Resolving a mathematical puzzle in quarks and gluons in nuclear matter

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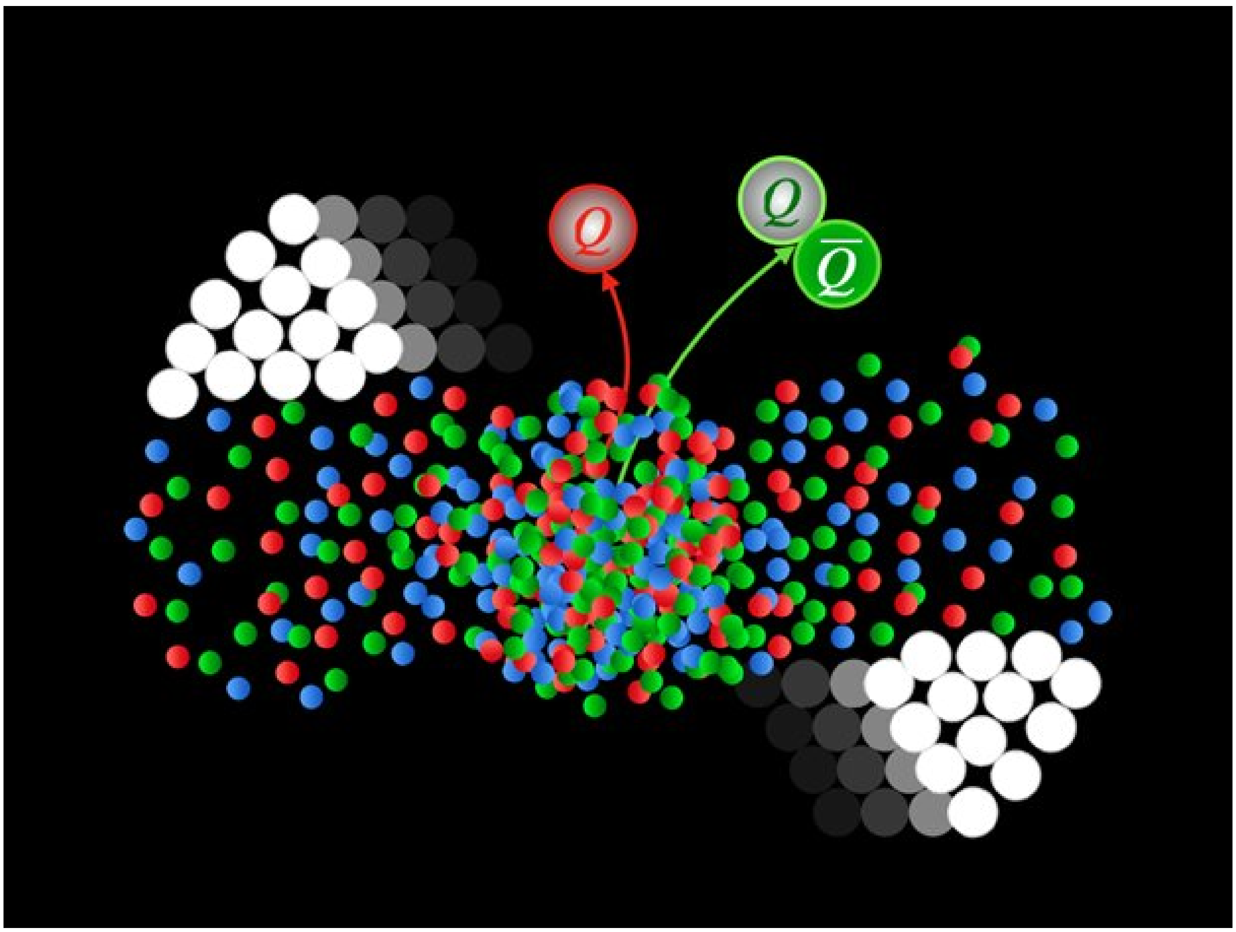

A cartoon of the quark-gluon plasma (small red, green, and blue circles) produced in a relativistic heavy ion collision between two heavy nuclei (white circles). The collision produces a heavy quark (red "Q") and a heavy quark-antiquark pair (green "QQ̄"). Credit: Bruno Scheihing-Hitschfeld and Xiaojun Yao

The building blocks of atomic nuclei are protons and neutrons, which are themselves made of even more fundamental particles: quarks and gluons. These particles interact via the strong force, one of the four fundamental forces of nature. They make up the nuclei at the heart of every atom. They also make up forms of hot or dense nuclear matter that exhibit exotic properties.

Scientists study the properties of hot and cold nuclear matter in relativistic heavy ion collision experiments and will continue to do so using the future Electron-Ion Collider. The ultimate goal is to understand how complex forms of matter emerge from elementary particles affected by strong forces.

Theoretical calculations involving the strong force are complex. One aspect of this complexity arises because there are many ways to perform these calculations. Scientists refer to some of these as gauge choices. All gauge choices should produce the same result for the calculation of any quantity that can be measured in an experiment. However, one particular choice, called axial gauge, has puzzled scientists for years because of difficulties in obtaining consistent results upon making this choice.

A recent study, published in *Physical Review Letters*, resolves this puzzle and paves the way for reliable calculations of hot and cold nuclear matter properties that can be tested in current and future experiments.

The exotic form of nuclear matter that physicists study in relativistic heavy ion collisions is called the quark-gluon plasma (QGP). This form of matter existed in the early universe. Physicists explore its properties in heavy ion collision experiments by recreating the extremely high temperatures last seen microseconds after the Big Bang. By analyzing experimental data from the collisions and comparing them with theoretical calculations, physicists can ascertain various properties of the QGP. A calculation method called axial gauge had previously seemed to imply that two QGP properties that describe how heavy quarks move through the QGP were the same.

Researchers at the Massachusetts Institute of Technology and the University of Washington have now found this implication to be incorrect. Their study also carefully analyzed the subtle conditions for when axial gauge can be employed and explained why the two properties are different. Finally, it showed that two distinct methods for measuring how gluons, which are particles that carry the strong force, are distributed inside nuclei must yield different results. This prediction will be tested at the future electron-ion collider.

More information: Bruno Scheihing-Hitschfeld et al, Gauge Invariance of Non-Abelian Field Strength Correlators: The Axial Gauge Puzzle, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.130.052302