Triggering on CP Violation

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Summary

If we zoom in close enough to things around us, or to ourselves, smaller and smaller structures can be identified. Our limbs and organs consist of cells, which consist of molecules which consist of atoms. Atoms, in turn, consist of a nucleus that is surrounded by a cloud of electrons, and the nucleus contains electrically charged protons and neutral neutrons. For a long time, protons and neutrons — like electrons — were thought to be elemental particles, particles that are not made up of other particles. At the end of the sixties, however, it became clear that protons and neutrons do contain other particles, called quarks [1].

In 1928, Paul Dirac proposed that for every particle, a so called anti-particle should exist [2], that has identical mass but opposite charge. In 1932 the first anti-particle was discovered, the anti-particle of the electron: the positron [3]. It has subsequently become clear that for each particle, a corresponding anti-particles exists.

In addition to particles, four fundamental interactions between particles exist in nature: gravity, the electromagnetic interaction and the weak and strong nuclear forces. An important property of the electromagnetic and strong nuclear interactions is that they act in the same way on particles and anti-particles (C symmetry) and also on particles and particles whose spacial coordinates have been inverted ($\mathbf{x} \rightarrow -\mathbf{x}$), i.e. for particles and their mirror image (P symmetry).

Until 1956, this was assumed to also hold for the weak nuclear force, although this had not been verified experimentally. When a measurement was proposed by Lee and Yang [4] and performed the same year [5], it was discovered that the weak force treats particles and their mirror image maximally differently. The combination of the C and P symmetries, CP symmetry was then proposed to be a conserved quantity, i.e. all forces are the same for particles and mirrored anti-particles. In 1964 it was shown that this was also not true, when the probability that a neutral kaon transforms into a neutral anti-kaon was observed to be different from the probability of the reversed process [6].

Originating from the sixties, a model has been created that describes the electromagnetic interaction and the weak and strong nuclear forces: the so-called Standard Model of particle physics. In the Standard Model, the possibility for *CP* violation to occur originates from the presence of a single complex-valued parameter, η. The value of this parameter influences many observable processes, which implies that as soon as the value of η has been measured with a first set of processes, predictions can be made for other processes. Using such a process, a measurement that is incompatible with its prediction with sufficient significance, is direct proof of the existence of physics beyond the Standard Model. The measurement described in this thesis is such a measurement.

This measurement is performed by measuring a single observable, ϕ_s, which is related to η, and whose value has been precisely predicted by the Standard Model to be close to zero [7]. To determine the value of ϕ_s, the decay-time and decay-angle dependent decay probability of B_s^0 mesons to a J/ψ and a meson is measured. A meson is a particle that consists of two quarks. The decay-time of a B_s^0 meson is the time between its production and decay as measured in its rest frame. The decay angles are defined by the directions of the final decay products: two charged muons ($\mu^+\mu^-$) and two charged kaons (K^+K^-).

B_s^0 mesons are produced in collisions between protons in the Large Hadron Collider at Cern. Since these mesons are predominantly produced in directions close to the direction of the proton beams, the LHCb detector has been optimised to measure the tracks and properties of particles, such as muons and kaons originating from a $B_s \to J/\psi\,\varphi$ decay, in the forward direction.

Throughout 2011 and 2012, the proton beams crossed each other approximately 15 million times per second. Of those 15 million crossings per second, approximately 12 million resulted in at least one collision between two protons. The detector produces about 60 kiB of data for each such event, which results in a total data rate of 700 GiB per second. Only a small fraction of all proton-proton collisions results in the production of a B_s^0 or $\overline{B}_s^0$ meson and only a fraction of those produced mesons decays according to $B_s \to J/\psi\,\varphi$. It is therefore not necessary to store all data, and to store only data from interesting crossings, it is filtered in two consecutive steps. The first of these filters is implemented in programmable chips and the second is a software application running on a farm of PC servers. This second filtering step is called the High Level Trigger.

The HLT is again divided in two stages, where the first stage (HLT1) is based on general selection criteria, such as the presence of two reconstructed muons with the same origin, to reduce the number of crossings that must be analysed to about eighty thousand per second with a minimal expense of CPU time. The second stage (HLT2) is then allowed to use more CPU time to obtain additional information that can be used to select data from interesting crossings with the highest possible efficiency.

Data that has been selected by the HLT is further processed before the statistical analysis of the decay-rate can be performed to determine ϕ_s. First, all tracks of charged particles are reconstructed and from those, suitable muon and kaons tracks are selected, that are combined to form candidate decays. A random combination of pairs of oppositely charged muons and kaons can resemble a real $B_s \to J/\psi\,\varphi$ decay to such an extent that it is accepted by the selection. Such candidates are not suitable for analysis, since they do not correspond to a real $B_s \to J/\psi\,\varphi$ decay, and they are removed using a statistical subtraction method.

To measure ϕ_s, maximum likelihood estimation is employed. Given the data, this method determines according to the theoretical decay-time and decay-angle dependent probability density of the $B_s \to J/\psi\,\varphi$ process, the most likely value of ϕ_s and its uncertainty.

Before the most likely value of ϕ_s can be determined, the theoretical model must be augmented to take the effects of experimental uncertainties on the measured quantities (decay-time and angles) and selection effects into account. The fact that the probability to reconstruct and select a $B_s \to J/\psi\,\varphi$ decay depends on its decay time, must, for example, be taken into account. In addition, the decay-time uncertainty model must be calibration and confirmed to be correct using real and simulated data.

Once these, and other, effects have been accounted for, the most likely estimate of ϕ_s and its uncertainty can be determined; it is given by:

$$\phi_s = \text{-}0.057 \pm 0.051 \pm 0.007 \quad \text{rad},$$

where the statistical and systematic uncertainties are given separately. The statistical uncertainty of this measurements is larger than the systematic uncertainty, which implies that the larger quantities of data that will be recorded by the LHCb detector during Run II of the LHC and by the upgraded detector after 2017, can be used to further reduce the uncertainty on the measurement to match the uncertainty on its Standard Model prediction.

The measurement of ϕ_s is compatible with its Standard Model prediction, which is given by [7]:

$$\phi_s = \text{-}0.0363^{+0.0014}_{-0.0012} \quad \text{rad}, \tag{D.14}$$

and thus there is, currently, no evidence for physics beyond the Standard Model.

References

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