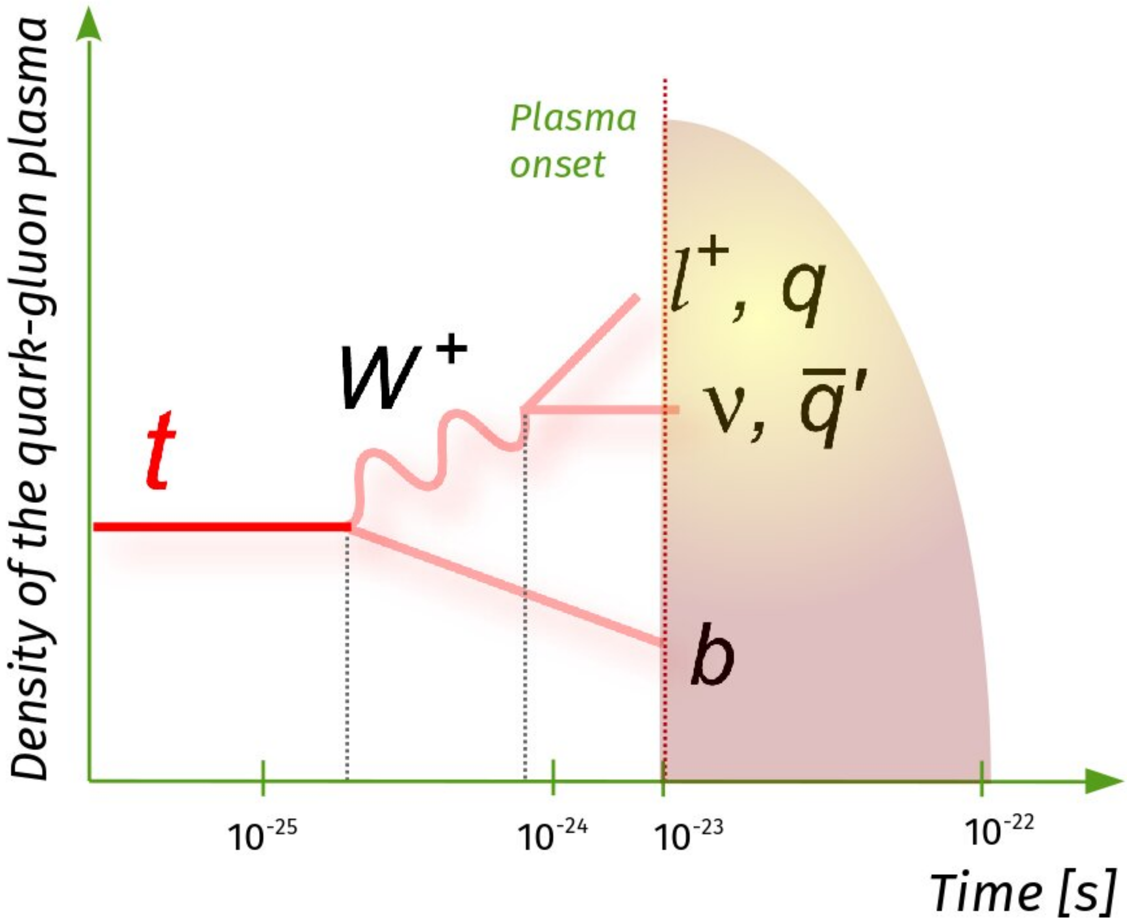
The first evidence of top quark production in nucleus-nucleus collisions

January 7 2021, by Ingrid Fadelli



Top quarks almost always decay into a b quark and W boson; the latter further decays into leptons or quarks that can be detected and form the so-called "final state". The sketch illustrates the process of the top quark decaying to other particles, and the average decay times of each particle are indicated on the x-axis. The quark-gluon plasma density evolution (y-axis) is illustrated as a function of time. Credit: CMS Collaboration.

The Compact Muon Solenoid (CMS) Collaboration, a large group of researchers from different institutes worldwide, has recently gathered the very first evidence of top quark production in nucleus-nucleus collisions. Their work, outlined in a paper published in *Physical Review Letters*, was based on lead-lead collision data gathered by the CMS particle detector, at CERN's Large Hadron Collider (LHC).

Up until a few years ago, when CERN's LHC had just started operating, most physicists studying heavy ions (i.e., high mass nuclei that have been fully stripped of electrons for acceleration purposes) were skeptical about the possibility that top quarks, the heaviest elementary particles known to date, could be studied in heavy ion collisions. In fact, at the time, it was still unclear whether the LHC was able to sustain collisions between heavy ions at a sufficiently high collision rate, also known as luminosity. Recently, however, LHC accelerator experts were able to achieve this rate and surpass the initial luminosity goals for heavy ion collisions.

Another reason why studying top quarks in heavy ion collisions seemed less feasible than in proton-proton (p-p) collisions is that when the LHC collides heavy ions, the maximum kinetic energy of individual nucleons is considerably smaller than the corresponding energy in p-p collisions. As the rate of top quark production depends in great part on the collision energy (i.e., the larger the energy, the easier it is to produce quarks), producing these particles in LHC-based heavy ion collisions seemed challenging.

The LHC was also set up to devote less time to heavy ion collisions and more to p-p collisions, reflecting the priorities of the particle physics community. For instance, in one year, it generally spends one month producing heavy ion collisions and six to seven months in p-p collisions.

Finally, heavy ion collisions produce far more particles than more common p-p ones, which can make detecting particles and analyzing heavy ion-related data collected by the LHC very challenging. Collectively, these factors hindered and slowed down the study of top quarks in heavy ion collisions, even if they were often identified in p-p collisions.

Five years ago, researchers at CERN, University of Jyväskylä, and Helsinki Institute of Physics published the first predictions of production rate of top quarks in heavy ion collisions. Despite the relatively low rate of production of the LHC, they argued that top quarks could help to probe the so-called quark-gluon plasma (QGP). QGP is a state of matter that is believed to have existed during the universe's first microsecond of life, which could also reside in the dense core of neutron stars in today's universe. This state of matter can be recreated in laboratory settings by colliding heavy ions, such as lead (Pb).

Top quarks can be useful both to probe QGP and to study the distribution of gluons within nuclei. These two uses, however, require different types of collisions, the former symmetric ones (e.g., lead on lead or Pb-Pb) and the latter symmetric and asymmetric ones (e.g., protons on lead or p-Pb). The LHC collides both symmetric and asymmetric beams, but before it could be applied to QGP and gluon-related studies, researchers had to prove with a high degree of confidence that top quarks can actually be detected in nucleus-nucleus collisions.

"In December 2015, the LHC delivered Pb-Pb collisions with a kinetic energy of 2.51 TeV per nucleon, meaning for the nucleon-nucleon collision, a grand total (center of mass energy per nucleon) of 5.02 TeV," members of the CMS Collaboration told Phys.org via email. "This was a big step over Run 1, but the luminosity was still too limited for top-quark study purposes and, as mentioned before, the heavy ion running time was only one month. So in short, that dataset was too small to claim evidence for top quark production."

After the dataset gathered in 2015 was released, the researchers carried out a series of studies aimed at gathering evidence of top quark production in heavy ion collisions. First, they measured top quark production in a small reference p-p sample taken in 2015 at the same center-of-mass energy of 5.02 TeV, then they measured it in p-Pb collisions recorded in 2016. Ultimately, they performed their analyses on Pb-Pb collisions.

"These new Pb-Pb data were accumulated at the very end of Run 2, in 2018, thanks to the ingenuity of our accelerator colleagues, who introduced improvements in the chain from the Pb ion source down to LHC, and the capability of the CMS experiment to record on tape, the full amount of heavy ion data delivered by LHC," members of the CMS Collaboration explained. "Overall, this resulted in a total accumulated luminosity approximately four times larger than in 2015. The larger data set eventually helped, but by itself, it wouldn't have been sufficient in case no top quark reconstruction improvements were introduced."

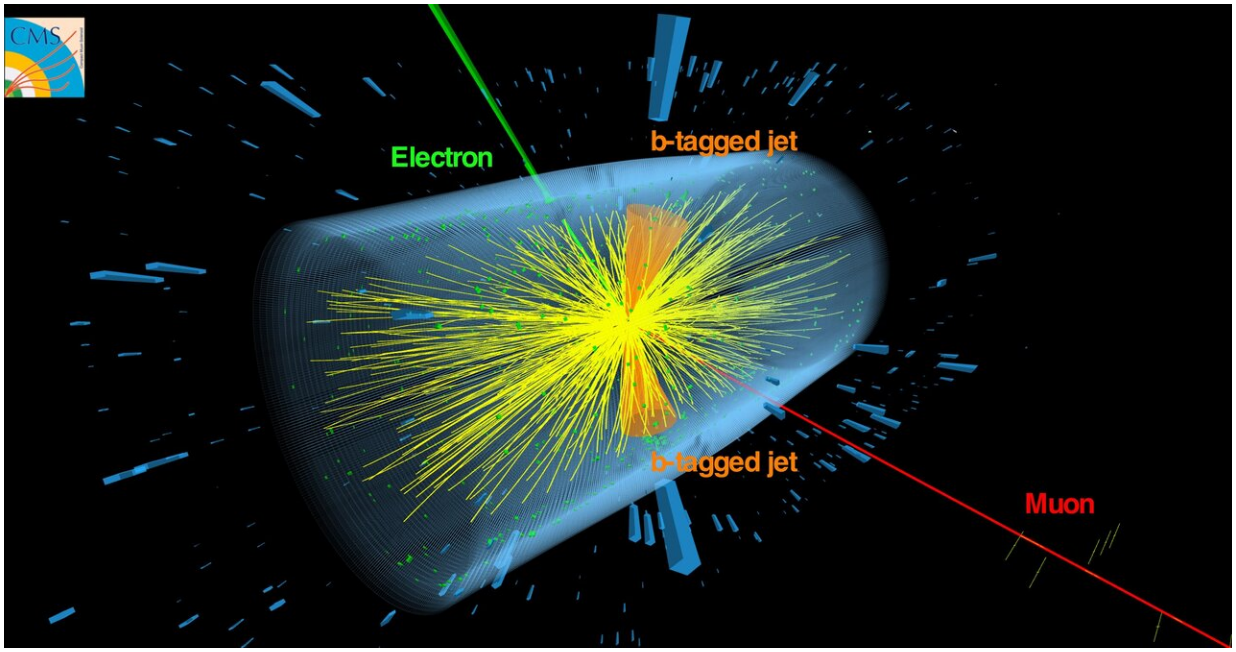
In their recent study, the CMS collaboration combined two experimental approaches: one that is affected by the presence of QGP and one that is agnostic to it. The first of these methods exploits the presence of bottom quarks (i.e., the lighter versions of top quarks). Bottom quarks can provide hints of top quark production, as the latter almost always decay into the former. The second approach, on the other hand, focused exclusively on the study of electrons and muons (i.e., heavier relatives of electrons).

"This second method was less sensitive, but it prevented a potential criticism: We have a relatively imprecise knowledge, so far, of how QGP affects the behavior of bottom quarks, and so in principle, the first method might be biased by still unknown effects," Andrea Giammanco, former coordinator of the Top Quark group of the CMS collaboration, told Phys.org. "As a result of the smallness of the top-quark signal, the large background (e.g., random combinations of unrelated particles, or detector-induced processes that mimic the signal), and the complexity of top quark reconstruction, the analysis was designed with a few unique features."

Initially, the CMS collaboration focused on re-optimizing identification algorithms in order to achieve performances comparable to those attained on p-p collisions, despite the challenges associated with the environment created by Pb-Pb collisions. Subsequently, they used advanced machine learning algorithms, which are promising tools for the analysis of data gathered by the LHC.

Notably, the CMS collaboration was the first to gather measurements that extract top quark signals based on lepton information alone. In addition, they used a new analysis technique that is entirely driven by data to carefully estimate background information.

"To avoid any human bias, our study was designed following a so-called 'blind' analysis procedure, whereby the selection criteria were optimized and fixed first using only a small initial part of the data, before being applied to the full data set," Giammanco said. "In the end, the agreement of the results from the two approaches between them, with the rate extrapolated from p-p collisions, and with the theoretical expectation, gave us confidence in the first concrete evidence for the production of top quarks in nucleus-nucleus collisions. Crucial to this successful outcome has been also the precise estimate of the actual luminosity, a task which our team, with the help of the CMS luminosity group, performed with high priority, too."



A lead-lead collision event interpreted as witnessing signatures of top quarks, i.e., electron, muons, and b quarks. Credit: CMS Collaboration.

Prior to this recent study, the LHC had enabled measurements of various elementary particles with large masses in heavy ion collisions, such as massive carriers of the electroweak force (i.e., W and Z bosons). Nonetheless, there was a lack of evidence for top quark production in heavy ion collisions, even if theoretical predictions suggested that they were produced at a sufficiently high rate. In addition to gathering the first evidence of top quark production in nucleus-nucleus collisions, the recent study by the CMS collaboration measured a collision rate that is aligned with theoretical predictions.

"Actually, our community had never had the chance before for probing such an energy regime (or 'energy scale') close to the top quark mass, putting the theory that bounds together nucleons in nuclei, called the 'strong force," under stringent tests," Georgios K. Krintiras, co-coordinator of the Luminosity Group of the CMS collaboration, told Phys.org. "Moreover, physics processes used so far, for example, the production of the W and Z bosons and particles of light, the photons, are only sensitive to the properties of QGP integrated over its extremely short lifetime (only a tiny fraction of a second, in technical terms, about seconds). Our paper, following up on recent theory considerations for unveiling the yoctosecond structure of QGP, is just the first step in using the top quark for providing key novel insights into the time structure of the medium created in heavy ion collisions."

The analyses carried out by the CMS collaboration in this recent study deviate from well-established research approaches and could thus open up new possibilities for investigating the time dimension of QGP. This could ultimately prove its existence by assembling the world's shortest movie of its development.

"The exceptionally high mass of top quarks we identified sets a new scale for probing the inner structure of the nuclei too, encoded in the so-called nuclear parton distribution functions (nPDFs)," Krintiras said. "Our current knowledge of how nucleons behave inside a nucleus is limited, mainly because of the lack of data at that scale."

Nucleons are made up of three fundamental particles known as quarks. The interactions between these quarks, which are mediated by a different class of particles known as gluons, are so intense that, theoretically, no external force should be able to affect their behavior, not even the strong forces between different particles inside a nucleus.

Research carried out at CERN in the '80s revealed that nucleons bound in nuclei tend to behave differently than those that are free, a finding that was confirmed by numerous subsequent studies. In this past research, the European Muon Collaboration (EMC) investigated the ratio of data they collected on per-nucleon muon scattering off iron and compared it with that related to the far smaller nucleus of deuterium, achieving surprising results that did not match their predictions. Similarly, researchers at the LHC are investigating the ratio between the measurements performed during Pb-Pb collisions, comparing it to those collected during p-p collisions.

"In this context, the top quark constitutes a theoretically precise probe of the gluon nPDFs in a poorly explored scale," Krintiras explained. "Precise knowledge of nPDFs is also a key prerequisite to extract detailed information on QGP properties from the experimental data."

The recent work by the CMS collaboration could also have important implications for the understanding and search for new physics. Although the research communities investigating heavy ion interactions and new physics are typically unrelated, this first evidence for the production of top quarks in heavy ion interactions has paved the way for a collaboration between these two physics communities.

"This search has inspired me to join forces with colleagues specialized in new physics, to propose one such search that would take advantage of the unique features of heavy ion collisions, and that could become possible with special heavy ion runs in the future," Giammanco said. "Two years ago, we organized a dedicated workshop, called "Heavy Ions and Hidden Sectors," to which we invited most of the people active in the minuscule niche of new physics searches in heavy ions, but also heavy ion experts who had never worked on new physics, new physics experts who had never worked with heavy ions, and LHC accelerator experts such that they could guide us on what could be possibly achievable in terms of heavy ion beam performance in future LHC runs."

Some of the sophisticated algorithms that the CMS collaboration developed to conduct this search are now being used as an argument within the research community who is searching for new physics. More specifically, it is currently being used to demonstrate that some of the fundamental limitations or challenges associated with searches for new physics can be overcome.

In their future work, the CMS collaboration plans to build on their recent findings to conduct additional searches for top quarks in heavy ion collisions. Moreover, the team would like to further improve the effectiveness of their experimental methods and algorithms.

"In our paper, the so-called 'observed statistical significance' of the signal amounts to 4.0 units of 'standard deviations' (σ), for both methods," Krintiras said. "In other words, if no top quarks were produced, there would be still a probability of 0.003% (that's the 4σ level) that the signal would arise from a background fluctuation. We'd like to decrease this probability further, reaching the higher threshold of 5σ that is considered the standard for declaring observation in our community."

To improve the observed statistical significance of the signal they detected and increase the reliability of their findings, the researchers will need to first increase the luminosity in their search. In fact, even if they are aligned with theoretical predictions, the collision rate values extracted in their recent paper are slightly lower than expected values. Increasing the statistical significance could help to determine whether this lower rate is a result of random fluctuations or indicates an underlying systematic trend.

"Notwithstanding the increasing interest in analyses surrounding nPDFs, we are still far from achieving a detailed understanding of the inner structure modifications in bound nuclei," Krintiras said. "The LHC nuclear data are heralded as a game-changer, since they provide the opportunity for a precise formalism of nPDFs for the lead nucleus, including advancements in our knowledge about bound gluons from top quark measurements. We can even foresee additional runs at LHC with higher usable luminosity offering further the chance for colliding one or more lighter nuclei than lead, hence bridging the currently large gap."

There is also a complementarity between the physics programs at LHC and the planned Electron-Ion Collider (EIC) at the Brookhaven laboratory, answering the crucial question of whether nPDFs are functions with universal applicability. Together, these efforts are expected to reveal with precision what the arrangement of the quarks and gluons that make up the protons and neutrons of nuclei is.

"With most of the total luminosity of the LHC Pb-Pb program still to be recorded in the next decade and promising performance projections for the future high-luminosity upgrade of the LHC, or even future, more powerful, colliders, also recommended by the recent update to the European Strategy for Particle Physics, top quark observables will be measured with ever-increasing precision and even become a precise probe of the QGP," Krintiras added. "This could prove its existence and make assembling the world's shortest movie possible, and even more, with an extremely high resolution."

More information: Evidence for top quark production in nucleus-nucleus collisions. *Physical Review Letters*(2020). DOI: 10.1103/PhysRevLett.125.222001

Citation: The first evidence of top quark production in nucleus-nucleus collisions (2021, January 7) retrieved 26 April 2024 from