LHCb Delivers a Key Piece in the CP-Violation Puzzle

A symmetry violation has been observed in a particle-decay process that—together with five related decays—could shed light on the matter–antimatter imbalance in the Universe.

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The known Universe has some 10^{12} galaxies that are made out of matter and no galaxies that are made out of antimatter. This is a surprising result because matter and antimatter are expected to exist in equal quantities. More formally, matter and antimatter are related by a symmetry known as *CP* symmetry, which states that a particle and its antiparticle should obey the same laws of nature. A necessary condition for the observed imbalance between matter and antimatter in the Universe is therefore a violation of *CP* symmetry—for a review see H. R. Quinn and Y. Nir [**1**]. Solving this puzzle has driven extensive experimental efforts that have revealed such a violation in different particle sectors. The Large Hadron Collider Beauty (LHCb) Collaboration at CERN has now measured a *CP* violation in a certain decay channel of $B^{\pm}$ mesons— a first for this particular decay [**2**]. The result suggests that careful characterization of this and related decays could reveal new physics beyond the standard model of particle physics.

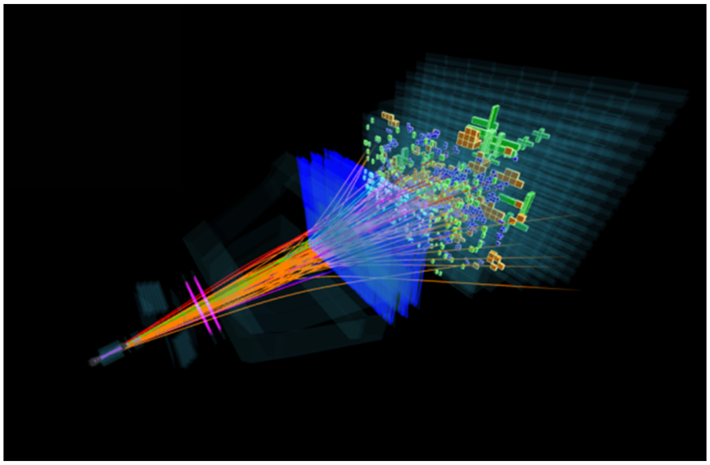

Figure 1: Reconstruction of an LHCb event from a 2016 experimental run.
Credit: CERN

CP violation was first detected in *K*-meson decays in 1964, a discovery that earned physicists James Cronin and Val Fitch the Nobel Prize in 1980. Dozens of experimental measurements have now reported *CP* violation in the decays of various *K*, *B*, and *D* mesons. Today, the LHCb Collaboration also reports the first *CP* violation in decays of baryons (specifically, Λ_b baryons) [**3**]. All these measurements can be accounted for with a single phase, known as the Kobayashi-Maskawa phase, which quantifies *CP* violation in the coupling of the *W* boson to quark–antiquark pairs. The fact that this phase explains all *CP*-violating phenomena so far observed in the laboratory had an important role in the construction of the standard model and earned Makoto Kobayashi and Toshihide Maskawa the Nobel Prize in 2008.

An open problem is that the *CP* violation associated with the Kobayashi-Maskawa phase is orders of magnitude too small to explain the observed surplus of matter in the Universe. This implies that an additional source of *CP* violation, as of yet unknown, must exist. *CP* violation is therefore intriguing to experimentalists and theorists alike, as it may offer a way of revealing new physics beyond the standard model.

To look for *CP* violation, physicists consider pairs of processes that are “*CP* conjugate” with respect to each other, meaning that one becomes the other if all the particles are switched with their respective antiparticles. The quantity measured is called *CP* asymmetry, which is the difference between the rates of the *CP*-conjugate processes divided by the sum of those rates.

The uncertainties associated with experimentally measuring and theoretically interpreting a *CP* asymmetry are often far smaller than those related to the individual decay rates of the *CP*-conjugate pair. Moreover, *CP* asymmetries are often sensitive to contributions from physics beyond the standard model, which are too small to be detected in measurements of the individual decay rates.

CP asymmetries are a consequence of interference between two transition amplitudes that contribute to a given decay process. For decays of mesons that are electrically neutral, one or both of these contributions could involve a phenomenon known as meson–antimeson mixing, in which case the *CP* violation is classified as “indirect.” If neither contribution involves such mixing, the *CP* violation is labelled as “direct.”

The LHCb experiment (Fig. **1**) revealed a *CP* asymmetry that occurs in the $B^{\pm} \to J/\psi\pi^{\pm}$ decays, which is a result of direct *CP* violation. The result is neither the first observation of *CP* violation in $B \to J/\psi$ decays nor the first observation of direct *CP* violation in *B*-meson decays. It is, however, the first observation of direct *CP* violation in $B \to J/\psi$ decays.

Why is this measurement of special interest? The answer lies in how it fits into a much larger jigsaw puzzle. Deviations from the standard model are expected to be small, so the experimental measurements and the theoretical calculations must have very small uncertainties to offer prospects for detection of such deviations. The main source of theoretical uncertainty is the strong interaction, which binds quarks together. A complication arises from the fact that the interaction is nonperturbative, meaning it cannot be described using approximations that take into account only one or two dominant contributions.

To make the problem tractable, physicists invoke a symmetry known as SU(3)-flavor symmetry, which is based on the fact that the strong interaction does not distinguish between up, down, and strange quarks, in the limit that their masses are all equal. In nature, these three quarks have different masses, so the symmetry is not exact. But the mass differences are small, so the symmetry approximately holds, enabling the definition of a small symmetry-breaking parameter that makes approximate calculations possible.

Theorists have shown that the SU(3)-flavor symmetry implies key relationships between six decay processes [**4**], including the $B^{\pm} \to J/\psi\pi^{\pm}$ decay probed by the LHCb Collaboration. Another of these processes involves a $B^0 \to J/\psi K_S$ decay, and its *CP* asymmetry, denoted $S_{\psi KS}$, currently provides the most precise determination of the *CP*-violating phase of the standard model. On the theoretical side, the uncertainty is small because this asymmetry is dominated by indirect *CP* violation, whose theoretical estimate is more precise. On the experimental side, the uncertainty is also small: Measurements have now reached an accuracy on the order of one percent, $S_{\psi KS} = 0.711 \pm 0.012$ [**5**].

The $B^0 \to J/\psi K_S$ decay is therefore extremely promising for identifying physics beyond the standard model, but it requires additional input from the other related decays. To bring the theoretical uncertainty to a level that is as low as the experimental uncertainty, one needs to consider the small contribution from direct *CP* violation. Calculating direct *CP* violation is far from trivial, but filling in the puzzle pieces of the decay rates and *CP* asymmetries in these six modes would make it possible.

This is where the LHCb result comes into play—it could offer crucial information that might help to minimize the uncertainties associated with the B^0 process. Studying interrelated decay processes will be a powerful strategy for systematically reducing such uncertainties. As measurements and theoretical predictions continue to be refined, the search for new sources of *CP* violation remains an exciting frontier in high-energy physics, offering the potential to unravel some of the deepest mysteries of the Universe.

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