

Charm-quark decays violate charge–parity symmetry

In the quest to understand how particles behave differently from their antiparticles, the LHCb experiment has a promising new result.

Every neutrino ever observed has been left-handed—its spin and linear momentum point in opposite directions—and every antineutrino has been right-handed. That’s because the weak interaction, the basis for all neutrino detection, violates the symmetries of both charge conjugation C (the replacement of particles by their antiparticles) and parity P (spatial inversion). It treats particles and their antiparticles not identically, but as mirror images of one another.

But the combination symmetry, CP , isn’t quite exact. Weak interactions that transform the flavors of quarks can differ from their antiparticle counterparts not just in their spatial arrangements but in their products and rates of production. CP violation is important because of its relevance to a fundamental question: Why is there anything in the universe at all?

The Big Bang should have yielded equal amounts of matter and antimatter, which should promptly have annihilated each other, leaving nothing but photons. Somehow, though, one in a billion matter particles survived, and they went on to form all the stars, planets, and everything else in the observable universe today. For that to have happened, the laws of physics seemingly must treat matter and antimatter differently (see the article by Helen Quinn, *PHYSICS TODAY*, February 2003, page 30).

Although CP violation has been observed in the decays of both strange and bottom quarks and is well described by the standard model of particle physics, the size of that violation is many orders of magnitude too small to explain all the matter that still exists. Particle physicists have thus been on the hunt for new physical effects, beyond those included in the

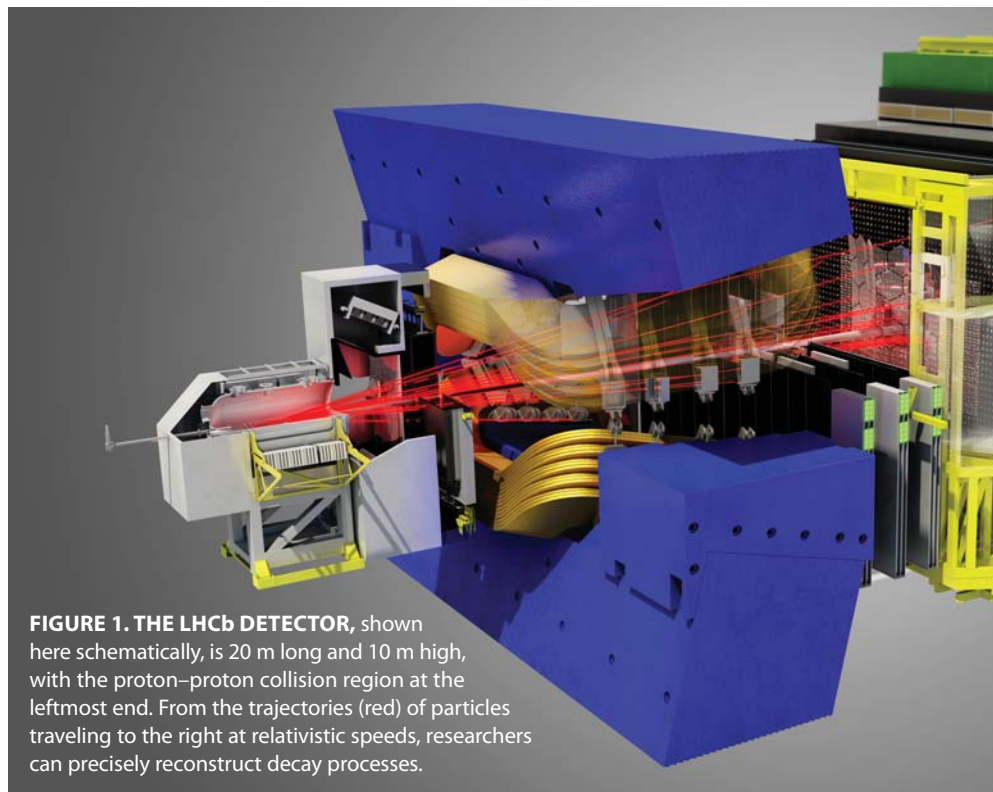


FIGURE 1. THE LHCb DETECTOR, shown here schematically, is 20 m long and 10 m high, with the proton–proton collision region at the leftmost end. From the trajectories (red) of particles traveling to the right at relativistic speeds, researchers can precisely reconstruct decay processes.

standard model, that could have supplied the additional CP violation to the early universe.

The Large Hadron Collider’s LHCb experiment, depicted in figure 1, has now taken the hunt to a new sector with the observation of CP violation in particles containing charm quarks.¹ Notably, it’s the first such violation to be seen in the family of quarks with charge $+\frac{2}{3}$. (The strange and bottom quarks, like the ubiquitous down quark, both have charge $-\frac{1}{3}$.) Of the other positively charged quarks, the top quark is too heavy and too short-lived to even form bound states, and the up quark, the lightest and most stable of all the quarks, doesn’t normally decay.

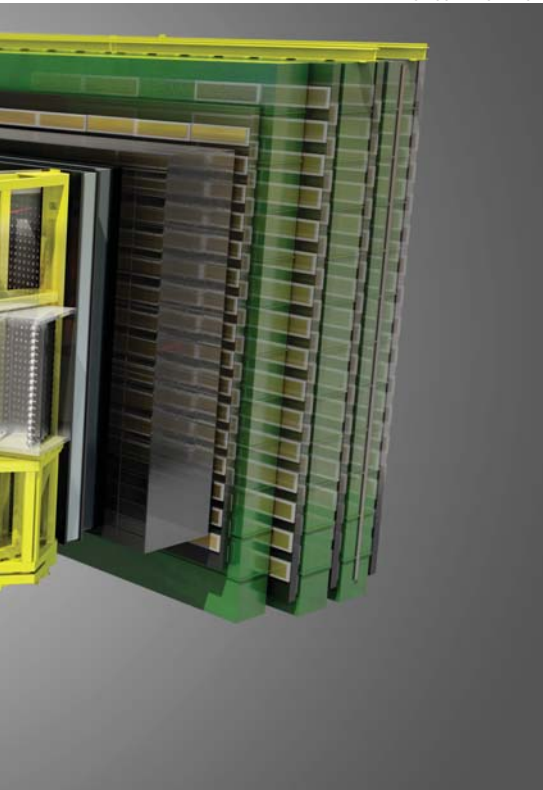
It’s not yet known whether the LHCb result represents new physics. The experimenters have pinned down the magnitude of charm CP violation rather precisely: Their measurement differs from zero by more than five standard deviations, the accepted threshold for calling the result an “observation.” But theoretical predictions have lagged behind, and calculations of the extent of standard-

model charm CP violation span a factor of 10. The LHCb measurement is at the upper end of that range.

To B or not to B

Each CP -violating quark flavor has a different story. For strange quarks, CP violation was first observed by James Cronin and Val Fitch in 1964—before the quark theory of matter was even experimentally confirmed—in the neutral-kaon system (see the article by James Cronin and Margaret Stautberg Greenwood, *PHYSICS TODAY*, July 1982, page 38). The kaons consist of flavor states K^0 , a down quark bound to a strange antiquark, and its antiparticle $\bar{K}^0$, a down antiquark bound to a strange quark. But they’re often observed as superpositions of those states that are either CP -odd (that is, they pick up a phase of -1 under CP transformation) or CP -even (that is, they pick up no phase).

Kaons are light—about half the mass of a proton—and they have only a few available decay modes, by far the fastest of which produces two pions. Because the pions are each other’s antiparticles,



the product state is CP -even, so it can ostensibly arise only from a CP -even kaon state. But as Fitch and Cronin found, the longer-lived CP -odd kaons, easily isolated by allowing all the CP -even ones to decay away, also decay into two pions a few times out of a thousand. For their discovery, they were awarded the 1980 Nobel Prize in Physics (see *PHYSICS TODAY*, December 1980, page 17).

The theoretical explanation was also the basis for a Nobel (see *PHYSICS TODAY*, December 2008, page 16). In the early 1970s, Makoto Kobayashi and Toshihide Maskawa formulated a matrix to describe how quarks of different flavors transform into one another. When they included only the two quark generations then known (up and down, charm and strange), the matrix allowed no CP violation. In an attempt to explain Fitch and Cronin's kaon result, the theorists postulated a larger matrix, which could accommodate CP violation, and thereby predicted a third generation of quarks. The prediction was correct: The top and bottom quarks exist.

In a popular parameterization of the theory, the CP -violating terms occupy the matrix elements farthest from the diagonal—those that describe transformations between first- and third-generation quarks. In the decay of second-generation strange quarks, those terms are introduced only via minor contributions from short-lived virtual quarks, so the overall CP violation is small. Bottom-quark decays, which incorporate the symmetry-violating terms directly, show much larger CP asymmetry.

Bottom-quark physics, however, is complicated. The B mesons come in multiple flavors—a bottom antiquark can bind to an up, down, strange, or charm quark—and each of them is massive enough to have hundreds of available decay modes, only a few of which yield products that are CP eigenstates. On the flip side, the system offers a rich variety of experimental observables, such as the phases through which different processes interfere with each other, that can potentially reveal CP violation and be tested against the standard model.

Toward that end, several labs around the world have invested in collider experiments specially tailored to the study of bottom quarks. They include LHCb (the “b” stands for beauty, another name for the bottom quark) and the so-called B factories at KEK in Japan and SLAC in the US (see *PHYSICS TODAY*, January 1999, page 22). Although the details differ, all were designed to study unstable particles created with significant momentum in one direction, so their decay lifetimes are relativistically lengthened. From the momenta of the products, it's possible to precisely reconstruct how far each particle traveled—and thus how long it lived—before decaying. The first observation of bottom-quark CP violation came from the B factories in 2001 (see *PHYSICS TODAY*, September 2001, page 19), and there have been many more since then, all consistent with standard-model predictions.

Charms are all o'erthrown

As a testing ground for studying CP violation, the charm quark combines the disadvantages of the strange and bottom

quarks. It's a second-generation quark, so the magnitude of symmetry violation is relatively small—on the order of 10^{-3} —and charm-bearing particles have many available decay modes to complicate the analysis. As it happens, LHCb observed CP violation through perhaps the most direct measure possible: a census of the numbers of D^0 mesons (charm quarks bound to up antiquarks) and their $\bar{D}^0$ antiparticles (up bound to anticharm) decaying to either $\pi^+ + \pi^-$ or $K^+ + K^-$.

Each of those product modes is its own set of antiparticles, so in a CP -invariant world, they'd be equally likely to arise from either D^0 or $\bar{D}^0$; any fractional difference thus reveals CP violation. To tell the D^0 and $\bar{D}^0$ mesons apart, the LHCb researchers focused on decay modes that produce the charmed mesons together with so-called tagging particles: a D^0 alongside a π^+ or antimuon, or a $\bar{D}^0$ together with a π^- or muon. The charge of the tagging particle reveals the flavor of the meson.

For a useful measurement of a small fractional difference, tens of millions of decays are needed just to overcome statistical uncertainties. And $\pi^+ + \pi^-$ and $K^+ + K^-$ together make up just 0.5% of all D^0 decays, putting the necessary number of charmed mesons in the billions.

But LHCb was up to the task. The LHC's 2015–18 run at a collision energy of 13 TeV yielded 600 trillion proton-proton collisions. (That's actually a lot less than at some of the other LHC experiments—LHCb deliberately lowers its collision rate due to detector requirements.) About 5% of those collisions produce charm quarks in one way or another. Not all of them yield D^0 mesons in conjunction with tagging particles in the detector angle of acceptance, but enough of them do.

On top of the statistical uncertainties, there are also systematic uncertainties. There's no guarantee, for example, that LHCb produces or detects particles and their antiparticles with equal efficiency. Fortunately, the two D^0 decay modes, $\pi^+ + \pi^-$ and $K^+ + K^-$, are equally influenced by systematic effects, so in the difference ΔA_{CP} of their fractional asymmetries, the systematic errors largely cancel out.

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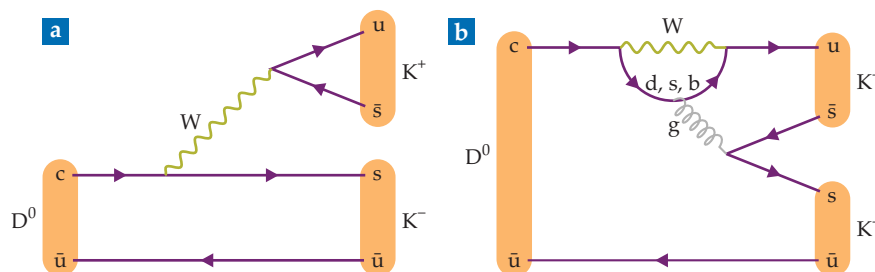


FIGURE 2. A D^0 MESON DECAY into two charged kaons is the sum of contributions from multiple processes that can be represented as Feynman diagrams. **(a)** The tree-level diagram, mediated by a single W boson carrying the weak force, contains only those quarks present in the initial and final particles: charm, up, and strange. **(b)** A loop-level diagram introduces a gluon and a quark of another flavor. (Adapted from ref. 5.)

Although ΔA_{CP} doesn't have a straightforward physical interpretation, it's similar in magnitude to the asymmetry of each decay mode separately, and importantly, if it's different from zero, then CP symmetry must be violated.

Over the years, LHCb, the B factories, and other experiments have tried many times to measure ΔA_{CP} . But until now the results have been consistent with no symmetry violation. The closest thing to a nonzero result came in 2012, when LHCb found a ΔA_{CP} of -8×10^{-3} , 3.5 standard deviations from zero.² Such a value, an order of magnitude in excess of nearly all the theoretical predictions, would have been astonishing if it was right, but further data from LHCb and elsewhere showed the result to be a statistical anomaly. The new measurement, -1.54×10^{-3} , differs from zero by a comfortable five standard deviations.

Know this sure uncertainty

The implications of the measurement remain to be seen. Standard-model predictions of the magnitude of charm CP violation range from roughly 10^{-4} to 10^{-3} , and in the weeks after the LHCb researchers announced their result, theorists argued both for³ and against⁴ the idea that it represents a new source of CP violation unexplained by the standard model.

The discrepancy stems from the complexity of charm-sector calculations. The simplest, so-called tree-level diagram of a D^0 decay, shown in figure 2a, contains no third-generation quarks, so it can't violate CP symmetry by itself. More complex loop-level diagrams, such as the one in figure 2b, can introduce CP violation, but their relative contributions to the decay rate are extremely challenging to

calculate. The calculations are simpler for bottom-quark decays, because the bottom quark's large mass allows for some mathematical approximations. But the charm quark is just light enough that those simplifications don't easily apply. So for now the question of how the LHCb measurement compares with the standard model remains open.

If it's finally established that charm decays do show signs of new physics, the next step will be to figure out what that physics is. Any model to explain the discrepancy will likely introduce new particles, predict similar CP -violating effects in other decays, or both, and future generations of experiments can seek to test those predictions.

There's also the question of whether the new physics can supply the many additional orders of magnitude of CP violation needed to explain matter's survival in the universe. Although charm CP violation can't disagree with the standard model by much more than a factor of 10, it could be the first sign that the standard model is a low-energy approximation, ill-equipped to describe the high-energy processes that were prevalent in the instants after the Big Bang but have rarely been accessed since then.

Johanna Miller

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