New Phenomena Searches in Heavy Ion Collisions

Snowmass 2021 Energy-Frontier – Letter of Interest

Liliana Apolinário[1], Lydia Beresford[2], Nora Brambilla[3], Émilien Chapon[4], Yang-Ting Chien[5], David d'Enterria[6], Albert De Roeck[6], Marco Drewes[7], Mateusz Dyndal[6], Hesham El Faham[7], Glennys R. Farrar[8], Sylvain Fichet[9], Andrea Giammanco[7], Victor P. Goncalves[10], Oliver Gould[11], Jan Hajer[7], Lucian Harland-Lang[12], Sonia Kabana[13], Simon Knapen[6], Vladimir Kovalenko[14], Georgios K. Krintiras[15], Jesse Liu[16], Steven Lowette[17], Michele Lucente[7], Daniel E. Martins[18], Guilherme Milhano[1,19], Matthew Nguyen[20], Vitalii A. Okorokov[21], James Pinfold[22], Arttu Rajantie[23], Patricia Rebello Teles[24], Federico Leo Redi[25], Ingo Schienbein[26], Matthias Schott[27], Gustavo Gil da Silveira[28], Rajeev Singh[29], Michael Spannowsky[30], Jiayin Sun[31], Ralf Ulrich[32], Merijn van de Klundert[33], and Michael Winn[34]

[1]LIP, Av. Professor Gama Pinto 2, 1649-003 Lisboa, Portugal
[2]Department of Physics, University of Oxford, Oxford OX1 3RH, UK
[3]Physik Department, Technische Universität München, München
[4]Institute of High Energy Physics, Beijing, China
[5]C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794, USA
[6]CERN, 1211 Geneva, Switzerland
[7]Centre for Cosmology, Particle Physics and Phenomenology,
Université catholique de Louvain, Louvain-la-Neuve B-1348, Belgium
[8]Centre for Cosmology and Particle Physics, New York University, NY, NY 10003, USA
[9]ICTP South American Institute for Fundamental Research & IFT-UNESP, Sao Paulo, Brazil
[10]Universidade Federal de Pelotas, Pelotas - RS, Brazil
[11]Helsinki Institute of Physics, University of Helsinki, FI-00014, Finland
[12]University of Oxford, England
[13]Instituto de Alta Investigación, Universidad de Tarapac a, Arica, 1000000, Chile
[14]Saint Petersburg State University, Russia
[15]Department of Physics and Astronomy, 1082 Malott, 1251 Wescoe Hall Dr. Lawrence, KS 66045
[16]Department of Physics, University of Chicago, Chicago IL 60637, USA
[17]Department of Physics, Vrije Universiteit Brussel, Brussels, Belgium
[18]Universidade Federal do Rio de Janeiro (UFRJ), Brazil
[19]Instituto Superior Téecnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1609-001, Lisboa, Portugal
[20]Laboratoire Leprince-Ringuet - École Polytechnique, 91120 Palaiseau, France
[21]National Research Nuclear University MEPhI, 115409 Moscow, Russia
[22]Centre for Particle Physics, University of Alberta, Edmonton, Alberta, Canada
[23]Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom
[24]Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[25]École polytechnique fédérale de Lausanne - EPFL, Lausanne, Switzerland
[26]Laboratoire de Physique Subatomique et de Cosmologie, Université
Grenoble-Alpes, CNRS/IN2P3,53 Avenue des Martyrs, 38026 Grenoble, France
[27]Johannes Gutenberg University Mainz, Germany

[28]Federal University of Rio Grande do Sul, Brazil
[29]Institute of Nuclear Physics Polish Academy of Sciences, PL 31-342 Kraków, Poland
[30]Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, U.K
[31]Università di Cagliari, Cagliari, Italy
[32]KIT, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
[33]DESY, 22607 Hamburg, Germany
[34]Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Dépt Physique Nucléaire (DPhN), Saclay, France

Thematic Areas:

■ (EF07) QCD and strong interactions: Heavy Ions
■ (EF08) BSM: Model specific explorations

Contact Information:

Marco Drewes [marco.drewes@uclouvain.be], David d'Enterria [david.d'enterria@cern.ch]

Wide-ranging experimental results and compelling theoretical arguments motivate the need for new physics beyond the Standard Model (SM). Laboratory tests of the SM and its extensions at the energy frontier capitalize on high center-of-mass energies to produce heavy states with large energetic detector signatures [1]. Meanwhile, efforts in heavy-ion physics focus on studying the collective behaviour of partons in the quark-gluon plasma [2]. Recently, proposals have been put forward to expand both cornerstone LHC programs by exploiting heavy-ion datasets as unique and complementary means to search for new phenomena [3]. This underscores the wealth of physics awaiting study at hadron colliders and its detectors beyond their original design goals. Fully exploiting these exciting opportunities requires synergies among experts in the accelerator, experiment, and theory communities.

This Letter of Interest outlines the rich science case for using ultrarelativistic heavy-ion beams to probe novel fundamental physics phenomena in the coming decade and beyond. We highlight the complementary advantages compared with existing approaches using proton-proton collisions. The planned Snowmass 2021 contribution extends the input to the European Strategy for Particle Physics [3] to include recent theoretical and experimental advances, sharpen open questions, and promote engagement from the US community and its international partners. The following topics are planned to be discussed:

Photon–photon collisions: Interacting electromagnetic fields in ultraperipheral heavy-ion collisions (UPCs) [4, 5] have fluxes many orders of magnitude larger than those accessible in *pp* collisions, and thereby can probe fundamental photon interactions and potential modifications from new physics in a very clean (experimental and theoretical) environment. Specific targets include light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) [6–9] sensitive to resonant production of axion-like particles ($\gamma\gamma \to a \to \gamma\gamma$) [8, 10–12]. Additional avenues include pair-production of electrons ($\gamma\gamma \to ee$) [13] and muons ($\gamma\gamma \to \mu\mu$) [13, 14]. Renewed interest in the poorly constrained electromagnetic dipole moments of the tau lepton [15] could be probed via the $\gamma\gamma \to \tau\tau$ process [16, 17]. In addition, more complicated hidden sectors, e.g. involving two-step cascades such as $\gamma\gamma \to a \to a'a' \to \mathrm{SM}$, have so far remained unexplored. Other Beyond Standard Model (BSM) phenomena that may be probed in $\gamma\gamma$-collisions include dark photons [2], e.g. from decays of pions ($\gamma\gamma \to \pi^0 \to \gamma A'$) [18] as well as tests of Born-Infeld QED [19] or non-commutative geometries [20, 21].

These studies complement exclusive production of states with weak-scale masses such as W boson pairs ($\gamma\gamma \to WW$) [22, 23] and the Higgs boson ($\gamma\gamma \to h \to bb$) [24]. BSM benchmarks include direct searches for doubly-charged Higgs bosons ($\gamma\gamma \to H^{++}H^{--}$) [25], and Dark Matter (DM) production via slepton ($\gamma\gamma \to \tilde{\ell}\tilde{\ell}$) [26, 27] or chargino ($\gamma\gamma \to \tilde{\chi}^+\tilde{\chi}^-$) [28] mediation. While pp collisions at the (HL-)LHC offer higher center-of-mass energies, these studies could be possible in large enough datasets of pA collisions, profiting from proton-tagging techniques using forward proton spectrometers (AFP and PPS) [29, 30].

In addition, non-perturbative production in the strong fields generated in UPCs via the magnetic analogue of the Schwinger effect [31, 32] can be used to search for magnetic monopoles [33].

New long-lived particles: The backgrounds in HI collisions are very different from pp collisions, as there is no pile-up and the risk of misidentifying the primary vertex is practically negligible [34]. At the same time, the track multiplicity in PbPb collisions is only about a factor 2 larger than that expected in pp collisions at the HL-LHC with ~ 200 pile-up events [35, 36]. 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 pp collisions when the signatures have a complicated topology, mostly come with very low p_T values, or their displaced vertices are in the forward direction. This has been studied for the case of long-lived particle searches [36, 37].

Thermal processes in the plasma: Thermal effects in the QGP can lead to new phenomena in QCD, such as possible experimental signatures of the $\mathcal{P}/\mathcal{CP}$ violation in strong interactions via various manifestations (chiral magnetic effect [38], chiral magnetic waves, etc.), and the production of exotic QCD states, such as strangelets [39] or sexaquarks [40] as potential DM candidates. They can also enhance the production cross section for magnetic monopoles [3, 31]. Moreover, in principle thermal masses in a plasma can open up new production channels for DM candidates [41], 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 in comparison to the early universe. Finally, spin polarization measurements in relativistic heavy-ion physics are important to study the properties of QGP and its vortical structure, and can help in the search for the chiral magnetic effect [42]. Experimental detection of Λ hyperon polarization [43] has generated intense theoretical studies for spin polarization [44–47].

References

[1] X. Cid Vidal et al. “Report from Working Group 3: Beyond the Standard Model physics at the HL-LHC and HE-LHC.” In: *Report on the Physics at the HL-LHC,and Perspectives for*

the HE-LHC. Ed. by A. Dainese et al. Vol. 7. Dec. 2019, pp. 585–865. DOI: `10.23731/CYRM-2019-007.585`. arXiv: `1812.07831 [hep-ph]`. №: CERN-LPCC-2018-05.

[2] Z. Citron et al. “Report from Working Group 5: Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams.” In: *Report on the Physics at the HL-LHC,and Perspectives for the HE-LHC*. Ed. by A. Dainese et al. Vol. 7. Dec. 2019, pp. 1159–1410. DOI: `10.23731/CYRM-2019-007.1159`. arXiv: `1812.06772 [hep-ph]`. №: CERN-LPCC-2018-07.

[3] R. Bruce et al. “New physics searches with heavy-ion collisions at the LHC.” In: *J. Phys. G* 47 (2020), p. 060501. DOI: `10.1088/1361-6471/ab7ff7`. arXiv: `1812.07688 [hep-ph]`.

[4] A. Baltz et al. “The Physics of Ultraperipheral Collisions at the LHC.” In: *Phys. Rept.* 458 (2008), pp. 1–171. DOI: `10.1016/j.physrep.2007.12.001`. arXiv: `0706.3356 [nucl-ex]`.

[5] S. Klein and P. Steinberg. “Photonuclear and Two-photon Interactions at High-Energy Nuclear Colliders” (May 2020). arXiv: `2005.01872 [nucl-ex]`.

[6] D. d’Enterria and G. G. da Silveira. “Observing light-by-light scattering at the Large Hadron Collider.” In: *Phys. Rev. Lett.* 111 (2013), p. 080405. DOI: `10.1103/PhysRevLett.111.080405`. arXiv: `1305.7142 [hep-ph]`. Erratum in: *Phys. Rev. Lett.* 116 (2016), p. 129901. DOI: `10.1103/PhysRevLett.116.129901`.

[7] *ATLAS*. “Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC.” In: *Nature Phys.* 13.9 (2017), p. 852. DOI: `10.1038/nphys4208`. arXiv: `1702.01625 [hep-ex]`. №: CERN-EP-2016-316.

[8] *CMS*. “Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.” In: *Phys. Lett. B* 797 (2019), p. 134826. DOI: `10.1016/j.physletb.2019.134826`. arXiv: `1810.04602 [hep-ex]`. №: CMS-FSQ-16-012, CERN-EP-2018-271.

[9] *ATLAS*. “Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector.” In: *Phys. Rev. Lett.* 123.5 (2019), p. 052001. DOI: `10.1103/PhysRevLett.123.052001`. arXiv: `1904.03536 [hep-ex]`. №: CERN-EP-2019-051.

[10] S. Knapen et al. “Searching for Axionlike Particles with Ultraperipheral Heavy-Ion Collisions.” In: *Phys. Rev. Lett.* 118.17 (2017), p. 171801. DOI: `10.1103/PhysRevLett.118.171801`. arXiv: `1607.06083 [hep-ph]`.

[11] M. Bauer, M. Neubert, and A. Thamm. “Collider Probes of Axion-Like Particles.” In: *JHEP* 12 (2017), p. 044. DOI: `10.1007/JHEP12(2017)044`. arXiv: `1708.00443 [hep-ph]`. №: MITP-17-047.

[12] *ATLAS*. “Measurement of light-by-light scattering and search for axion-like particles with 2.2 nb^{-1} of Pb+Pb data with the ATLAS detector” (Aug. 2020). DOI: `10.3204/PUBDB-2020-03018`. arXiv: `2008.05355 [hep-ex]`. №: CERN-EP-2020-135.

[13] *STAR*. “Probing Extreme Electromagnetic Fields with the Breit-Wheeler Process” (Oct. 2019). arXiv: `1910.12400 [nucl-ex]`.

[14] *ATLAS*. “Measurement of high-mass dimuon pairs from ultraperipheral lead-lead collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with the ATLAS detector at the LHC” (June 2016). URL: `cds.cern.ch/record/2157689`. №: ATLAS-CONF-2016-025.

[15] *DELPHI*. “Study of tau-pair production in photon-photon collisions at LEP and limits on the anomalous electromagnetic moments of the tau lepton.” In: *Eur. Phys. J. C* 35 (2004), pp. 159–170. DOI: `10.1140/epjc/s2004-01852-y`. arXiv: `hep-ex/0406010`. №: CERN-EP-2003-058.

[16] L. Beresford and J. Liu. “New physics and tau $g-2$ using LHC heavy ion collisions” (Aug. 2019). arXiv: `1908.05180 [hep-ph]`.

[17] M. Dyndal et al. “Anomalous electromagnetic moments of τ lepton in $\gamma\gamma \to \tau^+\tau^-$ reaction in Pb+Pb collisions at the LHC.” In: *Phys. Lett. B* 809 (2020), p. 135682. DOI: `10.1016/j.physletb.2020.135682`. arXiv: `2002.05503 [hep-ph]`.

[18] V. Goncalves and B. Moreira. “Dark photons from pions produced in ultraperipheral *PbPb* collisions.” In: *Phys. Lett. B* 808 (2020), p. 135635. DOI: `10.1016/j.physletb.2020.135635`. arXiv: `2006.08348 [hep-ph]`.

[19] J. Ellis, N. E. Mavromatos, and T. You. “Light-by-Light Scattering Constraint on Born-Infeld Theory.” In: *Phys. Rev. Lett.* 118.26 (2017), p. 261802. DOI: `10.1103/PhysRevLett.118.261802`. arXiv: `1703.08450 [hep-ph]`. №: CAVENDISH-HEP-17-04, DAMTP-2017-12, KCL-PH-TH-2017-11, CERN-TH-2017-062.

[20] J. L. Hewett, F. J. Petriello, and T. G. Rizzo. “Signals for noncommutative interactions at linear colliders.” In: *Phys. Rev. D* 64 (2001), p. 075012. DOI: `10.1103/PhysRevD.64.075012`. arXiv: `hep-ph/0010354 [hep-ph]`. №: SLAC-PUB-8635, FERMILAB-PUB-00-286-T.

[21] R. Horvat et al. “Light-by-Light Scattering and Spacetime Noncommutativity.” In: *Phys. Rev. D* 101.9 (2020), p. 095035. DOI: `10.1103/PhysRevD.101.095035`. arXiv: `2002.01829 [hep-ph]`.

[22] *CMS*. “Evidence for exclusive $\gamma\gamma \to W^+W^-$ production and constraints on anomalous quartic gauge couplings in pp collisions at $\sqrt{s} = 7$ and 8 TeV.” In: *JHEP* 08 (2016), p. 119. DOI: `10.1007/JHEP08(2016)119`. arXiv: `1604.04464 [hep-ex]`. №: CMS-FSQ-13-008, CERN-EP-2016-073.

[23] *ATLAS*. *Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector*. Tech. rep. Aug. 2020. URL: `cds.cern.ch/record/2727859`. №: ATLAS-CONF-2020-038.

[24] D. d’Enterria, D. E. Martins, and P. Rebello Teles. “Higgs boson production in photon-photon interactions with proton, light-ion, and heavy-ion beams at current and future colliders.” In: *Phys. Rev. D* 101.3 (2020), p. 033009. DOI: `10.1103/PhysRevD.101.033009`. arXiv: `1904.11936 [hep-ph]`.

[25] K. Babu and S. Jana. “Probing Doubly Charged Higgs Bosons at the LHC through Photon Initiated Processes.” In: *Phys. Rev. D* 95.5 (2017), p. 055020. DOI: `10.1103/PhysRevD.95.055020`. arXiv: `1612.09224 [hep-ph]`. №: OSU-HEP-16-11.

[26] L. Beresford and J. Liu. “Search Strategy for Sleptons and Dark Matter Using the LHC as a Photon Collider.” In: *Phys. Rev. Lett.* 123.14 (2019), p. 141801. DOI: `10.1103/PhysRevLett.123.141801`. arXiv: `1811.06465 [hep-ph]`.

[27] L. Harland-Lang et al. “LHC Searches for Dark Matter in Compressed Mass Scenarios: Challenges in the Forward Proton Mode.” In: *JHEP* 04 (2019), p. 010. DOI: `10.1007/JHEP04(2019)010`. arXiv: `1812.04886 [hep-ph]`. №: IPP/18/103.

[28] S. Godunov et al. “Quasistable charginos in ultraperipheral proton-proton collisions at the LHC.” In: *JHEP* 01 (2020), p. 143. DOI: `10.1007/JHEP01(2020)143`. arXiv: `1906.08568 [hep-ph]`.

[29] *CMS, TOTEM.* “Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV with the CMS-TOTEM precision proton spectrometer.” In: *JHEP* 07 (2018), p. 153. DOI: `10.1007/JHEP07(2018)153`. arXiv: `1803.04496 [hep-ex]`. №: CMS-PPS-17-001, TOTEM 2018-001, CERN-EP-2018-014.

[30] *ATLAS. Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS.* Tech. rep. Aug. 2020. URL: `cds.cern.ch/record/2727863`. №: ATLAS-CONF-2020-041.

[31] O. Gould and A. Rajantie. “Magnetic monopole mass bounds from heavy ion collisions and neutron stars.” In: *Phys. Rev. Lett.* 119.24 (2017), p. 241601. DOI: `10.1103/PhysRevLett.119.241601`. arXiv: `1705.07052 [hep-ph]`. №: IMPERIAL-TP-2017-OG-2.

[32] O. Gould, D. L. J. Ho, and A. Rajantie. “Towards Schwinger production of magnetic monopoles in heavy-ion collisions.” In: *Phys. Rev. D* 100.1 (2019), p. 015041. DOI: `10.1103/PhysRevD.100.015041`. arXiv: `1902.04388 [hep-th]`. №: IMPERIAL-TP-2019-DH-01, HIP-2019-2/TH, IMPERIAL-TP-2019-DH-01; HIP-2019-2/TH.

[33] Y. D. He. “Search for a Dirac magnetic monopole in high-energy nucleus-nucleus collisions.” In: *Phys. Rev. Lett.* 79 (1997), pp. 3134–3137. DOI: `10.1103/PhysRevLett.79.3134`.

[34] *CMS.* “Observation of top quark production in proton-nucleus collisions.” In: *Phys. Rev. Lett.* 119.24 (2017), p. 242001. DOI: `10.1103/PhysRevLett.119.242001`. arXiv: `1709.07411 [nucl-ex]`. №: CMS-HIN-17-002, CERN-EP-2017-239.

[35] *CMS.* “Pseudorapidity distributions of charged hadrons in xenon-xenon collisions at $\sqrt{s_{\mathrm{NN}}} =$ 5.44 TeV.” In: *Phys. Lett. B* 799 (2019), p. 135049. DOI: `10.1016/j.physletb.2019.135049`. arXiv: `1902.03603 [hep-ex]`. №: CMS-HIN-17-006, CERN-EP-2018-294.

[36] M. Drewes et al. “New long-lived particle searches in heavy-ion collisions at the LHC.” In: *Phys. Rev. D* 101.5 (2020), p. 055002. DOI: `10.1103/PhysRevD.101.055002`. arXiv: `1905.09828 [hep-ph]`. №: CP3-19-26.

[37] M. Drewes et al. “Searching for New Long Lived Particles in Heavy Ion Collisions at the LHC.” In: *Phys. Rev. Lett.* 124.8 (2020), p. 081801. DOI: `10.1103/PhysRevLett.124.081801`. arXiv: `1810.09400 [hep-ph]`. №: CP3-18-60.

[38] D. E. Kharzeev, L. D. McLerran, and H. J. Warringa. “The Effects of topological charge change in heavy ion collisions: Event by event P and CP violation.” In: *Nucl. Phys. A* 803 (2008), pp. 227–253. DOI: `10.1016/j.nuclphysa.2008.02.298`. arXiv: `0711.0950 [hep-ph]`.

[39] *STAR*. “Strangelet search at RHIC.” In: *Phys. Rev. C* 76 (2007), p. 011901. DOI: `10.1103/PhysRevC.76.011901`. arXiv: `nucl-ex/0511047 [nucl-ex]`.

[40] G. R. Farrar, Z. Wang, and X. Xu. “Dark Matter Particle in QCD” (2020). arXiv: `2007.10378 [hep-ph]`.

[41] C. Dvorkin, T. Lin, and K. Schutz. “Making dark matter out of light: freeze-in from plasma effects.” In: *Phys. Rev. D* 99.11 (2019), p. 115009. DOI: `10.1103/PhysRevD.99.115009`. arXiv: `1902.08623 [hep-ph]`.

[42] K. Fukushima, D. E. Kharzeev, and H. J. Warringa. “The Chiral Magnetic Effect.” In: *Phys. Rev. D* 78 (2008), p. 074033. DOI: `10.1103/PhysRevD.78.074033`. arXiv: `0808.3382 [hep-ph]`.

[43] *STAR*. “Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid.” In: *Nature* 548 (2017), pp. 62–65. DOI: `10.1038/nature23004`. arXiv: `1701.06657 [nucl-ex]`.

[44] W. Florkowski, A. Kumar, and R. Ryblewski. “Relativistic hydrodynamics for spin-polarized fluids.” In: *Prog. Part. Nucl. Phys.* 108 (2019), p. 103709. DOI: `10.1016/j.ppnp.2019.07.001`. arXiv: `1811.04409 [nucl-th]`.

[45] W. Florkowski et al. “Spin polarization evolution in a boost invariant hydrodynamical background.” In: *Phys. Rev. C* 99.4 (2019), p. 044910. DOI: `10.1103/PhysRevC.99.044910`. arXiv: `1901.09655 [hep-ph]`.

[46] F. Becattini and M. A. Lisa. “Polarization and Vorticity in the Quark Gluon Plasma” (Mar. 2020). DOI: `10.1146/annurev-nucl-021920-095245`. arXiv: `2003.03640 [nucl-ex]`.

[47] E. Speranza and N. Weickgenannt. “Spin tensor and pseudo-gauges: from nuclear collisions to gravitational physics” (June 2020). arXiv: `2007.00138 [nucl-th]`.