathrm{Pb}}^4}{9\pi^2 m^4 \omega^2} \exp\left(-4m/\omega\right), \qquad (1)$$

where m is the monopole mass, q_{m} is the magnetic charge, $R_{\mathrm{Pb}} = 6.62$ fm is the radius of a lead nucleus, $B = 4.5 \cdot 10^{16}$ T is the peak magnetic field strength of the two nuclei at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV, which occurs at $b \approx 2R_{\mathrm{Pb}}$, and $\omega = 1.19 \cdot 10^{26}\ \mathrm{s}^{-1}$ is the field inverse decay time. It should be noted that Eq. (1) was derived for scalar (spin-0) monopoles, and the effect of monopole spin should enhance the production cross-section [48]. Due to the coherence of the magnetic field, the potential $\mathrm{e}^{-4/\alpha}$ suppression is absent for composite monopole production via the Schwinger formalism in UPC. This fact was used in the recent searches performed by the MoEDAL Collaboration in Pb+Pb collisions [50, 51]. It is also worth mentioning that while the quoted semiclassical calculations apply to elementary monopoles, the effects of finite monopole size are expected to enhance monopole production in these models [48].

This Letter presents a search for magnetic monopoles with $|q_\mathrm{m}| = 1g_\mathrm{D}$ using 262 μb^{-1} of UPC Pb+Pb collision data collected by the ATLAS detector at the LHC in 2023 at $\sqrt{s_\mathrm{NN}} = 5.36$ TeV. The ATLAS experiment [52, 53] is a multipurpose particle detector with cylindrical geometry [54], comprising an inner detector (ID) tracker surrounded by a thin superconducting solenoid, EM and hadronic calorimeters, and a muon spectrometer. A software suite [55] is used in Monte Carlo (MC) 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.

This analysis primarily makes use of the ID pixel detector and the zero-degree calorimeters (ZDC). The high-granularity silicon pixel detector surrounds the collision region. The innermost pixel-detector layer, the IBL, consists of 280 pixel-sensor modules that cover the region $|\eta| < 3.03$, and was installed at a mean distance of 3.3 cm from the beam axis before the start of Run 2 [56, 57]. In addition to the IBL, the pixel detector contains three other barrel layers and two endcaps with three disks each. It is followed by silicon microstrip (SCT) and transition radiation tracking detectors. ZDCs are located at $z = \pm 140$ m from the interaction point, and detect neutral particles such as neutrons emitted from interacting nuclei.

Events of interest are selected by the first-level (L1) trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger (HLT) [58]. In UPC, soft photons emitted by one lead nucleus can excite the other, typically through the giant dipole resonance [59], and induce the emission of one or more neutrons, each of which carries, on average, the full per-nucleon beam energy. This can give rise to three distinct EM breakup topologies: 0n0n (no neutrons are emitted), 0nXn (at least one neutron is emitted by exactly one nucleus) and XnXn (at least one neutron is emitted by each nucleus). They are shown schematically in Figure 1. This analysis exploits the XnXn topology, mainly due to limitations in triggering on monopole production. Since low-energy monopoles typically do not reach the ATLAS calorimeters, they do not produce any trigger signal there. Therefore, the only viable option is to trigger at L1 on the presence of forward neutrons in the ZDC. The primary trigger for this analysis requires a L1 signal consistent with the presence of one or more neutrons in both arms of the ZDC. In addition, the total transverse energy recorded in the calorimeter is required to be



(a) (b) (c)

Figure 1: Schematic diagrams for magnetic monopole pair production in ultraperipheral Pb+Pb collisions for (a) no, (b) single and (c) mutual ion excitation due to extra soft-photon exchanges (0n0n, 0nXn and XnXn topologies, respectively). EM breakup of the ion, denoted by Pb*, results in the production of forward neutrons, detectable in the ATLAS ZDC. The signal process in this study consists primarily of events having the XnXn topology (c).

below 10 GeV. As the monopoles considered in this analysis have relatively low masses (below 150 GeV) and typically have low energy, they deposit their energy in the innermost parts of the ATLAS detector, primarily in the pixel detector, thereby producing a sizable number of δ-electrons. The presence of more than 100 clusters of pixel hits is required in the HLT, with no specific selection on the presence of any charged-particle tracks. Due to the large cross-section for double EM dissociation [60] and limitations in the allowed data-recording rate at L1, the trigger was prescaled so that approximately one event in every six was saved, resulting in an effective integrated luminosity of 262 μb^{-1}, compared to the 1.67 nb^{-1} recorded by unprescaled triggers.

MC simulated signal samples were produced using a semiclassical (nonperturbative) approach based on the FPA model. The semiclassical approximation breaks down [50] for sufficiently light monopoles, $m < 20$ GeV for 5.36 TeV Pb+Pb collisions, so monopole mass hypotheses below 20 GeV are not considered. For the distributions of monopole kinematic quantities, simplified predictions based on the FPA model are used to model back-to-back monopole pair production, in particular with isotropic polar angle distributions of the pairs and with a distribution of monopole momentum p that follows the relative probability [49]

$$d\sigma_{\text{FPA}}(|p|)/d\sigma_{\text{FPA}}(0) = \exp\left[-\frac{4}{\omega}\left(\sqrt{m^2+|p|^2}-m\right)\right].$$

The same model was used in the MoEDAL analysis [50]. A monopole charge of $|q_{\text{m}}| = 1g_{\text{D}}$ is set in all signal samples and the monopole masses considered are 20, 30, 40, 50, 60, 70, 90, 100, 120 and 150 GeV. The signal simulation setup includes all possible configurations for the EM breakup of the nuclei, as described below. A sample with no interacting particles was simulated as well, to mimic data events that contain only detector noise.

Signal efficiency estimates rely on an extension of the ATLAS detector simulation [61] based on GEANT4 [62]. This extension, originally developed for monopole searches in pp collisions [37–40], includes descriptions of monopole acceleration in the detector's magnetic field, ionization energy losses in matter and δ-electron production along the monopole's trajectory.

In order to correct the signal MC simulation for the XnXn topology requirement, exclusive dilepton (ee and $\mu\mu$) events from the process $\gamma\gamma \to \ell\ell$ are studied. Due to the relatively large instantaneous luminosity of Pb+Pb collisions at the LHC, additional neutrons might be generated in each bunch crossing and detected in one or both arms of the ZDC (EM pileup). This leads to an outflow of events, primarily from the 0nXn category, to the XnXn category. To account for this effect in MC simulation, the yield of simulated signal events is scaled by the effective probability for the XnXn topology, parameterized as a function of total system mass m_X and system rapidity y_X:

$$p^{\text{eff}}_{\text{X}n\text{X}n}(m_X, y_X) = 0.8 \times (2 f_{0n\text{X}n}\, p_{\text{EM}} + f_{\text{X}n\text{X}n})(1 + f_{\text{diss}}), \quad (2)$$

where $f_{0n\text{X}n}$ and $f_{\text{X}n\text{X}n}$ are the predicted fractions of events with single and double EM breakup, respectively, p_{EM} is the probability of having at least one neutron from EM pileup on a given detector side, and f_{diss} is the small fraction of dissociative (incoherent) events [63] from the $\gamma^*\gamma \to \ell\ell$ and $\gamma^*\gamma^* \to \ell\ell$ reactions, where γ^* denotes a virtual photon. The $f_{0n\text{X}n}$ and $f_{\text{X}n\text{X}n}$ values are based on the SUPERCHIC 4.2 MC predictions [64], and are provided differentially in dilepton invariant mass ($m_{\ell\ell}$) and dilepton absolute rapidity ($|y_{\ell\ell}|$). The value of p_{EM}, estimated as outlined in Ref. [65], is $p_{\text{EM}} = 0.038$ for the signal trigger and 2023 Pb+Pb data-taking conditions. The value of f_{diss} for the XnXn selection is estimated to be $f_{\text{diss}} = 0.13$, based on the study of exclusive dimuon and dielectron events [65, 66]. A possible enhancement of the dissociative contribution at the largest considered monopole masses (due to very small

Pb+Pb impact parameters), leading to larger values of $p^{\text{eff}}_{\text{X}n\text{X}n}$, is conservatively neglected. The factor of 0.8 in Eq. (2) accounts for mismodeling of $f_{0n\text{X}n}$ and $f_{\text{X}n\text{X}n}$ in SuperChic, based on the calculation in Ref. [64]. The model based on Eq. (2) is validated using UPC $\gamma\gamma \rightarrow \ell\ell$ data and good agreement (within 10%) is found. The value of $p^{\text{eff}}_{\text{X}n\text{X}n}$ is about 15% for $m_X = 40$ GeV and grows to about 30% for $m_X = 200$ GeV.

The backgrounds considered in this analysis are the background from particles produced in Pb+Pb interactions (collision background) and the beam-induced background (BIB). BIB is caused by beam particle losses in the LHC ring upstream of the ATLAS experiment, due to interactions with residual gas within the beam pipe or with machine elements [67–70]. It is characterized by particles moving almost parallel to the beam line.

A requirement of at most one reconstructed charged-particle track is used to suppress collision backgrounds and has only a minor impact on the signal efficiency because a monopole's trajectory in the axial magnetic field provided by a solenoid is straight in the $r{-}\phi$ plane and bends in the $r{-}z$ plane [71] (whereas the opposite applies to electrically charged particles). Charged-particle tracks are required to pass the track selection, which is optimized to suppress combinatorial (fake) tracks in the dense track environment around Pb+Pb collisions [72], and to have transverse momentum $p_{\text{T}} > 0.1$ GeV, $|\eta| < 2.5$, and a transverse impact parameter of $|d_0| < 1$ mm calculated relative to the measured beam-line position.

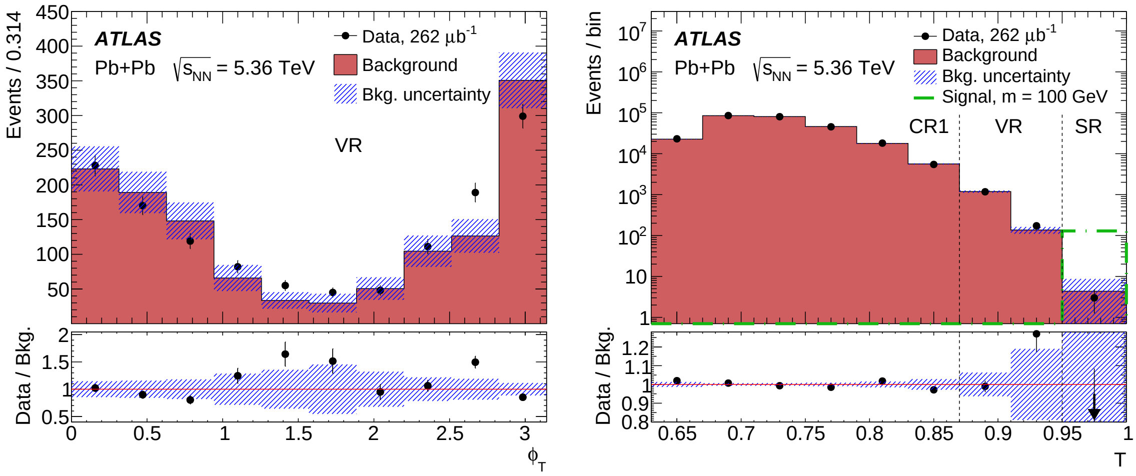
Signal events are required to have at most one topological cluster of calorimeter-cell energy deposits [73]. These topoclusters must have transverse energy $E_{\text{T}} > 0.1$ GeV and $|\eta| < 4.9$, and meet the cell significance criteria for the measured energy as outlined in Ref. [74] to suppress the contribution from electronic noise fluctuations.

Events are also required to have more than 150 pixel clusters [75], $n_{\text{PixCl}} > 150$, including more than 50 IBL clusters, $n_{\text{IBLCl}} > 50$. Clusters from the four pixel-sensor modules observed to have abnormal noise distributions in data are not considered in the cluster counting. Furthermore, events are rejected if the number of clusters in a particular module exceeds 90% of all pixel clusters in the event. The selection requirements imposed on tracks, topoclusters and pixel clusters fully suppress the collision background.

To further reduce the BIB, the azimuthal distribution of reconstructed pixel clusters is examined. A variable T, inspired by the *transverse thrust* [76], is defined as:

$$T = (1/n_{\text{PixCl}}) \sum_{i=1}^{n_{\text{PixCl}}} |\hat{r}_i \cdot \hat{n}| \, ,$$

where $\hat{r}_i$ is the direction (unit vector) of a given pixel cluster in the transverse plane with respect to the origin of the ATLAS coordinate system, and the transverse direction $\hat{n}$ maximizes the expression and corresponds to an azimuthal angle ϕ_T. The solution for $\hat{n}$ (or ϕ_T) is found iteratively. The direction of $\hat{n}$ roughly aligns in $r{-}\phi$ with the monopole's trajectory. The T variable has a maximum value of 1, for a set of fully aligned pixel clusters, and a minimum value of around $2/\pi$, for a uniform distribution of clusters in the transverse plane. Simulated signal events tend to have T values near unity, whereas the backgrounds with more uniform particle production in ϕ concentrate at much lower T values, typically just above $2/\pi$. A requirement of $T > 0.95$ is therefore used in the signal region (SR) selection, based on the simulated signal properties. The signal acceptance times efficiency of the SR selection varies between 4% and 0.2% for simulated events with low and high monopole masses, respectively, and is driven by the $n_{\text{PixCl}} > 150$ requirement.



(a) (b)

Figure 2: (a) ϕ_T distribution for data in the VR and (b) 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 panels show the ratio of data to the estimated background. The shaded bands represent the statistical uncertainty of the background. In (b) 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.

The background yield in this analysis is estimated using a fully data-driven method. A control region (CR1) is defined by requiring $T \leq 0.87$. It is observed that the event characteristics in CR1 are consistent with those of BIB. Since the BIB typically results in asymmetric event activity, an additional control region (CR2) enriched in BIB is defined from events passing a supporting trigger that selects events with ZDC activity on one side and no activity on the opposite side. The same event selection criteria as for the SR, except no requirement on T and a different topocluster requirement, are applied to CR2. To help enrich the CR2 sample in BIB events and consequently reduce the signal contamination, only events with 1–3 topoclusters are used, with at least one out-of-time energy deposit in the calorimeter, i.e. a topocluster with reconstructed time more than 10 ns before the bunch-crossing time. The presence of topoclusters with negative reconstructed time is one of the characteristic features of BIB [67]. The signal contamination in both CR1 and CR2 is studied in the MC simulated samples and is found to be negligible.

Events in CR2 are used to extrapolate the background contribution from CR1 to SR, by using the relation: $N^{\mathrm{SR}}_{\mathrm{bkg}} = (N^{\mathrm{CR1}}/N^{\mathrm{CR2}}_{T<0.87})N^{\mathrm{CR2}}_{T>0.95}$, where N^{CR1} is the event yield in CR1, and $N^{\mathrm{CR2}}_{T<0.87}$ ($N^{\mathrm{CR2}}_{T>0.95}$) is the number of CR2 events having $T < 0.87$ ($T > 0.95$). To cross-check this procedure, a validation region (VR) is defined by requiring $0.87 < T \leq 0.95$. Figure 2(a) shows the ϕ_T distributions in the VR. The CR2-based background estimate describes the data adequately. The enhanced event activity at $\phi_T \approx 0$ and $\phi_T \approx \pi$ is characteristic of BIB [67, 68].

The number of pixel clusters is correlated with the number of SCT space points [77], n_{SCTsp}. To address a small discrepancy between the CR1 and CR2 n_{SCTsp} distributions at low n_{SCTsp}, extra reweighting of the n_{SCTsp} distribution is performed for events in CR2 to better match the distribution observed in CR1. The correction applied to the n_{SCTsp} distribution improves the modeling of the n_{PixCl} distribution. This correction changes the shape of the T distribution by a few percent at low T and by about 10% at high T.

Figure 2(b) shows the T distribution in CR1, the VR, and the SR. The background in the SR is estimated to be 4 ± 4 (stat.) events.

The systematic uncertainties that were considered are related to the modeling of the detector response to the monopole, the overall noise level in the pixel detector, potential mismodeling of the XnXn selection, the background uncertainty, and the luminosity uncertainty. Uncertainties evaluated in one direction are assumed to be symmetric.

The uncertainty due to the ID material modeling in the GEANT4 simulation is accounted for by comparing the signal efficiency with its value in alternative signal samples. These samples differ by having modified descriptions of the ATLAS ID geometry: the passive material of the ID is scaled by 5%, the passive material of the IBL is scaled by 10%, or the passive material in the services region is scaled by 25%. These variations capture the full range of data–MC differences observed in studies of the ID material [78]. The changes in signal yield depend on the monopole mass hypothesis and range from 3% to 20% for the lowest and highest mass points, respectively.

The kinetic energy threshold below which δ-electrons are not propagated explicitly in the ATLAS simulation depends on the GEANT4 "range cut" parameter [79]. Reducing the value of this parameter by a factor of five produces less than a 3% signal yield change, which is taken as a systematic uncertainty.

The dE/dx formulas for ionization by monopoles (Bethe–Ahlen theory) have theoretical uncertainties of about ±3% in the kinematic region considered in this analysis [80]. Alternative signal samples where δ-electron production is reduced by 3% were therefore simulated. This results in a 1%–4% decrease in signal yield for the mass range considered, which is included as a systematic uncertainty.

Noise activity in the pixel detector is somewhat mismodeled in the simulation. Less activity is observed in MC simulated events with no interacting particles than in "empty" single-EM-dissociation (single-EMD) data events (with no tracks or topoclusters) selected by an unbiased trigger. To obtain better data–MC agreement, the MC simulated "empty" events are overlayed, on an event-by-event basis, with additional pixel clusters randomly assigned to pixel-cluster positions seen in "empty" single-EMD data events. The same degree of pixel-cluster overlay is then applied in MC signal events, resulting in a 1%–2% decrease in signal yield, which is taken as a systematic uncertainty. A similar procedure is used to estimate calorimeter noise, resulting in a 1% decrease in signal yield.

To cover the XnXn selection modeling, a 20% uncertainty is assigned to $p^{\mathrm{eff}}_{\mathrm{X}n\mathrm{X}n}$. A value of 20% is chosen to primarily cover the 10%–20% differences observed between the $f_{0n\mathrm{X}n}$ and $f_{\mathrm{X}n\mathrm{X}n}$ values in ATLAS data and those predicted by SUPERCHIC 4.2 [64]. It also covers differences between SUPERCHIC and alternative STARLIGHT [81] or GAMMA-UPC [82] predictions for $f_{0n\mathrm{X}n}$ and $f_{\mathrm{X}n\mathrm{X}n}$.

The difference between the background estimates from the reweighted and non-reweighted n_{SCTsp} distributions in CR2 is taken as a systematic uncertainty in the background estimate. The reweighting of other distributions that show slight differences between CR1 and CR2 has a negligible impact on the background estimate.

The uncertainty in the integrated luminosity of the data sample is 3.5%. It is derived from the calibration of the luminosity following a methodology similar to that detailed in Ref. [83], and using the LUCID-2 detector [84] for the baseline luminosity measurements. The total systematic uncertainty affecting the selection efficiency varies between 21% (lowest masses) and 38% (highest masses).

Three data events were found in the SR. This is consistent with the estimate of 4 ± 4 (stat.) $\pm$ 1 (syst.) background events. Consequently, exclusion limits are set at 95% confidence level (CL) using the $\mathrm{CL_s}$

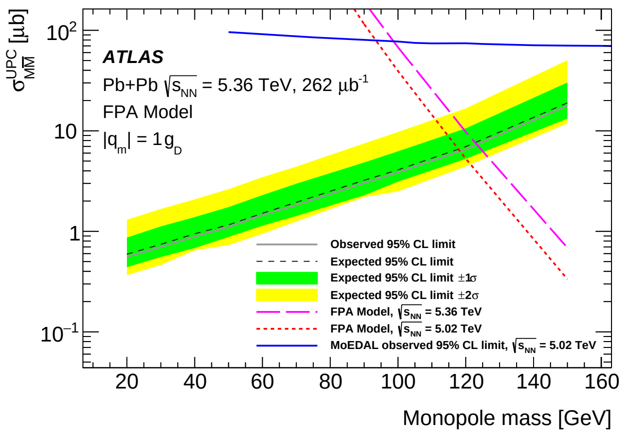


Figure 3: Expected and observed upper limits on the monopole pair-production cross-section in Pb+Pb UPC at $\sqrt{s_{\text{NN}}}$ = 5.36 TeV for $|q_{\text{m}}| = 1g_{\text{D}}$ and assuming the FPA model. The gray solid line (black dashed line) represents observed (expected) limits, whereas the darker and lighter shaded bands around the expected limits represent the $\pm 1\sigma$ and $\pm 2\sigma$ intervals, respectively. The limits are compared with FPA model predictions (dashed lines) and the observed limits by MoEDAL for $|q_{\text{m}}| = 1g_{\text{D}}$ at a lower center-of-mass energy of $\sqrt{s_{\text{NN}}}$ = 5.02 TeV [50] (blue line).

method [85] implemented in RooStats [86]. The cross-section limits are obtained by exploiting the selection efficiency and its uncertainty for each signal sample, the systematic uncertainty of the background estimate, and the integrated luminosity's uncertainty. Limits are calculated using the pseudo-experiment approach, with 20 000 "toys" per mass point. Figure 3 shows the obtained 95% CL limits. These results are compared with the FPA model predictions [48] (Eq. (1)) and with the observed limits MoEDAL [50] obtained using the trapping technique [87]. The present search excludes monopoles with masses below 120 GeV, and significantly improves on the previous cross-section limits reported by MoEDAL.

In conclusion, this Letter presents a search for magnetic monopoles with mass in the range 20–150 GeV in ultraperipheral heavy-ion collisions using 262 μb^{-1} of Pb+Pb collision data at $\sqrt{s_{\text{NN}}}$ = 5.36 TeV collected by the ATLAS detector at the LHC. This analysis uses an alternative way of detecting low-mass monopoles in heavy-ion collisions, complementary to the trapping technique used by the MoEDAL experiment. The targeted monopole signature is based on high ionization in the ATLAS pixel detector. The background is mainly beam-induced, and its yield is estimated using a data-driven procedure. No excess of events over the expected background is observed. The derived upper limits on monopole pair-production cross-sections, based on a non-perturbative semiclassical model and derived at 95% confidence level, are more stringent than the recently reported limits from MoEDAL, also using Pb+Pb collisions. Monopoles with a single Dirac magnetic charge and mass below 120 GeV are excluded.

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