Measurements of $|V_{ub}|$ at BaBar

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Abstract. The BaBar experiment, located at the Stanford Linear Accelerator Center (SLAC), produces millions of B mesons. The decays of the B mesons can be used to measure many elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which quantifies the quarks' flavor changing probabilities. One of the important and least known elements is $|V_{ub}|$. Its value is not predicted by the Standard Model. Its measurement is a critical constraint on the Unitarity Triangle, and thus, on the Standard Model itself. Our knowledge of $|V_{ub}|$ comes from measurements of the small $B \to X_u \ell \nu$ decay rates where a "b" to "u" quark transition is present. In these decays, the hadronic system in the final state can be reconstructed either inclusively or exclusively using tagged or untagged techniques. The precisions are limited by the uncertainties in the non-perturbative QCD calculations that are used to extract $|V_{ub}|$ from the measured decay rates. There are no new measurements from BaBar for this conference. However, in this talk, we highlight some features of the most recent ones and give you the references to all the BaBar measurements done so far in this field. We also summarize the state of the art of the $|V_{ub}|$ measurements and compare the direct experimental results with the values obtained by global fits to the Unitarity Triangle.

1. Introduction
The Standard Model describes particles and forces in a simple and elegant way. However, we know that it is incomplete and that it does not answer everything. Furthermore, it contains free parameters which are not predicted by theory and have to be experimentally measured. Four of these free parameters are found in the CKM quark mixing matrix, which describes the coupling between the quarks and the weak charged currents. By construction, this matrix is unitary, and one of the unitary condition is $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which can be represented graphically by the Unitarity Triangle (UT). The ultimate goal is to measure as precisely as possible the sides and the angles of this triangle, which can be achieve, in most cases, using the $B$ mesons available at $B$ factories. If some inconsistencies are found among the measurements, it can be sign of new physics. Measuring the $|V_{ub}|$ element is particularly interesting since it is one of the smallest and least known element. In the UT, it also corresponds to the opposite side of the well measured $\beta$ angle. Furthermore, discrepancies are currently seen between the $|V_{ub}|$ values coming from global fits to the UT and those coming from the direct experimental measurements.

To measure $|V_{ub}|$, we mainly use $B \to X_u \ell \nu$ decays, following two main experimental approaches: inclusive and exclusive. The first one does not specify the final $X_u$ hadron state while the second one does. Both approaches are similar since they need inputs from theory to describe the QCD part of these decays (corresponding usually to the biggest error in the $|V_{ub}|$ extraction) and they have to face high $b \to c \ell \nu$ backgrounds. Both approaches are also
complementary since the description of the QCD part from theory comes from independent calculations and the analysis techniques are also different. Within these two approaches, one can use two different experimental techniques. The first one uses tags. This technique takes advantage of the two $B$ mesons produced in each $e^+e^- \rightarrow B\bar{B}$ event since it implies to first reconstruct one $B$ meson and then search for the wanted signal in the remaining particles. The second technique uses no tag. The wanted signal is then searched for in all the particles present in the event. The choice of the experimental techniques usually leads to a trade off between high statistics (untagged techniques) and low systematic errors (tagged techniques).

2. Inclusive Measurements of $|V_{ub}|$ at BaBar

The inclusive approach (where $X_u$ is not specified) takes advantage of kinematic variables having different shapes than the dominant $b \rightarrow c\ell\nu$ backgrounds. Example of these variables are the lepton energy ($E_\ell$), the invariant mass squared of the lepton-neutrino system ($q^2$), the mass of the hadronic system ($m_X$) or a combination of these variables. The inclusive approach currently gives the best precision among all the $|V_{ub}|$ measurements and its total error is of the order of 7%. To date (i.e. this conference), the BaBar Collaboration has completed the following inclusive measurements of $|V_{ub}|$: tagged $m_X$ (2004) [1], untagged $E_\ell - q^2$ (2005) [2], tagged $m_X - q^2$ (preliminary, 2005) [3], untagged $E_\ell$ endpoint (2006) [4], untagged $E_\ell$ endpoint reinterpretation (2007) [5] and tagged $m_X$ with reduced model dependence (2006) [6]. We will highlight some interesting features of the three last ones.

The untagged $E_\ell$ endpoint (2006) [4] analysis provides the measured electron spectrum between $p_\ell = 2.0$ GeV/c and $p_\ell = 2.7$ GeV/c. Shape Functions (SF) [7], describing the motion of the $b$-quark inside the $B$ meson are used to extract $B(B \rightarrow X_u\ell\nu) = (2.27 \pm 0.26^{\text{exp}}_{0.33} +0.33\text{SF} \pm 0.17_{\text{theo}}) \times 10^{-3}$ and $|V_{ub}| = (4.44 \pm 0.25^{\text{exp}}_{0.42} +0.22^{\text{SF}}_{0.38\text{SF}} \pm 0.24_{\text{theo}}) \times 10^{-3}$. A new interpretation of these results can be driven using $b \rightarrow s\gamma$ decays in such a way that the dependence on the SF is reduced [5]. Thus, the results depend more on experimental uncertainties than on theoretical ones. This method was exploited for the first time in the tagged $m_X$ measurement [6], which gives $|V_{ub}| = (4.33 \pm 0.38^{\text{stat}}_{0.29} \pm 0.25^{\text{syst}}_{0.29}) \times 10^{-3}$. The latter analysis also showed that it is possible to relax significantly the $m_X$ cut while keeping the $b \rightarrow c\ell\nu$ background under control.

3. Exclusive Measurements of $|V_{ub}|$ at BaBar

The exclusive approach (where $X_u = \pi, \rho, \eta, \ldots$) implies the measurement of a specific branching fraction and the extraction of $|V_{ub}|$ using theoretical calculations of the Form Factor(s) (FF), which parameterize the QCD effects. For $B \rightarrow \pi\ell\nu$ decays, only one FF is needed and it depends only on $q^2$. Since the decay rate varies with $q^2$ and since the FF calculations are valid in specific ranges of $q^2$, the partial branching fractions are measured in $q^2$ bins. Then, $|V_{ub}|$ is extracted using different theoretical prediction for different $q^2$ intervals. The experimental FF shape can also be compared to the theoretical predictions. The exclusive approach currently gives $|V_{ub}|$ with a total error of the order of 18%, which is largely dominated by the errors on the FF calculations. To date, the BaBar Collaboration have completed the following exclusive measurements of $|V_{ub}|$: untagged $B \rightarrow \rho\ell\nu$ (2003) [8], tight untagged $B \rightarrow \pi/\rho\ell\nu$ (2005) [9], tagged $B \rightarrow \eta/\eta'/\ell\nu$ (preliminary, 2006) [10], tagged $B \rightarrow \pi\ell\nu$ (2006) [11] and loose untagged $B \rightarrow \pi\ell\nu$ (2007) [12]. We will highlight some interesting features of the two last ones.

The tagged $B \rightarrow \pi\ell\nu$ measurement (2006) [11], which is dominated by the statistical error at the moment, uses hadronic and semileptonic tags and three bins of $q^2$. This measurement was the first published tagged measurement in this field and had the lowest systematic error among all the measurements when published. The results are $B(B \rightarrow \pi\ell\nu) = (1.33 \pm 0.17^{\text{stat}}_{\text{syst}} \pm 0.11_{\text{syst}}) \times 10^{-4}$.
and $|V_{ub}| = (3.8 \pm 0.4_{\text{stat}} \pm 0.3_{\text{syst}}^{+0.7}_{-0.4_{\text{theo}}}) \times 10^{-3}$. The loose untagged $B \to \pi \ell \nu$ analysis (2007) [12] uses a typical neutrino reconstruction technique but avoids performing tight neutrino quality selections. Doing that, the signal efficiency increases significantly and allows the use of 12 bins of $q^2$, which is a dramatic improvement compared to what had been achieved before. The results are $B(B \to \pi \ell \nu) = (1.46 \pm 0.07_{\text{stat}} \pm 0.08_{\text{syst}}) \times 10^{-4}$ and $|V_{ub}| = (3.5 \pm 0.2_{\text{stat}} \pm 0.1_{\text{syst}}^{+0.6}_{-0.4_{\text{theo}}}) \times 10^{-3}$, which have the smallest statistical and systematic uncertainties of all the published $B \to \pi \ell \nu$ measurements. Furthermore, the FF shape has been measured and compared to the theory predictions in 12 $q^2$ bins. In the two analyses mentioned above, the dominating error on $|V_{ub}|$ comes from the uncertainties on the FF calculations. Note that, in order to give examples of numerical values of $|V_{ub}|$, we used in this section the HPQCD results for the FF calculations [13].

4. World Average and Global Fits to the Unitarity Triangle

According to HFAG [14], to date, the current best precision of $|V_{ub}|$ comes from inclusive studies ($\sigma \approx 7\%$). The exclusive studies ($\sigma \approx 18\%$) are becoming more competitive but they need more precise calculations of the FF. The global fits to the UT gives $|V_{ub}| = (3.54 \pm 0.17) \times 10^{-3}$ [15] and $|V_{ub}| = (3.44 \pm 0.16) \times 10^{-3}$ [16]. An interesting thing to note is that the global fit values agree well with the exclusive determinations of $|V_{ub}|$ (not so precise yet) but show a deviation ($\approx 2.6\sigma$) if we compare them to the inclusive measurements of $|V_{ub}|$ (quite precise).

5. Conclusion

We have listed all the inclusive and exclusive BaBar results for $|V_{ub}|$, which is a free parameter of the Standard Model. We have also highlighted some interesting features of recent measurements.

We have examined the current precision achieved on $|V_{ub}|$, which is currently driven by inclusive measurements. The biggest challenges in these analyses come from the theoretical description of the QCD and abundant $b \to c \ell \nu$ backgrounds. The precision of the exclusive measurements should improve in the future: important theoretical improvements are expected [17]. Finally, we have seen that there is an apparent discrepancy between the value of $|V_{ub}|$ coming from the inclusive measurements and that from the global UT fits. Is it sign of something? Will it disappear? It is important to pursue the measurements to answer these questions.

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