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Major Report

Opportunities for new physics searches with heavy ions at colliders

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Abstract

Opportunities for searches for phenomena beyond the Standard Model (BSM) using heavy-ions beams at high energies are outlined. Different BSM searches proposed in the last years in collisions of heavy ions, mostly at the Large Hadron Collider, are summarized. A few concrete selected cases are reviewed including searches for axion-like particles, anomalous τ electromagnetic moments, magnetic monopoles, and dark photons. Expectations for the achievable sensitivities of these searches in the coming years are given. Studies of CP violation in hot and dense QCD matter and connections to ultra-high-energy cosmic rays physics are also mentioned.

Keywords: physics beyond the standard model, heavy-ion collisions, hadron colliders, axion-like particles, magnetic monopoles, dark photons, tau lepton moments

(Some figures may appear in colour only in the online journal)

1. Introduction

A wide range of experimental and observational facts—such as e.g. the existence of dark matter (DM), the origin of matter-antimatter asymmetry, the generation of neutrino masses, etc—and compelling theoretical arguments—most notably the fine tuning of the Higgs boson mass, the absence of charge-parity (CP) violation in the strong interaction, the arbitrarily large range of Yukawa couplings, etc—motivate the need for new physics beyond the current Standard Model (SM) of particle physics. Laboratory tests of the SM and direct searches for its extensions at the energy frontier capitalize on proton–proton (p–p) collisions at high center-of-mass energies aiming at producing directly or indirectly new heavy states [1]. On the other hand, rather than on new physics searches, efforts in high-energy heavy-ion collisions have historically focused on studying the collective behavior of partons in the quark-gluon plasma, as a means to probe the thermodynamics of nonAbelian quantum field theories in the laboratory [2]. In the last years, however, multiple proposals have been put forward to expand both cornerstone Large Hadron Collider (LHC) programs by exploiting heavy-ion datasets as unique and complementary means to search for new phenomena [3]. An increasing number of studies have been appearing that exploit collisions with heavy ions at the LHC, as well as at the future Electron Ion Collider (EIC) facility [4], as a means to search for phenomena beyond the Standard Model (BSM). In particular cases, the potential production and/or detection of various new proposed particles—such as axion-like particles (ALPs) [5, 6], generic long-lived particles (LLPs) [7], dark photons [8], or magnetic monopoles [9, 10], to mention a few—have been shown to be enhanced in collisions with ions compared to their proton–proton counterparts.

Most of the proposals to search for BSM physics in heavy-ion collisions are recent and form an entirely novel direction of research. In late 2018, the first dedicated workshop on this topic[14] was organized in Louvain-la-Neuve. The workshop brought in members of different communities (theorists and experimentalists from both the heavy-ion and BSM research areas, as well as accelerator physicists) to discuss such opportunities, and written contributions were incorporated [3] into the discussions of the European Particle Physics Strategy Update in 2020 [11]. A follow-up workshop was organized in 2021 at ECT* Trento[15] to discuss updated proposals to exploit the potential of BSM searches either during upcoming

[14] 'Heavy-Ions and Hidden Sectors', agenda.irmp.ucl.ac.be/e/Heavy-Ions-and-Hidden-Sectors
[15] 'Heavy-Ions and New Physics' indico.cern.ch/e/Heavy-Ions-and-New-Physics

LHC runs or in dedicated efforts at the LHC or future colliders. This document summarizes the presentations of this later workshop and updates the discussions submitted to the European Strategy on Particle Physics [3], with the goal of incorporating them into the ongoing US Community Study on the Future of Particle Physics (Snowmass 2022). We outline a few selected physics cases, mostly connected with new light and feebly-interacting particles [7], discussed during the ECT* 2021 workshop that demonstrate the benefit of using ultra-relativistic heavy-ion beams to probe novel fundamental physics phenomena in the coming decade and beyond. Fully exploiting these exciting opportunities requires synergies among experts in the accelerator, experiment, and theory communities. Therefore, this writeup starts first by summarizing the expected LHC performances in terms of heavy-ion integrated luminosities (section 2) and is then followed by a selection of physics topics whose potential BSM impact is based on the aspects highlighted below:

1.1. BSM via photon–photon collisions

Arguably, photon–photon ($\gamma\gamma$) interactions provide the most competitive BSM search mode in collisions with heavy-ions compared to protons [12]. Thanks to their dependence on the square of the ion charge (Z^2), interacting electromagnetic fields in ultraperipheral heavy-ion collisions (UPCs) [13, 14] have fluxes many orders of magnitude larger than those accessible in p–p collisions. Thus, in the Pb–Pb case, the $\gamma\gamma$ cross sections can be enhanced by up to a factor of $Z^4 \approx 50 \cdot 10^6$ compared to their p–p or e^+e^- counterparts. With the added benefit of no pileup collisions in the same bunch crossing, UPCs with ions can thereby probe high-energy photon interactions and search for potential modifications due to new physics in a very clean (both experimentally and theoretically) environment. Specific target searches include:

- The resonant production of axion-like particles ($\gamma\gamma \to a \to \gamma\gamma$) [5,15–17] on top of the light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) continuum [16, 18–20]. The lower photon detection thresholds (including trigger and offline reconstruction) available at LHCb [21], as well as at the proposed next-generation ALICE-3 experiment [22], will provide improved limits during the upcoming LHC runs. Section 3 summarizes the latest developments in this field. For lower ALP masses, the EIC provides also interesting opportunities [23].
- Renewed interest in the poorly constrained anomalous electromagnetic moments of the tau lepton [24] has risen through the exploitation of the $\gamma\gamma \to \tau\tau$ process in UPCs [25, 26], and details are given in section 4.
- Other BSM phenomena that may be probed in $\gamma\gamma$ collisions include dark photons, searched for in photon-induced collisions ($\gamma A' \to e^+e^-$) and in the decay of neutral pions ($\gamma\gamma \to \pi^0 \to \gamma A'$) [27], as well as tests of Born-Infeld QED [28] or of noncommutative geometries [29, 30]. Such studies complement the exclusive two-photon production of states with weak-scale masses such as W boson pairs ($\gamma\gamma \to \mathrm{W^+W^-}$) [31, 32] and the Higgs boson ($\gamma\gamma \to \mathrm{H} \to b\bar{b}$) [33, 34]. BSM benchmarks include direct searches for doubly-charged Higgs bosons ($\gamma\gamma \to \mathrm{H}^{++}H^{--}$) [35], and DM production via slepton ($\gamma\gamma \to \tilde{\ell}\tilde{\ell}$) [36, 37] or chargino ($\gamma\gamma \to \tilde{\chi}^+\tilde{\chi}^-$)[38] mediation. In addition, more complicated hidden sectors, e.g. involving two-step cascades such as $\gamma\gamma \to a \to a'a' \to$ SM, remain so far unexplored.
- Nonperturbative production in the strong fields generated in UPCs via the magnetic analog of the Schwinger effect [39, 40] can be used to search for magnetic monopoles [41]. Recent updates with respect to the studies reported in [3] include: (i) a better understanding of the total and differential cross sections for monopole production by the Schwinger mechanism [40, 42], (ii) a demonstration that this mechanism applies to

composite (as well as point-like) monopoles [43], and (iii) the first search by the MoEDAL experiment at the LHC, yielding the strongest bounds so far on the mass of possible magnetic monopoles [44]. This topic is covered in section 5.

- Searches for lepton flavor violation (LFV) have been carried out usually at proton deep-inelastic facilities, such as HERA, through the conversion of a beam electron into a muon or tau via the process $ep \to \ell' X$, where $\ell' = \mu, \tau$. An observation of such processes would be a signal of new physics, e.g. in the form of leptoquark (LQ) particles that couple directly to leptons and quarks. The possibility to study LQ-based LFV scenarios using the proton beams at the EIC was considered first in [45, 46], but more recently also by exploiting the large nuclear photon fluxes in ALP-mediated processes [47].

While p–p collisions at the (HL-)LHC offer higher $\gamma\gamma$ center-of-mass energies, such studies are also possible in p–A collisions (again without pileup) that can profit in addition from proton-tagging techniques using forward proton spectrometers (AFP and PPS, respectively part of the ATLAS and CMS detectors) [48–50].

1.2. Soft BSM physics

Areas in which HI collisions can offer an advantage (compared to p–p) in part of the parameter space include probes of scenarios/phenomena that require the detection of soft objects, in particular with respect to backgrounds, triggers, low-$p_{\rm T}$ reconstruction, and limitations due to pileup, etc [51, 52]. The backgrounds in HI collisions are very different from p–p collisions, as there is practically no pileup and the risk of misidentifying the primary vertex is negligible [53]. At the same time, the track multiplicity in Pb–Pb collisions is only about a factor of two larger than that expected in p–p collisions at the HL-LHC with ~200 pileup events, and potentially even lower than in pp collisions if lighter nuclei are used [54]. Further, the lower luminosity permits to operate the LHC main detectors with very loose kinematic triggers. As a result, searches for new particles in HI collisions can be more sensitive than in p–p collisions when the signatures have a complicated topology, mostly come with very low-pT values (usually below about 10 GeV), or their displaced vertices are in the forward direction. This has been studied in the case of searches for heavy neutral leptons [51, 52] and presents advantages also for low mass dark photons [55]. The latter case is discussed in section 6 of this report.

1.3. Connections to other possible BSM phenomena

Thermal effects in the quark-gluon plasma (QGP) can also lead to new phenomena in QCD, such as possible experimental signatures of the $\mathcal{P}/CP$ violation in strong interactions (section 7) via various manifestations (chiral magnetic effect [56, 57], chiral magnetic waves, etc), the production of exotic QCD states, such as strangelets [58] or sexaquarks [59] as potential DM candidates, or baryon number violation due to the strong magnetic field [60]. They can also enhance the production cross section for magnetic monopoles [3, 39]. Moreover, in principle, thermal masses in plasma can open up new production channels for thermal-relic DM candidates [61], though the lifetime of the QGP is too short, in general, to produce them in significant amounts, unless one can benefit from the larger chemical potential present in partonic systems produced in the lab compared to the early universe.

High-energy collisions of heavy-ions are also of relevance to understand anomalies observed in interactions of ultrahigh-energy cosmic rays (UHECR) with nuclei in the atmosphere at energies (well) above the LHC range. Resolution of e.g. the ‘muon puzzle’ observed in such collisions [62–64] requires reducing the nuclear uncertainties present in the

Table 1. Projected integrated luminosity at each LHC experiment during a typical future 1-month run with Pb–Pb or p–Pb operation [72]. Assuming five 1-month runs with Pb–Pb and two with p–Pb, the total integrated luminosity projected until the end of Run 4 in the present baseline scenario is also listed. An operational efficiency of 50% is assumed, as well as 24 days available for physics operation after the initial commissioning.

	Runtime	ATLAS/CMS	ALICE	LHCb
Pb–Pb	1 month	2.1–2.5 nb^{-1}	2.5–2.8 nb^{-1}	<0.5 nb^{-1}
	5 months	10.5–12.5 nb^{-1}	12.5–14.0 nb^{-1}	<2.5 nb^{-1}
p–Pb	1 month	470–630 nb^{-1}	310–330 nb^{-1}	<170 nb^{-1}
	2 months	940–1260 nb^{-1}	620–660 nb^{-1}	<340 nb^{-1}

hadronic models that are used today [65] to describe the dominant p–Air (or Fe-Air) interactions. The possibility of an additional hard source of muons due to the early production and decay of BSM particles, such as e.g. $(B+L)$-violating sphalerons or new heavy gauge (Z') or scalar (h) bosons, have been suggested [66, 67]. Dedicated runs of p-O [2] and light-ion collisions at the LHC are required to improve the modeling and tuning of all nuclear effects in the current hadronic MC simulations before one can consider any BSM interpretation of UHECR anomalies. Section 8 discusses also the importance of understanding heavy-quark (in particular, top quark) production in ultrarelativistic HI collisions.

2. Future performance of the LHC with heavy ions

The present official schedule of the LHC foresees a continuation of the heavy-ion program throughout Run 3, scheduled to take place in 2022–2025, and Run 4, presently planned for 2029–2032, with mainly one-month runs of Pb–Pb or p–Pb collisions per year. A detailed baseline operational scenario has been worked out [68], relying on an improved production scheme in the injectors that allows reducing the bunch spacing to 50 ns from the previously used 75 ns [69], as well as upgrades of the collimation system [70, 71]. A range of LHC filling patterns has been worked out, with different distributions of the collisions between, on the one hand, the ALICE, ATLAS, and CMS experiments, and on the other, the LHCb experiment [68]. Therefore, some 50 ns bunch trains have to be displaced longitudinally to obtain collisions at LHCb, with the consequence of fewer collisions in the other experiments. It is presently planned to increase the beam energy from 6.37 Z TeV (corresponding to a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV, used previously in Run 2) up to 6.8 Z TeV in Run 3 ($\sqrt{s_{NN}} = 5.36$ TeV), and likely further up to 7 Z TeV in Run 4 ($\sqrt{s_{NN}} = 5.52$ TeV).

The expected integrated luminosity has been calculated using detailed simulations [72], and the results are shown in table 1. In a typical future one-month run, between 2.2–2.8 nb^{-1} can be expected at ALICE, ATLAS, and CMS, depending on the filling pattern, while at most five times less (<0.5 nb^{-1}) would be collected at LHCb. Five Pb–Pb runs in total until the end of Run 4 would accumulate 11–14 nb^{-1} at ALICE, ATLAS and CMS, and up to 2.5 nb^{-1} at LHCb. For p–Pb, the projected future performance per month of operation is 470–630 nb^{-1} at ATLAS and CMS, 310–330 nb^{-1} at ALICE, and up to 170 nb^{-1} at LHCb [73]. In the present planning, two such p–Pb runs are expected before the end of Run 4. Significant uncertainties apply for both operational modes, since the nominal Pb-beam parameters in the LHC are still to be demonstrated. The results depend also strongly on the operational efficiency, assumed at 50%. This factor accounts for downtime and unavailability of the LHC, faults and premature beam dumps, nonideal turnaround time, and the ramp-up period needed to reach nominal beam intensity. Because of the short running periods, the heavy-ion runs are particularly sensitive to this latter factor, and the gains from longer runs, if any, will therefore likely be larger than proportional to allocated running time.

Some improved, nonbaseline machine configurations have been studied in simulations, allowing incremental performance improvements [72]: decreasing β^{*}, decreasing crossing angles, and increasing the proton intensity in p–Pb runs. Some potential minor gains could be achieved also through increased operational efficiency or if the injectors were to achieve a brightness beyond the nominal specification. Beam studies are needed in order to conclude the feasibility of these improvements, which could typically bring gains in integrated luminosity of up to tens of percent, or even up to a factor 2 in certain cases (e.g. , for LHCb in p–Pb runs with significantly higher proton intensity). Because of the large total cross section, the integrated luminosity is mainly limited by the total intensity that can be injected, and there is a limit on how much the turnaround time can be compressed [72].

In addition to the baseline program using Pb-beams, a one-week pilot run with O-O and p-O collisions are planned to take place during Run 3. The detailed operational scenario worked out in [74], relies on low-intensity beams in order to simplify the validation and start production as soon as possible. The projected integrated luminosity is about $0.5\,\mathrm{nb}^{-1}$ for O-O and $1.5\,\mathrm{nb}^{-1}$ for p-O. The O run is motivated mainly by a physics interest (mostly to help understand the so-called 'muon puzzle' in cosmic-ray physics [64], see section 8), but also to some extent by the potential to gain experience with different ion species in the injector complex and LHC, in view of a possible extension of the LHC ion program beyond Run 4. Such an extension, proposed in [2], has the main aim of reaching a significantly higher integrated nucleon-nucleon luminosity than in Run 3 and Run 4. As no obvious large gain factors in the Pb–Pb luminosity are within reach, collisions of other ion species are being studied. Some first estimates of the achievable luminosity were presented in [2], however, they did not include realistic brightness limitations from the combined effect of space charge and intrabeam scattering in the injectors and are therefore considered too optimistic. Work is ongoing to refine the projected intensity and luminosity for a range of different ion species.

3. Searches for axion-like particles

Axion-like particles (ALPs) emerge as pseudo Nambu-Goldstone bosons of a new spontaneously broken global symmetry in many BSM scenarios like supersymmetry, Higgs extensions and composite dynamics models [5, 75]. Light pseudoscalars have been also proposed as promising dark matter candidates or dark-sector mediators. In many scenarios, ALPs couple to photons via the effective Lagrangian:

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}, \tag{1}$$

where a is the ALP field, $F^{\mu\nu}$ is the photon field strength tensor, and $g_{a\gamma} = 1/\Lambda_a$ is the dimensional ALP-γ coupling constant related to the high-energy scale Λ associated with the broken symmetry. In this scenario, the production and decay rates of ALPs are fully defined in the parameter space of the axion mass m_a and the $g_{a\gamma}$ coupling.

Ultraperipheral collisions of heavy ions provide a clean environment for ALP searches in the $m_a \lesssim 100$ GeV range [15]. From the experimental point of view, the final-state of interest

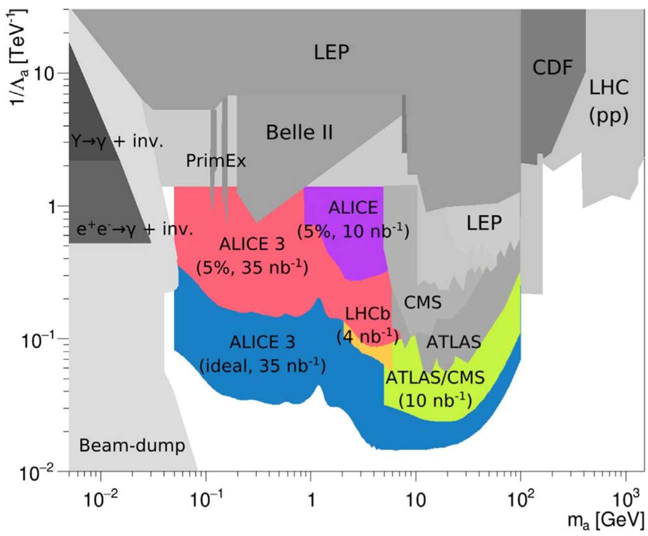

Figure 1. Bounds in the $(m_a, 1/\Lambda_a)$ plane from existing (gray) and future (colored, with heavy-ions at the LHC) ALP searches.

for ALP production is a pair of photons emitted almost back-to-back in an otherwise empty detector. The ALP signal would be visible as a peak in the diphoton invariant mass distribution on top of various background processes, mostly light-by-light scattering continuum, combinatorial background from $\pi^0\pi^0$ photoproduction and decay photons from spin-0 and spin-2 resonances [76]. Dedicated trigger strategies and high photon efficiency at low photon transverse momenta are crucial for a successful measurement.

The most stringent limits on ALPs in the m_a range from 5 to 100 GeV have been set in light-by-light scattering measurements performed in Pb–Pb UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV by the CMS [16] and ATLAS [17] collaborations. The ALICE and LHCb experiments can potentially improve those limits with future Run 3 and Run 4 data samples in a mass region $m_a \simeq 1$–5 GeV of otherwise difficult experimental access [21]. Also, ATLAS and CMS could extend the limits in the range $m_a < 5$ GeV provided a triggering strategy, and low-energy photon reconstruction are improved in future heavy-ion data taking. The future ALICE 3 experiment [22], a proposed next-generation heavy-ion experiment for Run 5 and beyond, has an opportunity to extend the coverage to even lower ALP masses. The expected performance of LHC experiments [15, 21] is shown in figure 1 together with existing limits (from [17]) and future ALICE 3 constraints estimated in two scenarios of 5% and 100% photon reconstruction efficiency corresponding to photons registered via conversions or in an ideal calorimeter. As can be seen in the figure, the ALICE 3 experiment is expected to fill the gap between beam-dump and ATLAS/CMS constraints and push the limits on ALP-γ coupling well below the 1 TeV^{-1} range for intermediate masses 50 MeV to 5 GeV, which is particularly interesting as ALPs found in this range could potentially explain the muon anomalous magnetic moment puzzle [5, 77].

4. Searches for anomalous electromagnetic moments of the τ lepton

Ultraperipheral collisions of heavy-ions at the LHC provide a highly interesting opportunity to study the electromagnetic properties of the τ lepton via the exclusive PbPb $\xrightarrow{\gamma\gamma}$ PbPb $\tau\tau$

process. So far, the strongest experimental constraints on the anomalous magnetic moment of the τ lepton (a_τ) come from the kinematics of the similar production process, $e^+e^- \xrightarrow{\gamma\gamma} e^+e^-\tau\tau$, measured by the DELPHI collaboration at the LEP2 collider [24]. Measuring a_τ with improved precision probes the τ lepton compositeness, and is sensitive to various BSM physics scenarios including supersymmetry [78], TeV-scale leptoquarks [79, 80], left-right symmetric models [81], and unparticles [82].

In recent studies [25, 26], it has been proposed to exploit existing and future heavy-ion datasets recorded by ATLAS and CMS experiments at the LHC for searches for τ anomalous electromagnetic moments. The $\gamma\gamma \to \tau\tau$ candidate events can be selected by requiring at least one τ lepton to decay leptonically, as this profits from the existing trigger algorithms of the ATLAS and CMS detectors. It should be noted that the production cross section of τ lepton pairs peaks at relatively low energy/transverse momentum. Therefore, the standard τ identification tools (as developed in ATLAS/CMS for high-p_{T} tau's) are not expected to be directly applicable. It has been therefore proposed to categorize the $\gamma\gamma \to \tau\tau$ candidate events by their decay mode.

Possible background processes which could fake the $\gamma\gamma \to \tau\tau$ signal include the two-photon quark-antiquark production ($\gamma\gamma \to q\bar{q}$) and the exclusive production of electron/muon pairs ($\gamma\gamma \to \ell^+\ell^-$). The $\gamma\gamma \to q\bar{q}$ processes have a significantly larger charged-particle multiplicity than the signal, and hence this background is fully reducible by exclusivity requirements. To suppress $\gamma\gamma \to \ell^+\ell^-$ backgrounds, additional requirements on the lepton +track system transverse momentum can be applied. A further possible sources of background are photonuclear events and semicoherent dilepton production ($\gamma^*\gamma \to \ell^+\ell^-$). A requirement of zero neutrons in both ion directions, as detectable in the Zero Degree Calorimeter systems, provides a straightforward way to estimate, and even fully suppress, such backgrounds.

Systematic uncertainties are expected to be dominated by modeling of the photon flux. Here one can use a control sample of $\gamma\gamma \to \ell^+\ell^-$ events to constrain such systematics, or even eliminate them in ratio analysis. It is predicted that by studying the existing ATLAS/CMS Run 2 Pb–Pb dataset, one can improve the current limits on (a_τ) by a factor of 2–3 [25, 26], thus significantly constraining many BSM physics scenarios.

The first observation of the $\gamma\gamma \to \tau\tau$ process has been recently presented at more than five σ level by the ATLAS and CMS experiments [83, 84], using Pb–Pb data collected at a center-of-mass energy per nucleon of 5.02 TeV. The cross section for this process, measured in a fiducial phase space, is consistent with leading-order QED calculations.

The ALICE experiment provides an opportunity to extend the measurement of $\gamma\gamma \to \tau\tau$ events down to low transverse momenta of leptons from τ decays in the pseudorapidity range $|\eta| < 0.9$ [85]. During the LHC Run 3 and Run 4, ALICE plans to collect data in the continuous readout mode and accumulate an integrated luminosity of about 2.7 nb^{-1} per one month of Pb–Pb data taking. Energy loss measurements in the ALICE Time Projection Chamber can be used for charged-particle identification and selection of leading electrons with $p_{\mathrm{T}} > 0.3$ GeV from one tau decay accompanied by one or three charged tracks from the opposite-sign tau decay. The triggerless data taking will allow ALICE to explore a kinematic region that is difficult to access by the ATLAS and CMS experiments, and to collect an order of magnitude larger $\gamma\gamma \to \tau\tau$ data samples. Besides, the low p_{T} region offers better sensitivity to negative a_τ values, thereby providing complementary information to ATLAS/CMS measurements.

Projections on a_τ measurements with the existing ATLAS/CMS Run 2 dataset [26] and with future ALICE data expected after one month of Pb–Pb data taking [85] are shown in

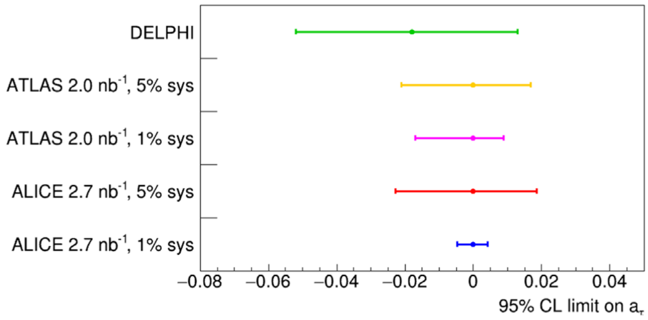

Figure 2. Expected 95% C.L. limits on a_τ measurements with available ATLAS/CMS Run 2 data (2 nb^{-1}) and with future ALICE data to be collected in 2022 (2.7 nb^{-1}) for two different assumptions on systematic uncertainty (1%, 5%) in comparison with DELPHI results [24].

figure 2. The precision of these measurements can be improved by collecting more data during LHC Run 3 and Run 4, although further progress might be limited by the level of systematic uncertainties.

5. Searches for magnetic monopoles produced via the Schwinger mechanism

Heavy-ion collisions offer a unique probe of the existence of magnetic monopoles (MMs), due to the strong, coherent magnetic fields produced in UPCs. The Schwinger mechanism [86] predicts the spontaneous creation of electron–positron pairs in the presence of a strong electric field via quantum-mechanical tunneling. If MMs exist, the magnetic counterpart of this process [9], via electromagnetic duality, would produce isolated magnetically-charged particles in sufficiently strong magnetic fields. The Pb–Pb collisions at the LHC generate the strongest coherent magnetic fields in the known Universe [87], with a peak value around 10^{20} G, four orders of magnitude higher than the strongest known astrophysical magnetic fields, around neutron stars. The MM production cross section for the Schwinger mechanism can be calculated semiclassically [39, 40], evading the breakdown of perturbation theory due to the strong monopole-photon coupling [88]. Both pointlike Dirac MMs and composite MMs can be produced by the Schwinger mechanism, with the latter somewhat enhanced [43, 89], making it the only known mechanism capable of producing composite MMs at colliders. Other collider searches for MMs, such as those based on p–p collision data, focus solely on pointlike Dirac MMs, due to an overwhelming exponential suppression factor for the production of composite monopoles in single particle collisions [10, 90].

The MoEDAL experiment at the LHC has conducted the first search for MMs produced in heavy-ion collisions via the Schwinger mechanism [44]. The MoEDAL detectors, the Magnetic Monopole Trappers (MMTs) and the Nuclear Track Detectors were exposed to the 2018 Pb–Pb collisions at the LHC at $\sqrt{s_{\rm NN}} = 5.02$ TeV and an integrated luminosity of 0.235 nb^{-1}. The MMTs consist of 880 kg of Al in the form of trapping bars placed in the region around IP8. Due to the large anomalous magnetic moment of a ${}^{27}_{13}$Al nucleus (100% natural abundance), it would bind a magnetically-charged particle with an energy of 0.5–2.5 MeV [91, 92]. Note that there is no magnetic field in the region that would affect the MM trajectories. After exposure, the MMT bars were scanned for trapped magnetic charges

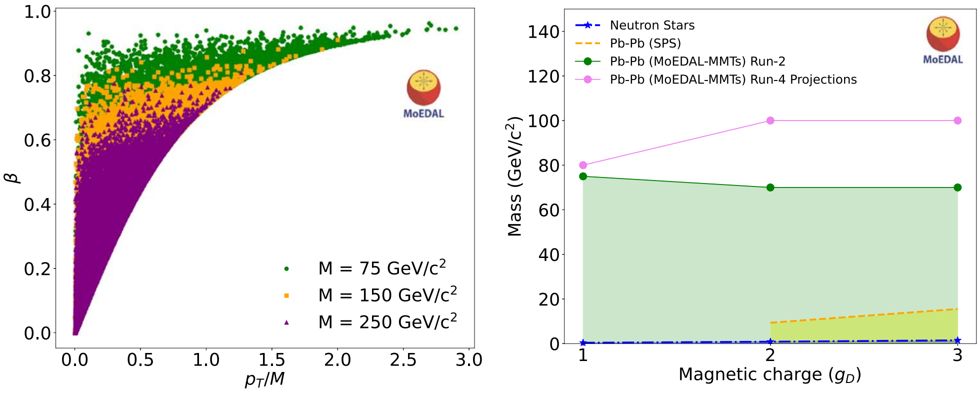

Figure 3. Left: Transverse momentum distribution for Schwinger MMs derived from the free-particle approximation, as a function of MM mass (M) plotted versus MM velocity β. Right: The 95% C.L. mass exclusion regions obtained from MoEDAL's search in Pb–Pb collisions at the LHC [44]. The conservative exclusion region is shaded in green. The projected limits for future Pb–Pb runs using the conservative Schwinger cross section and the MoEDAL-MMTs are also shown.

with a DC SQUID long-core magnetometer installed at the ETH Zurich Laboratory for Natural Magnetism.

The kinematics of MMs produced by the Schwinger mechanism may be simulated by using the free-particle approximation approach [42]. Figure 3 (left) shows the transverse momentum distribution for MMs, as a function of MM mass (M) plotted versus MM velocity β. The MM ionization energy losses, geometry and material content of the MoEDAL detector is modeled [93] in GAUSS [94], which is the LHCb simulation framework that uses GEANT4 as the simulation engine. Simulated MMs were propagated through MoEDAL detectors and the trapping efficiency, defined as the ratio of the number of MMs trapped by MMTs to the total number of generated MMs, was calculated. The nondetection of MMs by MoEDAL [44], in the first search utilising the Schwinger mechanism, resulted in the strongest bounds on the mass of possible MMs, excluding MMs with masses up to 75 GeV [44] as shown in figure 3 (right). The theoretical assumptions entering the search analysis were conservative, presenting opportunities for improved theoretical analyses to extend the mass bounds in the future. In particular, the total cross section underlying [44] and the projections in figure 3 (right) were taken to be the smallest of two different approximations, each of which is expected to provide an approximate lower bound on the true cross section [40]. The Nuclear Track Detectors in the MoEDAL-IP8 are currently being analysed for Pb–Pb Run 2 collisions with results expected in the near future. Run 4 projections for MoEDAL's MMTs are shown in figure 3 (right), highlighting the scope of future searches to extend the mass reach.

6. Searches for dark photons

Dark photons (DPs), also called U-bosons or 'hidden' photons A', are one of the possible candidate particles proposed as DM mediators. They are supposed to interact with the SM particles via a 'vector portal' due to the $U(1) - U(1)'$ gauge symmetry group mixing [8], which might make them visible in collisions of elementary particles and/or heavy ions. The corresponding Lagrangian is defined by the hypercharge field strength tensor of the SM photon field and the DM vector boson field: $\mathcal{L} \sim \epsilon^2/2\, F_{\mu\nu} F^{\mu\nu\prime}$. Here ϵ^2 is a kinetic mixing parameter, which characterizes the strength of the interaction of SM and DM particles [95–100]. This mixing allows for the decay of U-bosons to a pair of leptons, $U \to e^+e^-$ or $\mu^+\mu^-$.

A recent paper [101] has proposed to search for A' in UPCs with heavy ions via photon-dark photon collisions that produce an exclusive pair of electrons, $\gamma A' \to e^+e^-$. The existence of such a production channel would appear as an enhancement in the experimental cross section for exclusive dielectrons, as well to change in the azimuthal angular distributions, with respect to the expectations based on the Breit–Wheeler cross section for $\gamma\gamma \to e^+e^-$ [102]. From the expected data to be collected by the STAR experiment at RHIC, limits on the $m_{A'}$ versus ϵ^2 can be set, which will be the most competitive over $m_{A'} \approx 0.2$–1 GeV. Extensions of such a proposal to the case of UPCs at the LHC are under consideration.

Most commonly, light U-bosons are searched for in the decay of SM particles, e.g. through Dalitz decays of pseudoscalar mesons, such as pions ($\pi^0 \to \gamma U$) and η mesons ($\eta \to \gamma U$), as well as in the Dalitz decay of baryonic resonances, such as Δ's ($\Delta \to NU$). Dark photons can be as well as produced in the decay of neutral pions produced in UPCs ($\gamma\gamma \to \pi^0 \to \gamma U$) [27]. Dalitz decays provide the opportunity to observe DPs in dilepton experiments from low (SIS) to ultrarelativistic (LHC) energies, which stimulated a lot of experimental as well as theoretical activities—see the review [103]. The HADES Collaboration at GSI, Darmstadt, performed an experimental DP search in dilepton experiments at the SIS18 accelerator with both proton and heavy-ion beams [104]. The HADES experiment presented an upper limit for the kinetic mixing parameter ϵ^2 in the mass range of $m_U = 0.02$–0.55 GeV based on the experimental measurements of e^+e^- pairs from p–p and p–Nb collisions at $E_{\rm lab} = 3.5$ GeV as well as Ar–KCl collisions at 1.76 AGeV. Their result is consistent with the world data collected by various other experiments [103]. Later, the HADES result has been superseded by MAMI/A1 [105], NA48/2 [106] and BaBar [107, 108] measurements which further lowered the limit for ϵ^2 in this mass range. The NA48/2 experiment investigated a large sample of π^0 Dalitz decays obtained from inflight weak decays of kaons, the BaBar collider experiment used their accumulated e^+e^- datasets to survey a very large mass range up to $m_U = 8$ GeV, and the MAMI/A1 experiment [105] investigated electron scattering off a ^{181}Ta target at energies between 180 and 855 MeV to search for a DP signal. In the mass range discussed here, $m_U = 20$–500 MeV, the limit on ϵ^2 has thus been pushed down to about 10^{-6}. Moreover, a recent measurement of the excess electronic recoil events by the XENON1T Collaboration might be also interpreted in favor of DM sources, and in particular dark photons are possible candidates [109].

In [55] a procedure to define theoretical constraints on the upper limit of $\epsilon^2(m_U)$ from the heavy-ion (as well as p–p and p–A) dilepton data has been introduced. For that goal the light dark proton production channels have been incorporated in the Parton-Hadron-String Dynamics (PHSD) transport model [110–112], which describes the whole evolution of heavy-ion collisions based on microscopic transport theory by solving the equations-of-motion for each degree-of-freedom (partonic and hadronic) and their interactions. The PHSD model provides a consistent description of the production of hadrons, as well as of electromagnetic probes (dileptons and photons), in p–p, p–A, and A–A collisions from SIS18 to LHC energies [112, 113], i.e. it provides a rather good estimate of the SM backgrounds in searches for dark photon radiation to dileptons. Using the fact that the dark photons are not observed in dilepton experiments so far, one can require that their contribution cannot exceed some limit which would make them visible in the experimental data. By varying the parameter $\epsilon^2(m_U)$ in the model calculations, one can obtain upper constraints on $\epsilon^2(m_U)$ based on pure theoretical results for dilepton spectra under the constraint that the 'surplus' of DM contribution does not

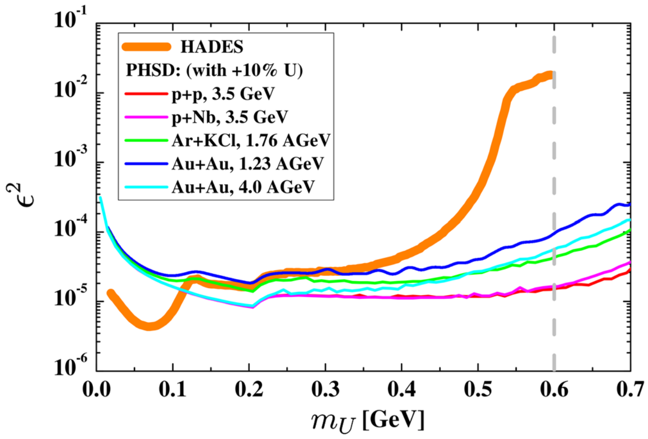

Figure 4. Kinetic mixing parameter ϵ^2 extracted from the PHSD dilepton spectra for p–p at $E_{\text{lab}} = 3.5$ GeV (red line), p–Nb at 3.5 GeV (magenta line), Ar–KCl at 1.76 AGeV (green line), Au–Au at 1.23 AGeV (blue line), Au–Au at 4.0 AGeV in comparison with the combined HADES results (orange line) [104]. The PHSD results are shown with 10% allowed surplus of the U-boson contributions over the total SM yield, *i.e.* $C_U = 0.1$. Figure adapted from [55].

overshine the SM contributions (which is equivalent to the measured dilepton spectra) within any requested accuracy.

In figure 4 we show the results for the kinetic mixing parameter ϵ^2 versus m_U extracted from the PHSD dilepton spectra for p–p at 3.5 GeV (red line), p–Nb at 3.5 GeV (magenta line), Ar–KCl at 1.76 AGeV (green line), Au–Au at 1.23 AGeV (blue line), Au–Au at 4.0 AGeV in comparison with the combined HADES results (orange line) from [104]. The PHSD results are shown with 10% allowed surplus of the U-boson contributions over the total SM yield. For comparison, figure 5 shows a compilation of current and future experimental upper limits for ϵ versus the dark photon mass set by worldwide experiments. We note, that this type of analysis can help to estimate the requested accuracy for future experimental searches of light DPs in dilepton experiments. This procedure can be extended for searches for DP of any masses with the corresponding production and decay channels implemented in the PHSD code. Moreover, it can be extended for an estimate of the contribution of other dark matter candidates to the hadronic observables in heavy-ion experiments.

ALICE, as the LHC experiment dedicated to heavy-ion physics, has good capabilities for electron identification in the low transverse momentum region, thereby enabling the measurement of a large sample of π^0 and η Dalitz decays of relevance for DP searches [115]. ALICE preliminary result from Run 1 p–p datasets limits of $\epsilon^2 = 3 \cdot 10^{-5}$ in the mass range of $m_U = 20$–100 MeV. The upgrade during LS2 will strongly improve the efficiency of $e^{\pm}$ measurements and data taking capabilities. ALICE estimates that the range of couplings $\epsilon^2 \approx (2$–$5) \cdot 10^{-8}$ will be reached in the mass range of $m_U = 0.02$–0.1 GeV using data samples to be collected in Runs 3 and 4: 6 pb^{-1} of p–p, 0.3 pb^{-1} of p–Pb at 0.5 T and 0.2 T magnetic field, 10 nb^{-1}, and 3 nb^{-1} in Pb–Pb collisions at 0.5 T and 0.2 T magnetic field, respectively [2] (red area in figure 5). Beyond this, the future ALICE 3 experiment [22] for Run 5 and Run 6 has a strong potential to further lower the limits on $\epsilon^2(m_U)$. Thanks to precision tracking performance down to very low p_T, improved tracking and mass resolution, and high efficiencies for dielectron reconstruction and identification, approximately $\times 60$ larger π^0 and η

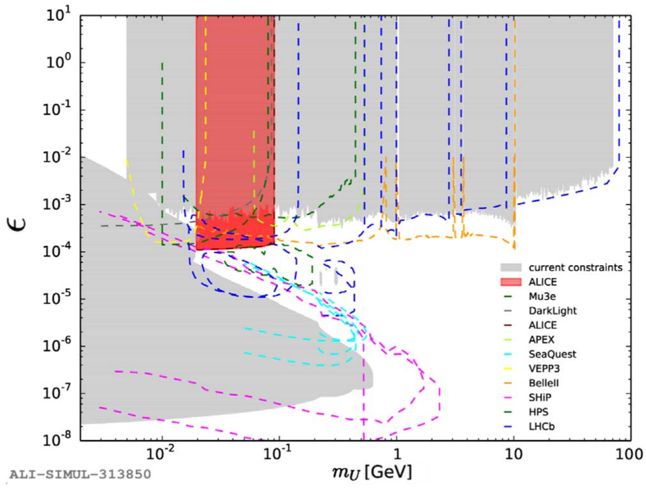

Figure 5. Dark photon limits in the ϵ coupling versus m_U mass plane. The red area indicates the expected 90% C.L. constraints from ALICE measurements before 2030. Figure adapted from [2, 114].

Dalitz samples will be measured, and mixing parameters as low as $\epsilon^2 \approx (4\text{–}10) \cdot 10^{-9}$ and $\epsilon^2 \approx (1\text{–}6) \cdot 10^{-8}$ will be reached in the π^0 and η mass region, respectively.

7. Chiral effects in hot and dense QCD matter

Studies of structures with nontrivial topology in the QCD vacuum, which determine the behavior of the $\mathcal{P}/\mathcal{CP}$ fundamental symmetries in hot quark-gluon matter, can shed light in our understanding of $\mathcal{P}/\mathcal{CP}$ symmetries in the strong interaction. As discussed in [116], collisions of relativistic nuclei generate very strong electric **E** and magnetic **B** fields. Owing to a nontrivial topology of the QCD vacuum, the interactions of the external extremely strong Abelian fields with the final-state QGP give rise to dissipationless transport phenomena [117] which may lead to interesting effects observable experimentally, such as e.g. (i) the chiral magnetic effect (CME), (ii) the chiral separation effect (CSE), (iii) the electric separation effect (ESE), and/or (iv) the emergence of the chiral vortical effect (CVE). Superpositions of the aforementioned effects may lead to collective modes in quark-gluon matter. A combination of CSE and the CME renders possible the existence of a new type collective mode in the QGP, such as the chiral magnetic wave (CMW). By analogy with CMW, it was theoretically predicted chiral vortical wave (CVW) involving the collective propagation of fluctuations of the electrical- and chiral-charge densities along the vorticity $\boldsymbol{\omega}$ direction [118].

A hard-sphere model of heavy-ion collisions without medium effects (electric conductivity *etc.*) predicts a peak value of the magnetic-field strength eB about tens of GeV^2 [119] even for collisions of light nuclei at energy ranges of the HE-LHC [120] and FCC [121, 122] projects. The absolute value of the magnetic field rapidly decreases with time and increases with atomic number, thereby providing new ways to search for experimental signatures of the nontrivial topology of the QCD vacuum. Due to high luminosity and high multiplicity per event in the HE-LHC and FCC energy domain, various multiparticle (azimuthal) correlation techniques can be used to investigate the wide set of aforementioned chiral effects. Also, the event shape engineering (ESE) technique is considered another promising tool to disentangle background contributions from possible physical signals. The corresponding measurements require larger data samples. Furthermore, the future heavy-ion collider projects under consideration can provide the opportunity for the study of the flavor dependence of the $\mathcal{P}/\mathcal{CP}$ violation via the measured correlations of different particle species. One can expect a mass ordering of the strength of chiral effects, in particular, of the CME. Heavy quarks appear to be less affected by the influence of the external **B** than light quarks even for the extremely strong $eB \sim 10$ GeV^2. Therefore one can qualitatively expect a smaller magnitude of the CME for charm and bottom particles. The measurements with heavy quarks can provide new unique information with regard to the sphaleron and the strong $\mathcal{CP}$ problem.

Preliminary measurements of three-particle correlators in p–p, p–Λ and p–π final-state pairs are consistent with the presence of the CVE, whose contribution is larger than that of the CME [123]. Investigations of the multipoint azimuthal correlations in particle ensembles with baryons can shed new light on the collective chiral modes in QGP. Furthermore, the study of small partonic systems (produced in p–A and light nuclei collisions) at ultrahigh energies may provide clearer signals for the formation of novel vortical structures which can be generated, in general, in asymmetric collisions due to the special geometry and unique dynamics [124]. High luminosity measurements in collisions of up to tens TeV will allow the precise measurements of global polarization of various particle species including multistrange baryons and heavy flavors (c, b) in the presence of the QGP phase. Such measurements would be useful for the experimental study of anomalous gravitomagnetic moment (AGM) deeply related with the axial charge separation along the rotation of the fluid [118] and consequent verification of the hypothesis that thermal effects can break the Einstein equivalence principle in quantum field theory [125].

8. Connections between ultrahigh-energy cosmic rays and heavy-ions physics

Measurements of collisions of cosmic ray (CR) particles with incoming energies in the range 10^{18}–10^{21} eV with nuclei in the upper atmosphere provide new unique opportunities for the study of multiparticle production processes at energies (well) above those reachable at the LHC and future colliders [65, 126]. The energy range for protons in the lab reference frame associated with such ultrahigh-energy cosmic rays (UHECR) includes the so-called Greisen-Zatsepin-Kuzmin (GZK) limit of $E_p \approx 10^{20}$ eV [127, 128] and somewhat expands it, taking into account possible uncertainties in the theoretical estimations of the limit energy values for UHECR and the experimental measurements [129, 130]. As shown in [131], the partonic medium produced in the central collisions of UHECR particles with air nuclei is characterized by high-energy densities at midrapidity and temperatures well above the critical ones for the creation of the QGP already at $E_p \gtrsim 10^{17}$ eV. The Bose–Einstein decoupling time is of the order of $\sim$10 fm even in collisions induced by $^4He^{2+}$ CRs. The particle source created in proton–nucleus collisions at $E_p \gtrsim 10^{19}$ eV is characterized by large space-time extents, which support the hypothesis of the creation of blobs of QGP in UHECR interactions [131], where phenomena due to partonic collectivity can take place [132].

One of the most remarkable features of recent UHECR measurements is the observed muon excess with respect to Monte Carlo model predictions at energies of primary particles above $\sim 10^{17}$ eV [62]. The role of QGP formation in the small partonic systems produced in UHECR energy range can be relevant for the resolving such a ‘muon puzzle’ [64]. In particular, collective hadronization in the QGP can play a significant role for air-shower development [63]. The study of the matter created in interactions of UHECR particles with air nuclei is relevant for both the present UHECR observatories and for heavy-ion collisions (including proton–nucleus and light nuclei) at future colliders. The upper $E_p \gtrsim 10^{20}$ eV boundary of the UHECR energy domain corresponds to the hundreds TeV and even $\mathcal{O}$(1 PeV) in $\sqrt{s}$. At such energies, the production of heavy quarks, including charm and beauty [133] and top [134] quarks, is large and opens a unique possibility for investigating the preequilibrium stages of the space-time evolution of the QGP. Cross sections for charm and beauty production in p–Air collisions at GZK-cutoff energies reach values of $\sigma(c\bar{c}) \approx 5$ b, and $\sigma(b\bar{b}) \approx 100$ mb, respectively. For top quarks, the first evidence for their production in heavy-ion interactions has been recently presented by CMS in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [135]. The sum of pQCD NNLO partonic cross sections for $t\bar{t}$ production results in an estimated value of $\sigma(t\bar{t}) \approx 70$ nb $\times A^2$ at $\sqrt{s_{\rm NN}} \approx 0.5$ PeV [136], implying $\sigma(t\bar{t}) \approx 1$ μb for p–Air collisions. A recent Monte Carlo study [137] showed that heavy-quark (c, b) production, as implemented for p–p collisions, cannot explain alone the muon puzzle in extended atmospheric showers, thereby confirming the need for additional nuclear effects [63]. However, the future detailed investigation of the production of heavy flavors, in particular top, in high-energy heavy- and light-ion collisions can provide novel insights into both fields—collider and UHECR physics—with interdisciplinary and cross-fertilizing aspects [136].

9. Summary

This short report presents several recent proposals that exploit heavy-ion (HI) collider data to search for physics beyond the Standard Model (BSM), and updates and expands those of a previous paper with similar scope [3]. A noncomprehensive but representative list of BSM processes accessible with HI at the LHC has been presented. Despite the lower nucleus–nucleus c.m. energies and beam luminosities compared to p–p collisions, HI are more competitive than the latter in particular in BSM scenarios, whereas in some others they can complement or confirm searches (or discoveries) performed in the p–p mode. The advantages of HI with respect to p–p searches are either based on comparatively enhanced underlying mechanisms of production: $\gamma\gamma$ processes in ultraperipheral collisions and 'Schwinger' production through strong classical EM fields, or on improved reconstruction of new physics signals in the 'soft' regime.

Topics reviewed in this paper include novel ways to search for axion-like particles and dark photons; proposals to constrain the anomalous electromagnetic moments of the tau lepton; deeper theoretical studies of magnetic monopole production in heavy-ion collisions, as well as the first experimental results from the dedicated MoEDAL detector at the LHC, yielding the strongest bounds so far. Proposals to improve our understanding of charge and parity violation in the strong interaction, and the synergy between HI collisions and the study of new phenomena in ultrahigh-energy cosmic rays have been also outlined. The topics covered here provide additional motivations, beyond the traditional QGP/QCD physics cases, to prolong the HI program at the LHC past their currently scheduled end in 2032 (Run 4), in particular with lighter ion systems, an LHC running mode that has not been operated so far.

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Data availability statement

No new data were created or analysed in this study.

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