TKK Science Award in Mathematics and Physics

Experimental Detection of Pentaquark States: Peering into the Inner Structure of the Building Blocks of Our Universe

By SONG Jianlan (Staff Reporter)

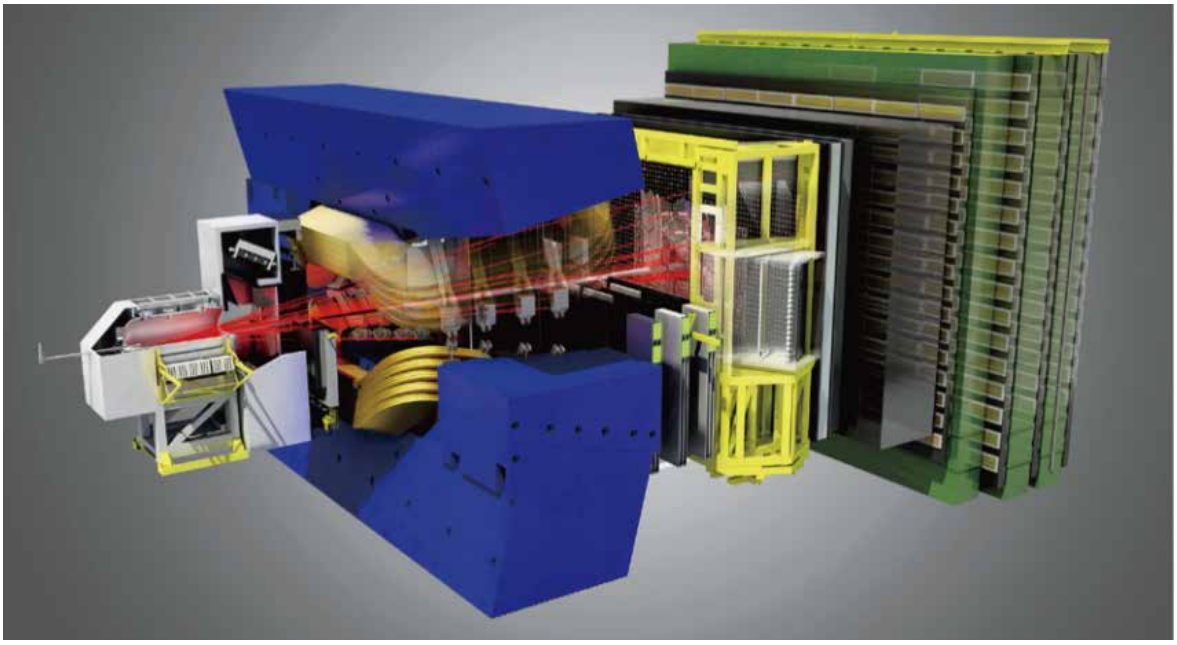
CAS Member GAO Yuanning
Recipient of TKK Science Award in Mathematics and Physics
(Photo by courtesy of GAO)

The 2020 TKK Science Award in Mathematics and Physics goes to Dr. GAO Yuanning, a Boya Chair Professor of particle physics at the School of Physics, Peking University, and the State Key Laboratory of Nuclear Physics and Technology, for his significant contributions to the observation of exotic pentaquark particles, which had long been predicted by theorists, at the Large Hadron Collider beauty (LHCb) experiment at the European Organization for Nuclear Research (CERN)'s Large Hadron Collider (LHC) in 2015. With a reasonable degree of confidence, GAO and his colleagues working on the LHCb collaboration gained a better perspective on actual structure of pentaquarks.

By catching the elusive pentaquark state and sketching its high profile, the LHCb physicists has not only added a long missing piece to the mosaic of quark model, but also offered some new insights into the nature of strong interactions between sub-atomic particles, which as described by GAO, is "an important stepping-stone to a better understanding of the strong force, the least known among the four forces in nature."

Pentaquarks: Somewhat of a Surprise in Quark Model

Physicists have long been exploring the fundamental structure of atoms, the once thought un-dividable basic building blocks of matter. They can be broken down



LHCb detector (©CERN)

into quarks, however, as proposed by Gell-Mann and Zweig in 1964, and their theoretical prediction was later verified by experiments on colliders.

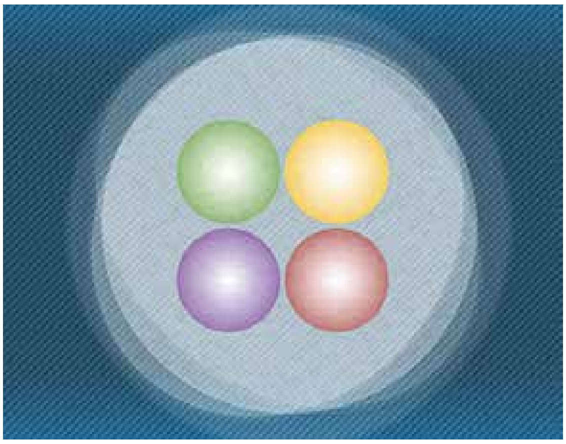
The 1960s saw Gell-Mann and Zweig's theory developing and standing out as the well-established quark model, and since then scientists have found hundreds of new sub-atomic particles either in cosmic rays or collider experiments. These particles are later classified as hadrons, defined by the strong interactive forces between their constituent quarks. Among them neutrons and protons are familiar for us. On the other hand, scientists also found six types of quarks, with different masses. Among them are charm quarks, a type of heavy quarks.

Physicists found that hadrons mostly fall into two categories: mesons each containing a quark and an anti-quark, and baryons each consisting of either three quarks or three anti-quarks. Gell-Mann and Zweig's model does not exclude the possibilities of alternative combinations of quarks to form a hadron, for example one formed by five quarks and hence called pentaquark state. Only one thing – no case of such hadrons had been found among the collision events of particles in any collider, despite the global efforts lasting over 50 years. Therefore, the (then imaginary) hadrons consisting of four or five quarks are named "exotic hadrons".

Could it be there any such exotic hadrons at all? Is the prediction given by the quark model wrong? These remained pending for verification for a long time. Theoretically it is challenging to predict the properties of hadrons via *ab initio* methods, therefore concerning the characteristics of exotic hadrons, physicists can only give qualitative descriptions or merely rough estimates in quantitative sense. This uncertainty in turn poses great difficulties for experimental detection and verification of them – after all, how can we recognize them if we don't know what they look like?!

Exotic hadrons are highly instable and would decay very soon, therefore we can only study them in high-energy accelerators. When accelerated to a speed approaching that of light, particles gain enough energies to collide with each other in the tunnel and decay into quarks or different combinations of quarks, and these products themselves can react with each other to produce something new – in this process some exotic hadrons might hopefully emerge from the "soup" of fleeting quarks and combination of quarks, leaving behind some traces that can be picked up by the detector on the end of the tunnel.

Now how to isolate such exotic quarks – presume that they do exist – from this hodgepodge of particles, becomes a problem.



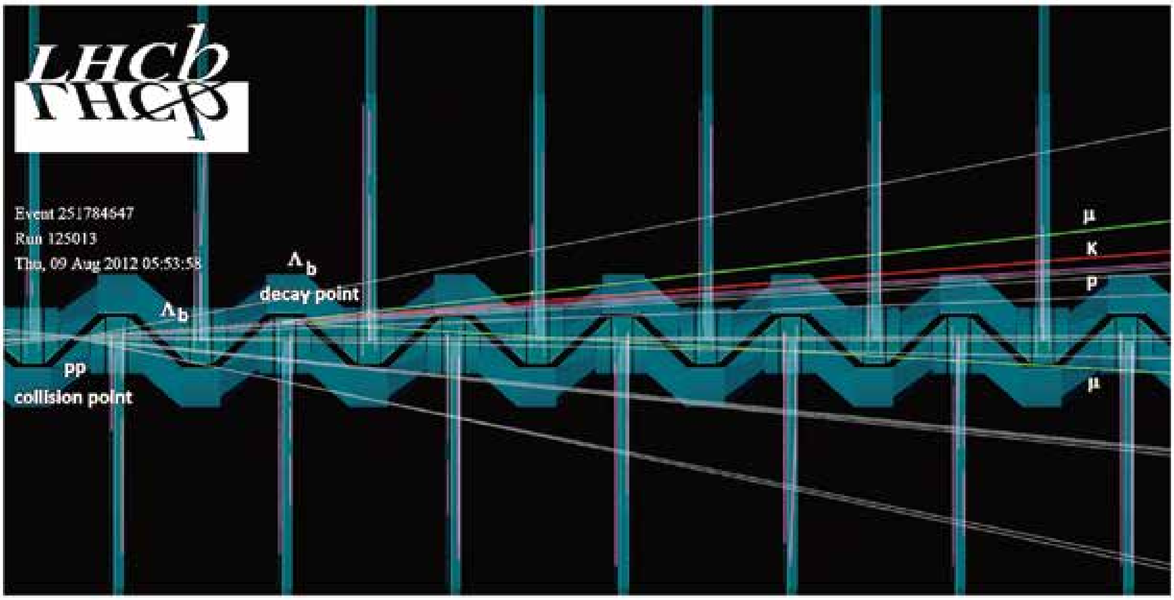
An illustration of Z_c(3900), the tetraquack particle detected and identified on BESIII (Credit: IHEP)

"Some complication could block us from detecting their traces," says GAO in a paper describing his team's detection of this elusive particle/state published in a special edition of the *Chinese Science Bulletin*.

Exotic hadrons each contain more quarks than their "conventional" counterparts, explains GAO, and this greatly reduces their occurrence and hence the chances of finding/tracking them. Once emerge from the massive amount of collision events in the accelerator, they could immediately decay into some secondary products. Moreover, he continues, their complicated composition would allow much more diverse mutual reactions between their secondary products, and hence would lead to a much more complicated network of decay pathways branching to different end states. It would be a headache for physicists to figure out what on earth has happened in the "soup", let alone to identify the "intermediate ingredients" as transients of this hodgepodge.

Although the existence of the pentaquark doesn't require a revision of the standard model of particle physics, earlier searches for a pentaquark composed of lighter quarks came up empty or detected candidate particles that could not be reproduced. Physicists stand to learn more about the complex forces between bound quarks.

Since 2003, a kind of charmonium-like particles have been detected in different experiments, and the development of charmonium physics gives new momentum to the exploration of exotic hadrons. Among the newly detected particle is Z_c(3900), an exotic hadron discovered in 2013 on the Beijing Electron-Positron Collider II, the main detector on the Beijing Spectrometer III. Containing a charm quark and an anti-charm quark, this particle carries an electric charge equals to either that of an electron or a positron – this appears to be intriguing for physicists. "This suggests that it contains at least four quarks," says GAO, "and very likely it is a molecular meson or tetraquark state



A typical $\Lambda_b^0 \to J/\psi K^- p$ decay event recorded by the LHCb detector (©CERN) that has long been searching for by physicists."

Exotic hadrons exist – aside from those containing either two or three quarks, there could be other combinations, like an alliance of four. This encouraging discovery has set a rosy background for the search for other exotic hadrons, including GAO and his colleagues' work on the pentaquark state.

Two years later in 2015, GAO and his colleagues detected "something exotic" when working on the LHCb experiment. The most important scientific objective of LHCb experiment is to explore the properties of hadrons containing heavy quarks. The previous discovery of new decay pathway on this detector, namely the decay from a bottom baryon to charmonium quarks, protons and exotic mesons ($\Lambda_b^0 \to J/\psi K^- p$), caught the eye of GAO and his colleagues. When analyzing the mass distribution of about 26,000 cases of such decay events, they observed a significant enhancement structure, which they figured could have resulted from some unknown hadrons. Each decaying into a charm quark and a proton, such mysterious particles produced an aquatic mass/energy spectrum, well separated from those contributed by the decays of Λ^* particles; and the amplitude of this enhancement could be best explained as produced by two charmonium pentaquark sates. These two pentaquarks states, with energies of 4,450 MeV and 4,380 MeV respectively, were formally named $P_c\,(4450)^+$ and $P_c\,(4380)^+$.

While collision events accumulated on the detector, a sample nine times bigger than the previous was available for analysis, and in 2017 the team got the chance to further optimize their calculation. A new pentaquark state with an energy of 4,312 MeV was hence identified, and the previously found pentaquark $P_c\,(4450)^+$ was further characterized as the superposition of two nearby states, whose energies were 4,440 MeV and 4,457 MeV, respectively.

Strong Interaction Pending for Exploration

Pentaquarks are here to stay. What is their inner structure like? How a pentaquark is put together?

Relying on the larger dataset from the LHC, the LHCb collaboration confirmed that quarks could combine into groups of five in 2016, and revealed the exotic quark particles were composed of quark-antiquark mesons and three-quark baryons. Last year, the same team reported that pentaquarks could also be formed by a three-quark baryon and a quark-antiquark meson, binding loosely into a "molecular" state.

"We, the LHCb China Team, hope more research will contribute to further understanding of the pentaquark and its characteristics," GAO says, "Together with continued progress in theory, we will be allowed to explore the true dynamics underlying the structure of exotic multi-quark particles."

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