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Leptonic B Decays at BaBar

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We will present the most recent results on leptonic B decays $B^{\pm(0)} \to K^{*\pm(0)}\nu\bar{\nu}$ and $B^{\pm} \to \mu^{\pm}\nu$, based on the data collected by the BaBar detector [1] at PEP-II, an asymmetric e^+e^- collider at the center of mass energy of the $\Upsilon(4S)$ resonance .

1. INTRODUCTION

Rare B decays have always been a standard probe for New Physics (NP) searches. The very low Standard Model (SM) rate of these decays often make them unaccessible with the present experimental datasets, unless NP effects enhance the rate up to the current experimental sensitivity. Moreover, as NP effects can modify the decay kinematic, particular attention must be payed in order to perform a model independent analysis.

A B-Factory provides an unique environment where to investigate these processes. The high number of $B\bar{B}$ pairs produced by a B-Factory often allows to approach the needed experimental sensitivity. Moreover, the clean environment and the closed kinematic of the initial state enable to obtaining a very pure sample where to look for these decays.

In this work, we are going to present the most recent results in the searches of $B^{\pm(0)} \to K^{*\pm(0)}\nu\bar{\nu}$ and $B^{\pm} \to \mu^{\pm}\nu$, based on the data collected by the BaBar detector [1] at PEP-II, an asymmetric e^+e^- collider operating at a center of mass energy of 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance.

2. ANALYSES OVERVIEW

The common feature of the analyses presented in this work is the presence of undetectable particles in the final state, the neutrinos ν. This particular characteristic calls for non-standard analysis techniques, which enable to deal with the lack of informations regarding these particles. Typically, the closed kinematic of an e^+e^- collision is exploited to constraint through energy and four-vector conservation the $B\bar{B}$ pairs, after both particles have been reconstructed.

Different approaches can be employed in the selection of the B meson which is not decaying into the channel of interest ($B_{\rm tag}$): a totally inclusive reconstruction is applied on the $B_{\rm tag}$, without trying to identify its decay product, whenever the additional kinematic constraint coming from the two-body nature of the signal B ($B_{\rm sig}$) can be exploited, as in $B^{\pm} \to \mu^{\pm}\nu$. The high efficiency obtainable with this method has as drawback a poor energy resolution. On the other hand, when more than one neutrino is present in the event, a recoil technique is needed: first, the $B_{\rm tag}$ is reconstructed either in a semileptonic $B_{\rm sl} \to D^{(*)}l\nu$ or hadronic $B_{\rm had} \to DY$ ($Y = \pi, K$) system. Then, the channel of interest is searched in the rest of the event (ROE), defined as the set of tracks and calorimeter clusters not associated with the $B_{\rm tag}$. Both hadronic and semileptonic recoil are employed for the $B^{\pm(0)} \to K^{*\pm(0)}\nu\bar{\nu}$ search. This method allows a very high resolution and purity, but has clearly a low efficiency (1%-0.1%).

3. $B^{\pm(0)} \to K^{*\pm(0)}\nu\bar{\nu}$ SEARCH

3.1. Theoretical Introduction

In the SM $b \to s\nu\bar{\nu}$ processes occurs through FCNC and are therefore forbidden at the tree-level. As these transitions proceeds through one-loop box or electroweak penguin diagrams, they are expected to be highly suppressed. In

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particular, due to the absence of photon penguin contributions and long distance effects, the $B^{\pm(0)} \to K^{*\pm(0)}\nu\bar{\nu}$ decay rate can be calculated in the SM with less theoretical uncertainties with respect to the corresponding $b \to sl^+l^-$. The expected branching ratio ($\mathcal{B}$) is $\mathcal{B}(B \to K\nu\bar{\nu}) = (1.3^{+0.4}_{-0.3}) \times 10^{-5}$ [2]. However, this value can be enhanced in NP scenarios, where several mechanism can contribute to the rate. For example, in Ref. [2], non-standard Z^0 couplings give rise to a contribution which can bring and enhancement up to a factor 10. Moreover, new sources of missing energy, such as light dark matter [3] or unparticles [4, 5], if accompanied by a K^*, would contribute to the rate.

The kinematic of the decay can be described in terms of $s_{\nu\nu} = m^2_{\nu\nu}/m^2_B$, where $m_{\nu\nu}$ is the invariant mass of the neutrinos pairs and m_B is the B meson mass. As NP can strongly affect the decay in terms of the $s_{\nu\nu}$ shape [2, 5], it is important to not rely on any theoretical model when performing the analysis.

A previous search by the Belle Collaboration sets the upper limits (UL) of $\mathcal{B}(B^\pm \to K^{*\pm}\nu\bar{\nu} < 1.4 \times 10^{-4}$ and $\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu} < 3.4 \times 10^{-4}$ [7] The results presented here are the first completely model-independent search for $B^{\pm(0)} \to K^{*\pm(0)}\nu\bar{\nu}$.

3.2. $B^{\pm(0)} \to K^{*\pm(0)}\nu\bar{\nu}$ Analysis

The $B^{\pm(0)} \to K^{*\pm(0)}\nu\bar{\nu}$ search is performed in the recoil of both an hadronic (HAD) and a semileptonic (SL) system: the two different tagging strategies provide non overlapping samples whose results can be combined as independent measurements. Moreover, the two analyses have been developed in close synergy in order to combine the final results more consistently as possible.

The event selection start from the $B_{\rm tag}$ reconstruction: for the SL analysis, neutral D mesons are reconstructed in the $K^-\pi^+$,$K^-\pi^+\pi^0$,$K^-\pi^+\pi^-\pi^+$ and $K^0_S\pi^+\pi^-$ modes [1]. Charged D mesons are reconstructed in the $K^-\pi^+\pi^+$ and $K^0_S\pi^+$ final states. In the hadronic analysis, the $B_{\rm had}$ is reconstructed in $B_{\rm had} \to DY$ where $Y = n\pi + mK + rK^0_S + q\pi^0$ with $n + m + r + q < 6$ and D is a generic charmed meson. About 1000 different decay chains are considered. Charmed mesons are reconstructed in the same final states used in the SL analysis, along with the additional channels $D^+ \to K^+\pi^-\pi^+\pi^0, K^0_S\pi + \pi^-\pi^+, K^0_S\pi^+\pi^0$. For each reconstructed tagging B, a K^* is searched in the ROE. A neutral K^* can be reconstructed in the $K^+\pi^-$ mode, while a charged K^* in the $K^0_S\pi^+$ and $K^+\pi^0$ modes.

Considering that signal events have no additional neutral particles produced in association with the K^*, one of the most discriminating variable between signal and background is the extra neutral energy $E_{\rm extra}$, defined as the sum of the energies of the electromagnetic calorimeter neutral clusters not used to reconstruct either the $B_{\rm tag}$ of $B_{\rm sig}$.

In the SL analysis, the signal yield is extracted through a Maximum Likelihood (ML) fit to the final $E_{\rm extra}$ distribution, after selection criteria are applied to suppress continuum background. In HAD analysis, a loose selection is applied and all discriminating variables (including $E_{\rm extra}$) are used as inputs for a Neural Network (NN), whose output variable $NN_{\rm out}$ is fitted to extract the number of signal events.

The final selection efficiency for the SL analysis is $(5.6 \pm 0.7) \cdot 10^{-4}$ for $K^{*+} \to K^+\pi^0$, $(4.3 \pm 0.6) \cdot 10^{-4}$ for $K^{*+} \to K^0_S\pi^+$ and $(6.9 \pm 0.8) \cdot 10^{-4}$ for $K^{*0} \to K^+\pi^-$, while for the HAD analysis is $(6.7 \pm 0.6) \cdot 10^{-2}$ for $K^{*+} \to K^+\pi^0$, $(6.1 \pm 0.7) \cdot 10^{-2}$ for $K^{*+} \to K^0_S\pi^+$ and $(19.2 \pm 1.6) \cdot 10^{-2}$ for $K^{*0} \to K^+\pi^-$. The large difference is due to the fact that in the first case we normalize the $\mathcal{B}$ measurement to the total number of produced $B\bar{B}$ pairs, while in the second we use the number of reconstructed $B_{\rm tag}$.

The main systematics to the signal efficiency comes from the tagging and the cut on the selection variables. The uncertainties on the signal yield is mainly due to background distribution parameterization. An uncertainty related to the residual model dependence is also taken into account.

No significant signal is observed in the two analysis. A Bayesian approach is employed to set upper limits (UL) at 90% of confidence level on the neutral ($\mathcal{B}^0$) and charged ($\mathcal{B}^\pm$) mode separately and on their combination. The ULs are extracted from the two-dimensional posteriori PDF $P(\mathcal{B}^\pm, \mathcal{B}^0)$, where all the systematics are taken into account and the common ones are assumed to be fully correlated. The combined UL extracted are

[1] Charge conjugation is implied throughout this document, unless explicitly stated.

$$\begin{aligned}\mathcal{B}(B^{\pm} \to K^{*\pm}\nu\bar{\nu}) &< 8 \times 10^{-5} \\ \mathcal{B}(B^{0} \to K^{*0}\nu\bar{\nu}) &< 12 \times 10^{-5} \\ \mathcal{B}(B \to K^{*}\nu\bar{\nu}) &< 8 \times 10^{-5}\end{aligned} \quad (1)$$

These results are more restrictive than previous measurements from BaBar [6] and Belle [7].

4. $B^{\pm} \to \mu^{\pm}\nu$ SEARCH

4.1. Theoretical Introduction

In the SM, the purely leptonic B decays $B^{\pm} \to l^{\pm}\nu$ ($l = e, \mu, \tau$) proceed through the annihilation of the two quarks in the meson to form a virtual W boson. The branching ratio can be cleanly calculated in the SM,

$$\mathcal{BR}(B^{+} \to l^{+}\nu_{l}) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B, \quad (2)$$

where G_F is the Fermi coupling constant, m_l and m_B are the lepton and B meson masses, and τ_B is the B^+ lifetime. The decay rate is sensitive to the Cabibbo Kobayashi Maskawa matrix element V_{ub} and the B decay constant f_B which describes the overlap of the quark wave functions within the meson. Currently, the uncertainty on f_B is one of the main factors limiting the determination of V_{td} from precision $B^0\bar{B}^0$ mixing measurements. Given a measurement of V_{ub} from semileptonic decays such as $B \to \pi l \nu$, f_B could be extracted from a measurement of the $B^{\pm} \to l^{\pm}\nu_l$ branching ratio.

The SM estimate of the branching ratio for $B^{\pm} \to \tau^{\pm}\nu_{\tau}$ is $(1.59 \pm 0.40) \times 10^{-4}$ assuming $\tau_B = 1.638 \pm 0.011$ ps, $V_{ub} = (4.39 \pm 0.33) \times 10^{-3}$[8] determined from inclusive charmless semileptonic B decays and $f_B = 216 \pm 22$ MeV [9] from lattice QCD calculation. Due to helicity suppression, $B^{\pm} \to \mu^{\pm}\nu_{\mu}$ and $B^{\pm} \to e^{\pm}\nu_e$ are suppressed by factors of 225 and 10^7 respectively, leading to branching ratios of $\mathcal{B}(B^{\pm} \to \mu^{\pm}\nu_{\mu}) \simeq 4.7 \times 10^{-7}$ and $\mathcal{B}(B^{\pm} \to e^{\pm}\nu_e) \simeq 1.1 \times 10^{-11}$.

Purely leptonic B decays are sensitive to physics beyond the SM due to possible insertion of New Physics (NP) heavy states in the annihilation process. Charged Higgs boson effects may greatly enhance or suppress the branching ratio in certain two Higgs doublet models [10]. Moreover, as in annihilation processes the longitudinal component of the vector boson is directly involved, this decay allows a direct test of Yukawa interactions in and beyond the SM. In particular, in a SUSY scenario at large $\tan\beta$ ($O(m_t/m_b) >> 1$), non-standard effects in helicity-suppressed charged current interactions are potentially observable, being strongly $\tan\beta$ dependent:

$$\mathcal{B}(B^{\pm} \to l^{\pm}\nu_l) \approx \mathcal{B}(B^{\pm} \to l^{\pm}\nu_l)_{\rm SM} \times \left(1 - \tan\beta^2 m_B^2/M_H^2\right)^2. \quad (3)$$

These decays are also potential probes for Lepton Flavour Violation (LFV) in the ratios $R_B^{\mu/\tau} = \mathcal{B}(B^{\pm} \to \mu^{\pm}\nu)/\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu)$ and $R_B^{e/\tau} = \mathcal{B}(B^{\pm} \to e^{\pm}\nu)/\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu)$ [11].

4.2. $B^{\pm} \to \mu^{\pm}\nu$ Analysis

$B^{\pm} \to \mu^{\pm}\nu_{\mu}$ is a two-body decay so the muon must be mono-energetic in the $B_{\rm sig}$ rest frame. The momentum p^* of the muon in the B rest frame is given by

$$p^* = \frac{m_B^2 - m_\mu^2}{2m_B} \approx \frac{m_B}{2} \approx 2.46\text{GeV}. \quad (4)$$

where m_B is the B mass and m_μ is the muon mass. At BaBar, the CM frame is a good approximation to the $B_{\rm sig}$ rest frame, so we initially select well-identified muon candidates with momentum $p_{\rm CM}$ between 2.4 and 3.2 GeV/c in the CM frame. Since the neutrino produced in the signal decay is not detected, any other charged tracks or neutral deposits in a signal event must have been produced by the decay of the $B_{\rm tag}$. Once the $B_{\rm tag}$ is reconstructed from the remaining visible energy in the event, we can refine the estimate of the muon momentum in the $B_{\rm sig}$ rest frame (p^*). We use the momentum direction of the $B_{\rm tag}$ and assume a total momentum of 320 MeV/c in the CM frame (from the decay of the $\Upsilon(4S) \to B^+B^-$) to boost the muon candidate into the reconstructed $B_{\rm sig}$ rest frame.

Backgrounds may arise from any process producing charged tracks in the momentum range of the signal, particularly if the charged tracks are muons. The two most significant backgrounds are B semileptonic decays involving $b \to u\mu\nu_\mu$ transitions where the endpoint of the muon spectrum approaches that of the signal, and non-resonant $q\bar{q}$ (continuum) events where a charged pion is mistakenly identified as a muon. Continuum backgrounds are suppressed using event shape variables, as the light-quark events tend to produce a jet-like event topology as opposed to B^+B^- events which tend to be more isotropically distributed in space. Several topological variables are combined in a Fisher discriminant [12].

The two-body kinematics of this decay is now exploited by combining p^* and $p_{\rm CM}$ in a second Fisher discriminant, whose output p_{FIT} is used to extract the number of signal events through a ML fit. The final selection efficiency is 4.64 ± 0.19 %.

The main systematic to the measurement comes from the background PDF parameterization.

No signal is observed and a Bayesian approach is used to extract the UL

$$\mathcal{B}(B^\pm \to \mu^\pm \nu_\mu) < 1.3 \times 10^{-6} \tag{5}$$

at the 90% confidence level. These results are more restrictive than previous measurements from BaBar [13] and Belle [14].

5. CONCLUSIONS

The results presented in this work are on the final BaBar dataset, consisting of about 426 fb^{-1}. The $B^{\pm(0)} \to K^{*\pm(0)}\nu\bar{\nu}$ search is the first completely model independent result on these channel, which does not rely on any theoretical assumption to perform the analysis. The upper limit on $\mathcal{B}(B^\pm \to K^{*\pm}\nu\bar{\nu})$, $\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$ (as well as the combined measurement) and $\mathcal{B}(B^\pm \to \mu^\pm\nu)$ are currently the most stringent UL on these channels.

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