Status, open problems and prospects of the decay $B^+ \to \ell^+ \nu_\ell$

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The study of rare B-decays at SuperB provides unique opportunities to understand the Standard Model (SM) and constrain new physics (NP). We discuss the new physics potential of the leptonic $B^+ \to \ell^+ \nu_\ell$ decays from the proposed SuperB experiment with 75ab^{-1} of data (5 nominal years of data taking).

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1. Introduction

SuperB [1] is a high luminosity e^+e^- collider that will be able to indirectly probe NP at energy scales far beyond the reach of any accelerator planned or in existence. Just as detailed understanding of the SM was developed from stringent constraints imposed by flavour changing processes between quarks, the structure of any NP is severely constrained by flavour processes. The pattern of deviations from the SM can be used to test the NP. If NP is found at the LHC, then the many golden measurements from SuperB (of which $B^+ \to \ell^+ \nu_\ell$ is an example) will help decode the subtle nature of the NP. However if no new particles are found at the LHC, SuperB will be able to search for NP at energy scales up to 100 TeV. In either scenario, flavour physics measurements that can be made at SuperB play an important role in understanding the nature of NP.

In the SM the purely leptonic B meson decays $B^+ \to \ell^+ \nu_\ell$ proceed at the lowest order through an annihilation diagram with a W^+ exchange. The SM branching ratio (BR) can be calculated as [2]

$$BR(B^+ \to \ell^+ \nu_\ell)_{\rm SM} = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \ , \tag{1.1}$$

where G_F is the Fermi constant, m_ℓ and m_B are the lepton and B^+ masses, respectively, and τ_B is the B^+ lifetime. The BR is sensitive to the CKM matrix element $|V_{ub}|$ [3] and the B decay constant f_B.

The SM estimate for $BR(B^+ \to \tau^+ \nu_\tau)$ is $(1.20 \pm 0.25) \times 10^{-4}$, this assuming $\tau_B = 1.638 \pm 0.011$ ps [4], $|V_{ub}| = (4.32 \pm 0.16 \pm 0.29) \times 10^{-3}$ (errors are statistical and systematic, respectively) [5], and $f_B = 190 \pm 13$MeV [6]. The main uncertainties on the expected SM BR come from the $|V_{ub}|$ and f_B parameters. To a very good approximation, helicity is conserved in $B^+ \to \mu^+ \nu_\mu$ and $B^+ \to e^+ \nu_e$ decays, leading to $BR(B^+ \to \mu^+ \nu_\mu) = (5.4 \pm 1.1) \times 10^{-7}$ and $BR(B^+ \to \mu^+ \nu_\mu) = (1.3 \pm 0.4) \times 10^{-11}$. However, reconstruction of $B^+ \to \tau^+ \nu_\tau$ decays is experimentally more challenging than $B^+ \to \mu^+ \nu_\mu$ or $B^+ \to e^+ \nu_e$ due to the large missing momentum from multiple neutrinos in the final state.

Purely leptonic B decays are sensitive to NP, where additional heavy virtual particles replace the W^+ and contribute to the annihilation processes. Charged Higgs boson effects may greatly enhance or suppress the decay rate in some two-Higgs-doublet models [7]. Similarly, there may be enhancements through mediation of leptoquarks in the Pati-Salam model of quark-lepton unification [8]. Direct test of Yukawa interactions in and beyond the SM are possible in the study of these decays, as annihilation processes proceed through the longitudinal component of the intermediate vector boson. In particular, in a SUSY scenario at large $\tan\beta$, non-SM effects in helicity-suppressed charged current interactions are potentially observable, being strongly $\tan\beta$-dependent and leading to [7]

$$\frac{BR(B^+ \to \ell^+ \nu_\ell)_{\rm NP}}{BR(B^+ \to \ell^+ \nu_\ell)_{\rm SM}} \simeq \left(1 - \tan^2\beta \frac{m_B^2}{M_H^2}\right)^2 \ , \tag{1.2}$$

where M_H is the charged Higgs mass and $BR(B^+ \to \ell^+ \nu_\ell)_{\rm NP}$ is the NP expectation in the before mentionned NP models. As can be see from eq. 1.2, a measurement of the BR allows to set a constraint on the $\tan\beta - M_H$ plane.

2. Experimental Technique

The recoil technique has been developed in order to search for rare B decays with undetected particles, like neutrinos, in the final state. The technique consists of the reconstruction of one of the two B mesons (B_{tag}), produced through the $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ resonance, in a high purity hadronic or semi-leptonic final states, allowing to select a pure sample of $B\overline{B}$ events. Having identified the B_{tag}, everything in the rest of the event (ROE) belongs by default to the signal B candidate (B_{sig}), and so this technique provides a clean environment to search for rare decays. In this analysis, the B_{tag} is reconstructed in the hadronic modes (HD) $B \to D^{(*)}X$, where $X = n\pi + mK + pK^0_S + q\pi^0$ ($n+m+p+q < 6$), or semi-leptonic modes (SL) $B \to D^{(*)}\ell\nu$, ($\ell = e,\ \mu$).

In the search for $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$ decays, the signal is given by a single track identified as a muon and electron, respectively, in the ROE. In the search of $B^+ \to \tau^+\nu_\tau$ decays, a single track as a muon, electron or pion is selected from the ROE, compatible with the $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$, $\tau^+ \to e^+\nu_e\overline{\nu}_\tau$ and $\tau^+ \to \pi^+\overline{\nu}_\tau$ decays, respectively. Furthermore, a single track and a neutral pion in the ROE is searched to reconstruct $\rho^+ \to \pi^+\pi^0$ candidates compatible with the $\tau^+ \to \rho^+\overline{\nu}_\tau$ decay.

One very important variable is the lepton momentum (p'_ℓ) in the B_{sig} rest-frame, as the $B^+ \to \ell^+\nu_\ell$ channels ($\ell = e,\mu$) produce monoenergetic leptons. This variable allows to separate $B^+ \to \ell^+\nu_\ell$ from $B^+ \to \tau^+(\to \ell^+\nu_\ell\overline{\nu}_\tau)\nu_\tau$ events, and provides additional discrimination against other sources of background. The closed kinematics of the hadronic recoil technique allow to easily calculate the B_{sig} rest frame from the reconstructed B_{tag} and beam energies. However, the semi-leptonic recoil technique poses a problem due to the presence of a neutrino in the B_{tag} reconstruction. As the only missing particle in the B_{tag} is a neutrino, it is possible to calculate CM angle between the B_{tag} and $D^{(*)}\ell$ momenta. Yet, as the B_{sig} and B_{tag} are back-to-back in the CM frame, this means that the B_{sig} momentum is contained in a cone around the $D^{(*)}\ell$ system. Using this information and the magnitude of the B_{sig} CM momentum ($p^*_B = \sqrt{(E^*_{\text{beam}}/2)^2 - m^2_B}$, with E^*_{beam} the total beam energy in the CM-frame), it is possible to construct an estimator of p'_ℓ as the arithmetic average of the p'_ℓ calculated using all possible B_{sig} directions around the $D^{(*)}\ell$ system.

Finally, for these kind of decay modes with undetected particles in the final state, the most powerful variable for separating signal and background is the so-called extra energy, E_{extra}, which is defined as the extra energy in the electromagnetic calorimeter not associated with the B_{tag} or B_{sig} candidates. For the signal this variable peaks strongly near zero.

3. Current Experimental Status

The latest state of the art results on $B^+ \to \ell^+\nu_\ell$ decay rates from both BaBar and Belle collaborations are summarized in table 1. The current best knowledge on $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$ channels are upper limits at 90% C.L. In contrast, the $B^+ \to \tau^+\nu_\tau$ channel is a well established decay, with a value $(1.64 \pm 0.34) \times 10^{-4}$ (combining all the experimental findings [5]), which is in agreement with the SM expectation. However, this last experimental result is a source of tension within the the CKM global fit. The indirect determination of $B^+ \to \tau^+\nu_\tau$ turns out to be at 2.6σ (3.2σ) from the experimental value, as estimated by the CKMfitter [9] (UTfit [10]) collaboration. More precise experimental findings are needed to disentangle the current state of affairs.

Observable	BaBar	Belle
$BR(B^+ \to \tau^+ \nu_\tau)$ (SL)	$(1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$ [11]	$(1.54^{+0.38+0.29}_{-0.37-0.31} \times 10^{-4}$ [12]
$BR(B^+ \to \tau^+ \nu_\tau)$ (HD)	$(1.8^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}$ [13]	$(1.79^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-4}$ [14]
$BR(B^+ \to e^+ \nu_e)$ (SL)	$< 0.8 \times 10^{-5}$ [11]	—
$BR(B^+ \to e^+ \nu_e)$ (HD)	$< 1.9 \times 10^{-6}$ [15]	$< 0.98 \times 10^{-6}$ [16]
$BR(B^+ \to \mu^+ \nu_\mu)$ (SL)	$< 1.1 \times 10^{-5}$ [11]	—
$BR(B^+ \to \mu^+ \nu_\mu)$ (HD)	$< 1.0 \times 10^{-6}$ [15]	$< 1.70 \times 10^{-6}$ [16]

Table 1: *Summary of the experimental findings on $B^+ \to \ell^+ \nu_\ell$. The first and second errors are statistical and systematic. Upper limits are at* 90% *C.L.*

4. SuperB detector layout studies

Even though the expected SuperB increase in the instantaneous luminosity of a factor of 100 already promises significant improvements on the leptonic $B^+ \to \ell^+ \nu_\ell$ decays, additional activities for detector optimization are currently ongoing. The SuperB baseline detector configuration is very similar to BaBar but the boost ($\beta\gamma$) is reduced from 0.56 to 0.28. This reduction increases the geometrical acceptance and so the reconstruction efficiency. A new layer is added to the vertex detector as close as possible to the beam pipe in order to not to degrade the time-dependent measurements. Additionally, the inclusion of two new devices that will increase further the geometrical acceptance of the detector is beging considered: a particle identification device (Fwd-PID) placed in the fordward region and an electromagnetic calorimeter (Bwd-EMC) located in the backward region, covering the polar angular regions of $(17,25)$ and $(152,167)$ degrees, respectively.

The Fwd-PID is a highly performant PID device for K/π separation based on time-of-flight measurements, located in a region previously covered only by the tracking system. This new device will improve particle identification in a momentum region from 1.6 to 5.0 GeV where the tracking system alone is poorly performant. The Bwd-EMC will be used as a veto device, which means that no neutrals measured in it will be used to reconstruct the $B_{\rm tag}$ and $B_{\rm sig}$ candidates. Additional background suppression can be achieved by cutting on the total energy deposited in the Bwd-EMC, as the signal is expected to peak strongly at zero.

The SuperB fast simulation has been used to produce signal and the main background (generic $B\bar{B}$ decays) samples in the previously mentioned detector setups. This test showed that the reduced boost has the effect of increasing the signal efficiency by $\sim 7\%$ with an additional background suppression of $\sim 6\%$. The impact of the Fwd-PID device is to increase the signal and background reconstruction efficiencies by the same amount of 2.5%, due to an increase of the tag-side kaons identification efficiency in the forward region. Finally, the impact of the Bwd-EMC is to reduce the backgrounds by $\sim 10\%$ with a negligible effect on the signal. The total effect is, at a fixed integrated luminosity, an increase in the total sample efficiency with a higher signal to background ratio S/B.

5. Expected sensitivities

The $S/\sqrt{(S+B)}$ ratio, which would be the statistical significance of the *BR* measurement in a *cut-and-count* analysis, can be used as a measure of the expected sensitivities in SuperB. This ratio only takes into account the statistical uncertainties, and needs to be modified in order to consider the irreducible systematic uncertainties,

$$\text{Significance} = \frac{S}{\sqrt{(S+B+(\varepsilon_{\text{syst}}S)^2)}} \,, \tag{5.1}$$

where $\varepsilon_{\text{syst}}$ is the total relative systematic error. No significant observation is expected at SuperB of the highly suppressed $B^+ \to e^+\nu_e$ decay, therefore it will be excluded from the subsequent discussion.

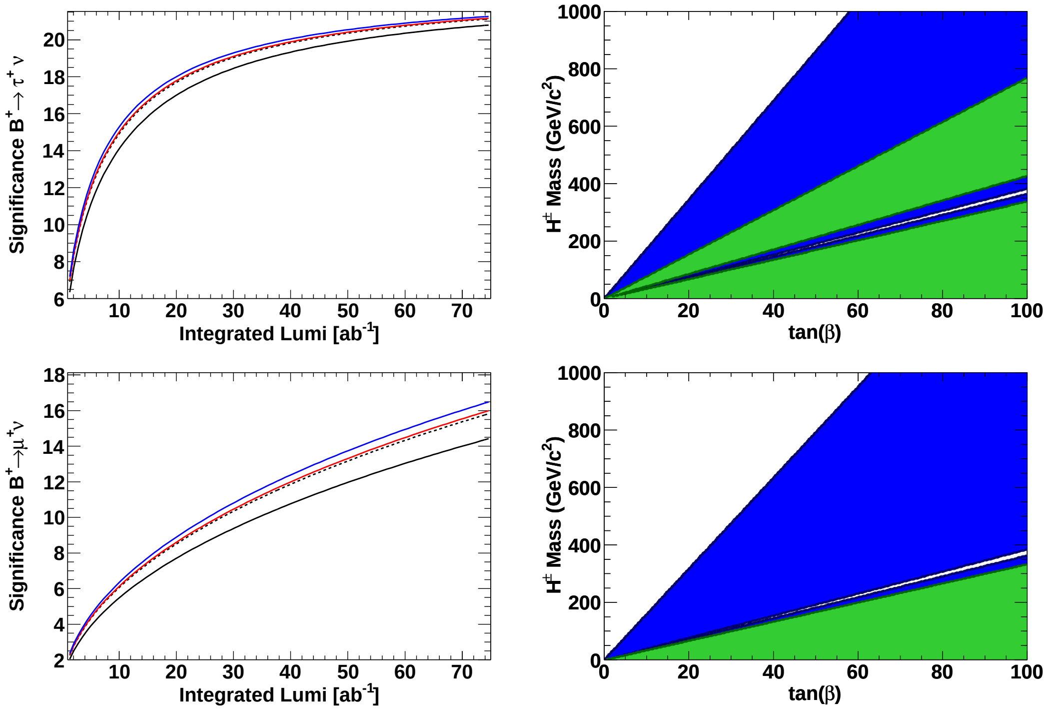

Figure 1: *left: Significance of the BR($B^+ \to \tau^+\nu_\tau$) (top) and BR($B^+ \to \mu^+\nu_\mu$) measurements as a function of integrated luminosity for the studied detector setups: BaBar (solid-black), SuperB baseline (dotted-black), Fwd-PID (red) and Bwd-EMC (blue). right: Excluded region on the* $\tan\beta - M_H$ *plane for the current (green) and expected sensitivities of SuperB at* 75 ab^{-1} *(blue) from the BR($B^+ \to \tau^+\nu_\tau$) (top) and BR($B^+ \to \mu^+\nu_\mu$) (bottom) measurements.*

The irreducible systematic uncertainties on $BR(B^+ \to \tau^+\nu_\tau)$ (mainly due to B_{tag} and B_{sig} reconstruction efficiencies and $B\overline{B}$ counting) is 8.7%, which is currently a factor of ~ 2 smaller than the statistical error. It is evident that this measurement will be systematic dominated in the near future if no effort is made to reduce the systematic error. The uncertainty will saturate at ~ 9% already at ~ 50 ab^{-1}, which is only 2/3 of the total expected dataset of SuperB. Experience has shown that systematics can be reduced with higher statistics, as it is possible to study larger control samples. It is then assumed that the systematic uncertainty can be reduced by a factor of two, which can be considered as a moderately conservative scenario. Under this hypothesis, we obtain the top-left plot of figure 1, where we show the statistical significance as a function of the integrated luminosity, which gives an uncertainty of 4.5% at 75 ab^{-1}. In order to translate this into an excluded region in the $\tan\beta - m_H$ plane, it is needed as well to make some hypothesis on the systematic error of the SM branching ratio (see eq. 1.2). The main uncertainties coming from $|V_{ub}|$ and f_B (see eq. 1.1), it will be assumed that the statistical error on $|V_{ub}|$ scales with luminosity and that the systematic component can be reduced by a factor of two. For the uncertainty on f_B we use 1.5%, which is the expectated error for the SuperB era estimated by FLAG [17]. In the right-top plot of figure 1 the excluded region (blue) for the expected sensitivities on the $BR(B^+ \to \tau^+\nu_\tau)$ at 75 ab^{-1} is shown. For comparison we show (green) the excluded region with the current uncertainties. As can be seen, the excluded region can be significantly increased with the expected sensitivities at SuperB full dataset.

In the case of the $B^+ \to \mu^+\nu_\mu$ channel, the irreducible systematic uncertainty is $\sim 4.0\%$. As with $B^+ \to \tau^+\nu_\tau$ decay, it is assumed that the systemtic errors can be reduced by a factor of two for the SuperB era, which gives the left-bottom plot of figure 1. As can be seen, the $BR(B^+ \to \mu^+\nu_\mu)$ measurement will not be systematic dominated in contrast to the $BR(B^+ \to \tau^+\nu_\tau)$. As shown in the bottom-right plot of figure 1, the corresponding constraint on the $\tan\beta - M_H$ plane will be competitive with the one obtained from $B^+ \to \tau^+\nu_\tau$ decays.

6. Summary

In summary, we have investigated the reach of SuperB in the search of the $B^+ \to \ell^+\nu_\ell$ decays with both the hadronic and semi-leptonic techniques. Preliminary results based on the SuperB fast simulation have shown a significant increase on the signal to background ratio due to the boost reduction and the impact of the Fwd-PID and Bwd-EMC devices. It has also been shown that under moderately conservative hypothesis on the evolution of the systematic uncertainties both $B^+ \to \tau^+\nu_\tau$ and $B^+ \to \mu^+\nu_\mu$ decays will give competitive an unprecedent reduction of the NP parameter space ($\tan\beta - M_H$ plane) for the expected SuperB sensitivities at 75 ab^{-1} of data.

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