Primordial Soup Was Full of Flavors

Top quarks and antiquarks have been detected in heavy-ion collisions at the Large Hadron Collider, showing that all six quark flavors were present in the Universe's first moments.

By **Niseem Magdy Abdelrahman**

Quarks, the fundamental building blocks of matter, are usually confined within hadrons, such as protons and neutrons, by the strong force. But in the first moments after the big bang, quarks and gluons moved freely in an extremely hot, dense state of matter called a quark–gluon plasma (QGP) [**1**]. This "primordial soup" was the Universe's first form of matter, existing for roughly 10 microseconds after the big bang, until the Universe cooled sufficiently for quarks and gluons to combine [**2**]. Scientists recreate and study these early-Universe conditions by smashing together ultrarelativistic heavy nuclei at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in New York, the Large Hadron Collider (LHC) at CERN in Switzerland, and similar facilities. Such experiments have confirmed the presence within QGPs of five quark flavors—up, down, strange, charm, and bottom—but the final quark flavor, top, has proved elusive. Now the LHC's ATLAS experiment has observed the production of top-quark pairs ($t\bar{t}$) in lead–lead (Pb + Pb) collisions, providing definitive evidence that these particles can be produced within and interact with a QGP [**3**]. By revealing how these heaviest-known quarks behave in this extreme environment, the observation unlocks new insights into the properties of the QGP and the fundamental interactions of quarks and gluons under conditions that closely resemble those of the Universe's earliest moments.

Quarks offer a useful probe of QGPs through several key phenomena including jet quenching, heavy-quark energy loss, and quarkonia suppression [**4**]. Jet quenching and heavy-quark energy loss both refer to the way that quarks lose energy as they traverse a QGP. This energy loss can be studied by analyzing the suppression of particle yields in heavy-ion collisions compared to proton–proton collisions. Quarkonia suppression refers to the phenomenon in which the QGP formation significantly reduces the production of heavy-quark–antiquark bound states (quarkonia) such as charmonium (charm–anticharm) and bottomonium (bottom–antibottom) in heavy-ion collisions compared to proton–proton collisions. Observing top quarks participating in such QGP interactions would constitute a powerful addition to this tool set. But the mass of the top quark is approximately 173 GeV—roughly 40 times heavier than the bottom quark and over 70,000 times heavier than the up quark—and its correspondingly short lifetime ($\sim 10^{-25}$ seconds) has made the particle challenging to detect within such a high-energy environment.

Last year, the ATLAS Collaboration reported the observation of top-quark-pair production in proton–lead (p + Pb) collisions [**5**]. Those results enabled the researchers to constrain the nuclear parton distribution functions (nPDFs), which describe the way a nucleon's momentum is distributed among its constituent quarks and gluons (partons) when bound in an atomic nucleus. Such nuclear modifications of the PDFs—especially the gluon distribution—play a crucial role in perturbative quantum chromodynamics at high energies [**6**, **7**].

In their groundbreaking new work, the ATLAS Collaboration measured $t\bar{t}$ production using Pb + Pb-collision data collected in 2015 and 2018. Unlike p + Pb collisions, Pb + Pb collisions create a long-lived QGP, in which $t\bar{t}$ pairs are difficult to identify. The team's analysis, which achieved the 5-sigma threshold for an official discovery, relied on the so-called dilepton decay

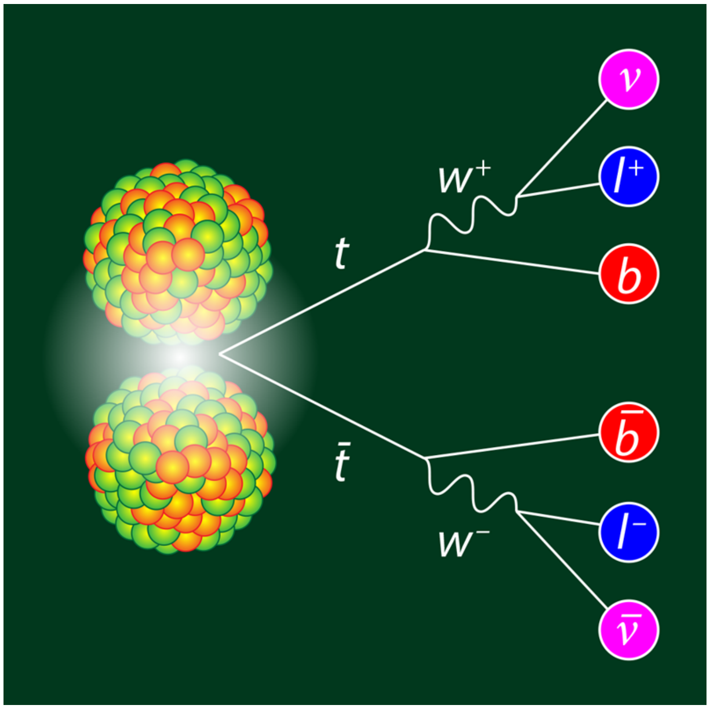

Figure 1: Collisions between lead nuclei at the Large Hadron Collider are now known to produce top-quark–antiquark pairs, which have been measured through the dilepton decay channel. Through this decay channel, each quark (antiquark) quickly decays into a bottom quark (antiquark) and a W^+ (W^-) boson. The W^+ (W^-) boson subsequently decays into a positively (negatively) charged lepton and a corresponding neutrino.
Credit: APS/Alan Stonebraker

channel, in which the top-quark–antiquark pair decays into a pair of leptons (an electron and a muon), corresponding neutrinos, and a bottom-quark–antiquark pair (Fig. **1**) [**3**]. From these new observations, the researchers strengthened their earlier constraints on nPDFs, which will improve our understanding of the structure of nuclei at extreme energy densities. So far, the measured $t\bar{t}$ production cross-section in Pb + Pb collisions is consistent with existing theoretical predictions that incorporate nPDFs [**8**].

The ATLAS Collaboration's landmark observation marks the beginning of a new era in heavy-ion physics. Future experiments with larger datasets will refine the $t\bar{t}$ production cross-section measurements and further constrain the nPDFs. Increasing the luminosity of Pb + Pb collisions in future LHC runs will make possible more precise studies of top-quark behavior in the QGP, while complementary studies at the upcoming Electron-Ion Collider at Brookhaven National Laboratory could offer further insights into nuclear structure. But the detection of top quarks in the Pb + Pb-generated QGP already has profound implications. By confirming that all six quark flavors were present in the primordial soup, the result deepens our understanding of QCD and informs models of the early Universe.

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