For a few millionths of a second, shortly after the Big Bang, the Universe was filled with an astonishingly hot, dense matter made of all kinds of elementary particles moving at near light speed. This mixture was dominated by quarks – fundamental bits of matter – and by gluons, carriers of the strong force that normally bound quarks together into familiar protons and neutrons. In those first evanescent moments of extreme temperature, however, quarks and gluons were free to move on their own in what is called a quark-gluon plasma (QGP).

To recreate conditions similar to those of the very early Universe, powerful accelerators make head-on collisions between massive ions. For instance gold nuclei are collided at Relativistic Heavy Ion Collider (RHIC in operation since 2000) located at Brookhaven National Laboratory in the US or lead nuclei at the Large Hadron Collider (LHC in operation since 2010) at CERN in Switzerland. In these heavy-ion collisions the hundreds of protons and neutrons in two such nuclei smash into one another at energies of a few trillion electronvolts each. This forms a miniscule fireball in which all composite constituents “melt” into the QGP. Its temperature is of order of 4 billion Celsius (compare to about 30 million in the core of the Sun).

The fireball instantly cools, expands, and the individual quarks and gluons (collectively called partons) recombine into a blizzard of ordinary matter that speeds away in all directions to be finally registered by enormous detectors. The debris contains a wealth of particles such as (anti-)pions and (anti-)kaons, which are made of a quark and an antiquark; (anti-)protons and (anti-)neutrons, made of three quarks; and many others.

Over the last two decades researchers created for the first time the QGP formed in heavy-ion collisions at RHIC. One of surprising discoveries was that it behaves like a perfect fluid with small viscosity rather than like a gas, as it was expected back then. The properties of the QGP have largely been confirmed by heavy-ion experiments at the LHC at a factor of 14 higher energy. Studies of the QGP medium shed light on many mysteries about the nature of the quark-gluon interactions that hold together our visible world and how they evolved from this early Universe.

Another interesting feature of highly charged ions circulating in the LHC machine is that they radiate photons, the quanta of light. If two nuclei going in opposite directions pass very close to each other, photons radiated from each beam can collide together and produce new particles, just as in any other collisions. This class of events is called photon-photon ($\gamma\gamma$) collisions. A large incoming rate of $\gamma\gamma$ interactions in heavy-ion collisions at the LHC makes it a very powerful tool for searches for new particles, which have never been observed before.

The much greater collision energies available at the LHC in so-called Run 2, which spanned years 2015-2018, push measurements to even higher energies than are accessible at RHIC, thus creating larger volumes of hotter QGP allowing its more detailed characterisation. Theoretical understanding of these measurements is challenging, however, it is one of the most important problems in Quantum Chromodynamics (QCD), the theory that explains how quarks and gluons can interact between themselves. In addition, understanding the results in the theoretical framework of QCD will result in a deeper insight into the nature of ordinary nuclear matter.

Within this project scientists from AGH University of Science and Technology from Kraków carry out a set of high-impact measurements focused on so called hard probes (particles of very high momenta) produced in heavy-ion collisions registered by the ATLAS experiment. In 2015 and 2018 data-taking, lead-lead collisions were delivered at the energy of 5.02 TeV per nucleon pair, and in 2016 proton-lead beams were collided at 5.02 and 8.16 TeV. Our team contributed to a number of measurements published based on the 2015 data solely, as well as with lower-energy collisions collected in years 2010-2013 by ATLAS. Results of this project will advance our understanding of matter in the QGP state, as well as of ordinary nuclear matter, and will allow to set the stage for the future heavy-ion explorations at yet higher beam intensities at the LHC. Moreover, this project aims at conducting pioneering search for new particles and observables in $\gamma\gamma$ collisions which are deemed to be one of the promising ways for discovery of new physics at the LHC. For measurements limited by statistical precision a combination of the results from ATLAS and CMS is proposed for the first time. This approach has a potential of increasing sensitivity to discoveries.