CKM ANGLE MEASUREMENTS AT LHCb

Sergey Barsuk
Laboratoire de l’Accélérateur Linéaire
Université Paris-Sud 11, Bâtiment 200, 91898 Orsay, France
on behalf of the LHCb collaboration

Abstract. Expected reach of the LHCb experiment on the CKM angle measurements is discussed on the examples of the $B_{d,s}$ mixing phases and the angle $\gamma$.

1 Introduction

The unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix is visualized in terms of six unitarity triangles (UT) of equal area (Jarlskog invariant), quantifying the $CP$ violation. Two of them, $bd$ and $tu$, have comparable sides, and are the most relevant for $b$ physics. Owing to the results from $B$-factories and Tevatron, the precision of UT parameters have significantly improved, the UT apex is precisely constrained. The angles are known to the precision of $\Delta\alpha \approx 6^o$, $\Delta\beta \approx 1^o$ and $\Delta\gamma \approx 20^o$, where $\beta$ and $\gamma$ are still dominated by experimental error. The precision of the sides is dominated by theoretical uncertainties. The $R_b$ side is determined to theoretical uncertainty of $\sim 8\%$ from $V_{ub}$ measurement, while the $R_t$ side ($|V_{td}/V_{ts}|$) is known to a precision of $\sim 5\%$. For both $R_b$ and $R_t$ limitations come from lattice calculations. For $R_t$ improvement is expected from radiative penguin studies. Comparing the precision of UT angle to the precision of the opposite side, we notice, that constraining the apex with the ($\beta, R_b$) is limited by the $R_b$ precision, while constraining the apex with ($\gamma, R_t$) is limited by the precision on $\gamma$. Already present knowledge of the $R_t$ requires the angle $\gamma$ to be measured with a precision of $5^o$.

LHCb is an experiment dedicated to the study of $CP$ violation and other rare phenomena in $b$ decays [1, 2]. The LHCb detector is a single-arm forward spectrometer, insuring efficient charged particle tracking and neutral particle reconstruction, particle identification and robust trigger. The experiment will run at a reduced LHC luminosity tuneable in the range $2 \div 5 \times 10^{32} \, cm^{-2} \, s^{-1}$. At LHCb a $10^{12} \, bb$ pairs will be annually produced, including all the $b$ hadron species, with the biggest samples of $B_s, B_d, B_s$ and $\Lambda_b$, $B_u:B_d:B_s:B_c:B_{\Lambda_b} \approx 4:4:1:0:1:1$. Complementing detailed studies of lighest $B$ mesons at $B$-factories and Tevatron, the LHCb experiment is expected to contribute to the studies of $B_s, B_c$ and $\Lambda_b$. The LHCb physics program mainly comprises precision measurements of the Standard Model (SM) parameters and search for effects beyond successful SM description via $CP$ asymmetries and rare decays, with the $b$ physics as a central actor. The CKM angle measurements are discussed below, while for rare decays reach at LHCb, see e.g. [3].

*e-mail: barsuk@lal.in2p3.fr*
2 $B_{d,s}$ mixing phases

The exploration of the UT angles covers the mixing phases, $\phi_d = 2\beta$ for $B_d$ system and $\phi_s = -2\chi$ for $B_s$ system, and the $\alpha$ and $\gamma$ angles. Most awaited are the study of $\phi_s$ phase, which in the SM is expected to be small, $0.0037$, and thus attractive for the new physics (NP) search, and the angle $\gamma$ to constrain the UT triangle in combination with the $R_t$ side and to search for possible NP contribution to loops by comparing the tree-mediated processes to those involving penguin loops. These studies rely on the $CP$ (often time-dependent) asymmetry measurements.

The first asymmetry study will be that of the $\phi_d$ phase, using the $B_d \to J/\psi K_s$ decay. The comparison with the value well-established by $B$-factories, provides a powerful systematics control for further asymmetry studies. Also important is to establish the direct $CP$ violating term from the $B_d \to J/\psi K_s$ decay asymmetry. In one year\(^b\), having a 240$k$ clean ($S/B \sim 1.4$) signal events reconstructed, LHCb should be able to achieve the precision of 0.02 on the $\sin 2\beta$ value\(^c\). This can be compared to the BABAR and BELLE combined precision of $\sim 0.018$ expected at the end of the $B$-factories, and to an error of 0.01 for 30 $fb^{-1}$ expected with ATLAS and CMS\(^d\).

The best channel for the $\phi_s$ phase measurement is $B_s \to J/\psi \phi$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. $B_s \to J/\psi \phi$ is a $P \to VV$ decay, and the final state is thus a mixture of $CP = +1$ and $CP = -1$ components. To disentangle $CP$ eigenstates, a partial wave analysis is required. LHCb is expected to reconstruct 131$k$ $B_s \to J/\psi \phi$ events with $S/B$ ratio of 10. This results in a $\phi_s$ sensitivity of 0.01 for the integrated luminosity of 10 $fb^{-1}$. This is better than ATLAS and CMS expected sensitivities of 0.04 for an integrated luminosity of 30 $fb^{-1}$.

Including pure $CP$ eigenstates, $B_s \to \eta_s((h^+h^-h^-h^+)\phi(K^+K^-), B_s \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma), B_s \to J/\psi(\pi^+\pi^-\pi^o(\gamma\gamma)), B_s \to J/\psi(\pi^+\pi^-\eta(\gamma\gamma)), B_s \to D_s^+(K^+K^-\pi^+)D_s^-(K^+K^-\pi^-)$, despite the smaller statistics, provides a control over the method.

A by-product of this analysis is the $\Delta \Gamma_s$ measurement. The expected LHCb sensitivity on $\Delta \Gamma_s/\Gamma_s$ of about 0.01 is small compared to the SM prediction of $\Delta \Gamma_s/\Gamma_s \sim 0.1$.

Following the $\delta\beta^{NP}$ estimation, LHCb will compare the $\chi$ angle from tree-mediated diagram, $B_s \to J/\psi \phi$, to that from pure penguin decay, $B_s \to \phi \phi$. This will yield an estimate of the NP contribution, $\delta \chi^{NP} = \chi^{tree} - \chi^{penguin}$, with sensitivity of 3$\sigma$ in one year of data taking.

The NP contribution in $B_s$ mixing could be parametrized\(^5\) via $M_{12} = (1 + h_s \cdot e^{2i\sigma_s})M_{12}^{SM}$, where $M_{12}^{SM}$ is the dispersive part in the SM. Then $\Delta m_s$

\(^b\)Throughout the paper a nominal LHCb year corresponds to 2 $fb^{-1}$.

\(^c\)Throughout the paper only expected statistical error is quoted.

\(^d\)The integrated luminosity of 30 $fb^{-1}$ corresponds to the ATLAS and CMS running at luminosity of about 10$^{33}$ cm$^{-2}$s$^{-1}$, where these experiments expect to study $b$ physics.
and $\phi_s$ measurements can be used to constrain NP in the oscillation: $\Delta m_s = \Delta m^S_M [1 + h_s \exp(2i\sigma_s)], \phi_s = \phi^S_M + \text{arg}(1 + h_s \exp(2i\sigma_s))$. For $2\sigma_s \neq n\pi$, LHCb is expected to constrain $h_s < 0.1\, @\, 90\% \, CL$ with one year of data.

3 CKM angle $\gamma$

Precise $\gamma$ measurements will allow to constrain the apex of the UT and also to search for possible NP effects in loops by comparing $\gamma$ value as determined from the tree-mediated diagrams to that from the processes involving loops.

The $CP$ violation in the purely tree process $B_s \rightarrow D_s^+ K^-$ (both diagrams $\sim \lambda^3$) followed by $D_s \rightarrow K K \pi$, occurs due to the interference via mixing. The corresponding phases are $\Delta \mp (\gamma + \phi_s)$, where $\Delta$ is the strong phase difference. From the four tagged time-dependent rates measured experimentally, one can extract $\Delta$ and $\gamma + \phi_s$ simultaneously. The $K/\pi$ separation is essential for this analysis to suppress reflection from the $B_s \rightarrow D_s \pi$ decay, which has a 20 times larger branching fraction. Applying the LHCb particle ID, a residual contamination of $B_s \rightarrow D_s \pi$ is shown on top of the $B_s \rightarrow D_s K$ invariant mass spectrum in Fig. 1a. The expected LHCb annual yield [6] is $6.2k$ events with $S/B > 1.4\, @\, 90\% \, CL$. The error on $\gamma + \phi_s$ of $10^\circ$ in one LHCb year, directly translates to the sensitivity on $\gamma$, since small value of $\phi_s$ is measured with the $B_s \rightarrow J/\psi \phi$ decay.

A class of $B \rightarrow D^{(*)} K^{(*)}$ decays provides a powerful tool for $\gamma$ measurement. Applying various methods [7-9] and their combinations to variety of $B \rightarrow D K$ decays [10], LHCb is expected to achieve a statistical error of $\sim 4^\circ$ in one year.

$B_d \rightarrow \pi \pi$ and $B_s \rightarrow K K$ channels allow $\gamma$ determination sensitive to possible NP contribution to the penguin loop. Four time-dependent asymmetries are measured with $\gamma, \phi_d, \phi_s$, and relative penguin-to-tree contribution $P/T = d e^{i\theta}$ as parameters. The phases $\phi_d$ and $\phi_s$ are measured separately (see Sec. 2). Fleischer [11] suggested to use $U$-spin symmetry assumption, $d_{\pi \pi} = d_{KK}$ and $\theta_{\pi \pi} = \theta_{KK}$, which allows not only to solve system for $\gamma$, but since the system

![Figure 1: Invariant mass of $D_s K$ from $B_s \rightarrow D_s K$ decay with $B_s \rightarrow D_s \pi$ reflection (a), invariant mass of $K^+ K^-$ from $B_s \rightarrow K^+ K^-$ with major reflections without (b) and with (c) particle identification.](image)
becomes overconstrained, also to check the initial assumption of $U$-spin symmetry itself. This analysis requires reliable $K/\pi$ separation (Fig. 1b,c). In one year LHCb is expected to reconstruct $25k B_d \to \pi\pi$ events and $37k B_s \to KK$ events with $S/B$ of 2 and $>7$ respectively, leading to $\sigma(\gamma) \sim 4^\circ$ under the assumption of perfect $U$-spin symmetry.

4 Outlook

With an accumulated luminosity of $10 fb^{-1}$ LHCb will be able to measure the angle $\gamma$ to a precision $\sigma_{stat} \sim 5^\circ$ from tree-mediated processes, $\sigma_{stat} \sim 2^\circ$ from processes where NP could enter $D^0$ mixing, and $\sigma_{stat} \sim 2^\circ$ (under $U$-spin symmetry assumption) from processes involving penguin loops, thus providing a powerful probe for NP. The $B_s$ mixing phase $\phi_s$ will be measured to a precision $\sigma_{stat} \sim 0.01$ providing a constraint on NP by comparing tree-mediated with pure penguin processes.

References


* Sensitivity of the method degrades with the $U$-spin symmetry breaking [12]. With no constraints on $\theta_{s\pi,KK}$ and 20% breaking of $d_{s\pi} = d_{KK}, \sigma(\gamma) \sim 10^\circ$. The method is believed to fail for larger $U$-spin symmetry breaking.