

Determination of $|V_{ub}|$ at Belle II

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Semileptonic B meson decays involving low-mass charged leptons e or μ are expected to be free of non-Standard Model contributions and therefore play a critical role in determinations of $|V_{ub}|$ and $|V_{cb}|$. Of all the CKM matrix parameters, $|V_{ub}|$ is the least precisely measured and in most need of additional studies in order to better constrain the apex of the Unitarity Triangle. We focus on exclusive reconstruction of charmless semileptonic B meson decay $B \rightarrow \pi \ell \nu$, and present prospects and estimates for measuring $|V_{ub}|$ at Belle II with the full planned dataset of 50 ab^{-1} of integrated luminosity.

1 Introduction

Precise measurements of CKM matrix elements are necessary to probe the quark mixing mechanism of the Standard Model (SM) ^{1,2} and to search for possible physics beyond it. Semileptonic decays of B mesons involving low-mass charged leptons e or μ are expected to be free of non-SM contributions and therefore play a crucial role in precise determinations of CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$. Eq. 1 represents the differential branching fractions for B meson decays to pseudoscalar^a states

$$\frac{d\mathcal{B}(B \rightarrow P\ell\nu)}{dq^2} = |V_{ub}|^2 \frac{G_F^2 \tau_B}{24\pi^3} p_P^3 |f_+^P(q^2)|^2, \quad (1)$$

where q^2 is the squared value of the momentum transferred to the lepton pair, f_+^P is one of the pseudoscalar form-factors, τ_B and p the lifetime and momentum magnitude of the B meson and the pseudoscalar, respectively, and G_F the Fermi constant. From Eq. 1 it can be seen that in order to determine the value of the $|V_{ub}|$ element, one needs a good measurement of the branching fraction and a good understanding of the form-factors that come into play.

Of all the CKM matrix elements, $|V_{ub}|$ is the least precisely known due to the limited theoretical understanding of the form-factors and challenges with experimental measurements, so additional studies are needed in order to constrain the apex of the Unitarity Triangle even further. With Belle II we are entering an era of precision measurements, where we will be able to determine the value of $|V_{ub}|$ with precision at the percent level ³.

The most commonly studied decay mode to determine the magnitude of the CKM matrix element $|V_{ub}|$ is $B \rightarrow \pi \ell \nu$, because it offers a clean experimental measurement of the branching fraction and a precise theoretical calculation of the $B \rightarrow \pi$ form-factors. One of the problems with existing determinations of $|V_{ub}|$, the so-called V_{ub} puzzle, is a persistent discrepancy between $|V_{ub}|$ measurements based on inclusive and exclusive charmless B meson decays. In inclusive measurements we focus on all decays of the form $B \rightarrow X_u \ell \nu$ at the same time and try to

^aThis form has been simplified for low mass charged leptons e and μ .

reconstruct them inclusively, and in exclusive measurements we focus on specific decays, as in this case.

2 Reconstruction methods at B factories

Branching fraction measurements of leptonic and semileptonic B mesons are possible using several different experimental techniques that differ only in the way how the companion B meson is reconstructed. In this review we will only focus on the untagged (inclusive tag) method or the tagged method with hadronic tag decays.

In untagged analyses⁴ we first reconstruct our signal B meson, with the exception of the escaped neutrino. Since the detector hermetically covers a relatively large portion of the full solid angle, we can inclusively determine the 4-momentum of the companion B meson by adding up the 4-momenta of all the remaining charged tracks and neutral clusters in the event, as shown in Eq. 2.

$$p_{B_{comp}} = \sum_{i = \text{tracks and clusters}}^{\text{rest of event}} (E_i, \mathbf{p}_i). \quad (2)$$

Due to the well known initial $\Upsilon(4S)$ state, we can determine the missing 4-momentum as

$$p_{miss} = p_{\Upsilon(4S)} - p_{B_{sig}} - p_{B_{comp}}, \quad (3)$$

which is equal to the 4-momentum of the missing neutrino, if neutrino is the only missing particle in the event. The untagged method has an efficiency of about $\mathcal{O}(10\%)$, so it is the recommended approach with smaller data samples. The downside is the lower q^2 resolution, since 4-momentum of the companion B meson is determined in an inclusive way.

In tagged analyses with the hadronic tag reconstruction⁵ we first fully reconstruct the companion B meson in several hadronic decay modes. After having a good companion B meson candidate, we require that the rest of event is consistent with the signature of the signal decay. The missing 4-momentum can be imposed in the same way as in Eq. 3, taking into account the different method for $p_{B_{comp}}$ calculation. Knowing exactly how the companion B meson was reconstructed, this enables us to calculate q^2 with better precision, however, the efficiency drops to about $\mathcal{O}(0.1\%)$, so this method is better suited for abundant data samples.

3 Belle II prospects

Luminosity at the Belle II experiment is to be increased by a factor of 40 compared to that of Belle, and we hope to acquire 50 ab^{-1} of data, 50 times more than in the case of its predecessor. In addition to more data, the detector itself is being upgraded, with improvements in almost all aspects, such as tracking and particle identification. Improvements were also made on the software side, with smarter and more precise algorithms. In order to study the impact of Belle II in the future, we are able to make some predictions using Monte Carlo (MC) simulations. The MC data sample used in these studies was a mixture of generic $B\bar{B}$ events and continuum $q\bar{q}$ events, where $q = u, d, s, c$, which were produced in a Belle II Monte Carlo campaign in 2015 and correspond to a size of 500 fb^{-1} .

In case of the tagged MC study, the most relevant improvement, besides the detector upgrade, is the better tagging algorithm with significantly higher tagging reconstruction efficiency. From the MC study it was concluded that the overall reconstruction efficiency for $B \rightarrow \pi\ell\nu$ is about 0.55% ³, which is significantly higher than the overall reconstruction efficiency of 0.3% of the tagged measurement reported by Belle⁵.

In case of the untagged MC study, improvements were made in the treatment of the remaining tracks and clusters in the event. Studies showed that the rest of event consists of a considerable amount of tracks and clusters which should not be taken into account. These objects, dubbed as

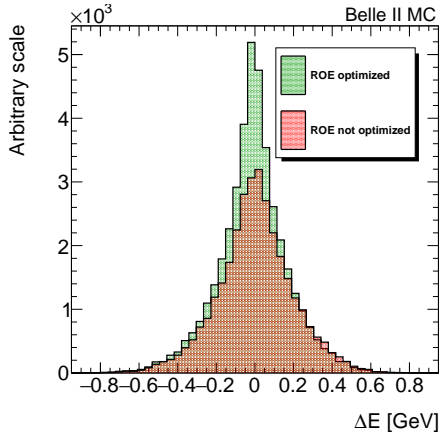


Figure 1 – The ΔE distribution of signal $B \rightarrow \pi\ell\nu$ candidates before and after rest of event clean-up. ΔE is a variable which compares the B meson energy to the CMS energy of the initial beam. Signal candidates peak at zero.

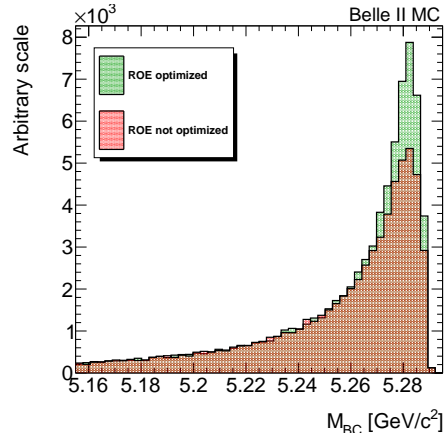


Figure 2 – The M_{BC} distribution of signal $B \rightarrow \pi\ell\nu$ candidates before and after rest of event clean-up. M_{BC} is a variable which constrains the B meson to the CMS energy of the initial beam. Signal candidates peak at nominal B meson mass with a narrow width.

extra tracks and clusters, are for example produced in secondary interactions of primary particles with detector material, or are fake candidates stemming from imperfect reconstruction. Either way, such cases should be discarded from our selection by cleaning up the rest of event. Taking all improvements into account, the overall reconstruction efficiency for this channel is around 20 %³, as opposed to 11 % reported in the untagged measurement of $B \rightarrow \pi\ell\nu$ decays performed by Belle⁴. Figures 1 and 2 show the improvement effect of the rest of event clean-up on Belle II MC on the ΔE and M_{BC} distributions, respectively.

Even though these studies were performed on a smaller MC sample, it is possible to extrapolate the errors to larger values of integrated luminosity, where one should keep in mind that the total error has contributions which do not scale with increasing data. Eq. 4 shows the general formula for error scaling with separate contributions to the total error,

$$\sigma_{\text{tot}}(\mathcal{L}) = \sqrt{(\sigma_{\text{stat}}^2(\mathcal{L}_0) + \sigma_{\text{sysred}}^2(\mathcal{L}_0)) \times \frac{\mathcal{L}_0}{\mathcal{L}} + \sigma_{\text{sysirred}}^2(\mathcal{L}_0)}, \quad (4)$$

where \mathcal{L} is the arbitrary integrated luminosity which we are interested in, \mathcal{L}_0 is the integrated luminosity at which the initial studies/measurements were made, σ_{stat} is the statistical error, σ_{sysred} the reducible part and σ_{sysirred} the irreducible part of the systematic error. Based on the tagged and untagged Belle analyses at 711 fb^{-1} ⁵ and 605 fb^{-1} ⁴, it is possible to estimate the precision limit of the irreducible systematic error to 2.0 % and 1.6 %³, respectively.

The $|V_{ub}|$ parameter was extracted from a simultaneous fit to the branching fraction distributions and LQCD input. The LQCD input used were the average form factor parameters of⁶ and⁷, performed by⁸. Optimally, LQCD input will become more precise as the Belle II detector acquires data, so it is possible to take LQCD error forecasts into account^{3,9}. Figure 3 shows an example of a fit at $\mathcal{L} = 5 \text{ ab}^{-1}$, while Figure 4 shows the precision of $|V_{ub}|$ for multiple values of integrated luminosity from 5 to 50 ab^{-1} for current LQCD and LQCD forecast in the next decade³. With the full Belle II dataset and the LQCD forecasts in 10 years we estimate the precision on $|V_{ub}|$ to be 1.7 % and 1.3 % in the case of the tagged and untagged analysis, respectively.

4 Conclusions

In this paper we present prospects on $|V_{ub}|$ CKM matrix parameter measurements with the full planned Belle II data sample using detailed MC studies. We estimate the precision to at least a

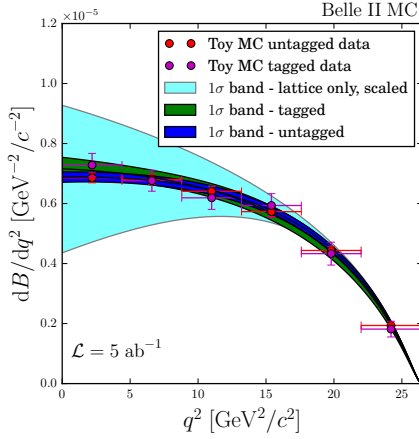


Figure 3 – An example of a Belle II simultaneous fit to MC data and LQCD input at 5 ab^{-1} including LQCD forecasts in 5 years for the tagged and untagged analysis.

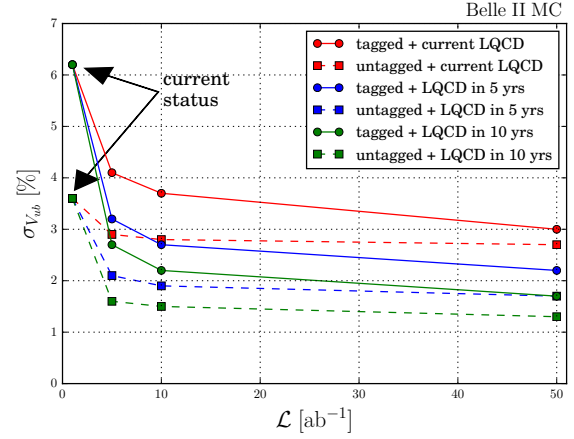


Figure 4 – $|V_{ub}|$ precision estimates for the tagged and untagged reconstruction method at 5, 10 and 50 ab^{-1} of integrated luminosity for current LQCD and LQCD forecasts in 5 and 10 years.

1.7 % and 1.3 % in the case of a tagged and untagged reconstruction method of the companion B meson, respectively.

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