Measurement of CP asymmetry in neutral B meson mixing with semileptonic decays at LHCb

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Why we live in a Universe made of matter is one of the open questions in particle physics. At the Big Bang, an equal amount of matter and antimatter was created; a dynamical mechanism happening in the early Universe, called baryogenesis, introduced a first asymmetry by favouring the production of matter over antimatter. One of the necessary conditions for baryogenesis to happen is that a fundamental symmetry of nature, the CP symmetry, must have been violated during baryogenesis. However, the resulting matter-antimatter asymmetry is many orders of magnitude smaller than the measured one, a difference that can be explained only by introducing beyond the Standard Model (BSM) physics. Measurements of CP-violating observables can place constraints on the parameter space of BSM theories.

To understand this imbalance, the LHCb experiment focuses on the search for new physics through studies of CP-violation and decays of heavy-flavour hadrons. In particular, this project aims to study the CP-asymmetry observed in neutral B meson oscillations, an observable that theoretical studies [2] have linked directly to the CP violation required in the baryogenesis. However, this process is highly suppressed in the Standard Model, with a CP asymmetry value that is too small to explain the current observation of baryon asymmetry, but can be enhanced by new physics effects. Run 3 at the LHC, which took place from 2022 to 2026 and operated at a centre of mass energy of 13.6 TeV, combined with the upgraded LHCb detector, provides a new opportunity to further gain knowledge on these processes.

CP violation in mixing is an extensively studied effect in the Standard Model. Neutral B mesons can spontaneously oscillate into their antiparticle states through weak interactions, a consequence of the fact that the flavour eigenstates $B^0, \bar{B}^0$ do not correspond to the mass eigenstates B_L, B_S. Therefore, a particle that was produced as a B^0 can decay as a $\bar{B}^0$. CP violation enters when the process $B^0 \to \bar{B}^0$ has a different rate than the opposite. To measure such an effect, the flavour of the B meson at decay has to be reconstructed by considering a flavour-specific final state f, commonly chosen to be the semileptonic one, in which the B meson decays to a hadron, a lepton and its neutrino. From the charge of the lepton, the flavour of the B meson can be univocally identified. By measuring the decay rates for the process $\overline{B} \to B \to f$ and its charge-conjugated process, the CP asymmetry in mixing can be measured as:

$$a_{sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \overline{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \overline{f})}.$$

At hadron colliders such as LHC, identifying flavour at production to measure such decay rates can be quite inefficient. The measurement is done instead with the untagged asymmetry method, in which the respective numbers of B^0 and $\bar{B}^0$ decays are measured as a function of the decay time t. Any difference between the two yields $N(B^0, t)$ and $N(\bar{B}^0, t)$ will result in an asymmetry that contains different contributions on top of the CP asymmetry one, such as the production asymmetry of the B meson and the detection asymmetry of the final state. The biggest challenges of the measurement are the missing energy due to the neutrino that escapes the detector, which affects the decay time and invariant mass reconstruction, and the treatment of the detection asymmetries.

The measurement has been carried out at LHCb using Run 1 data, obtaining uncertainties of $\mathcal{O}(10^{-3})$ [1]; for Run 2, the measurement is still ongoing and close to completion. Now, with Run 3 increased luminosity (27.89 fb^{-1}, compared to 3.23 and 5.90 fb^{-1} for Runs 1 and 2), the aim is to reach a precision of $\mathcal{O}(10^{-4})$, sufficient to place meaningful phase-space constraints on BSM theories.

Literatur

[1] Roel Aaij u. a. "Measurement of the Semileptonic CP Asymmetry in $B^0 - \bar{B}^0$ Mixing". In: *Phys. Rev. Lett.* 114 (2015), S. 041601.

[2] Gilly Elor u. a. "Baryogenesis and Dark Matter from B Mesons". In: *Physical Review D* 99.3 (Feb. 2019), S. 035031. ISSN: 2470-0010, 2470-0029.