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Recent results on leptonic and semileptonic B decays from Belle

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Semileptonic and leptonic B decays are powerful probes to search for physics beyond the Standard Model (SM) as they can be calculated in the SM with high precision. We report recent results on rare B decays with leptons from the Belle experiment at the KEKB e^+e collider. The $B \to D\tau\nu$ mode is sensitive to New Physics effects such as a charged Higgs or leptoquark current, while the world average of the branching ratio shows a discrepancy from the SM. Recently, Belle has performed a measurement of this mode using τ decays to hadronic final states, which is essentially independent of previous measurements from Belle. With this method, the τ lepton polarization in $B \to D\tau\nu$ has been measured for the first time. Recent results on purely leptonic decay, $B \to \mu\nu$ will also be discussed. The analyses are based on the full data set of Belle containing 772 million $B\bar{B}$ pairs.

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1. Introduction

Semileptonic and leptonic decays of B mesons offer a precise way to test the Standard Model (SM) and search for New Physics contributions. In this proceeding several recent and new results from the Belle experiment are summarised. These are: the precision measurement of the CKM matrix element $|V_{cb}|$; two measurements of the ratio $R(D^*)$; the measurement of the $B \to \eta' \ell \bar{\nu}_\ell$ decay; and limits of the very rare $B \to \mu\nu$ decay.

2. The Belle experiment and experimental techniques

The Belle experiment, located at the KEKB accelerator in Tsukuba (Japan), recorded data from e^+e^- collisions from 1999-2010. The integrated luminosity recorded at the centre-of-mass energy of the $\Upsilon(4S)$ resonance corresponds to 711 fb^{-1} . The $\Upsilon(4S)$ resonance decays almost nearly into two B mesons, whose decay products can be studied to search for semileptonic or leptonic decays. The production cross section for charmed, light quark or lepton production at this centre-of-mass energy are also sizeable and it is beneficial for many analyses to reconstruct the full event. Therefore, one of the B mesons is reconstructed in either a fully hadronic or a semileptonic decay modes, while the other B meson is reconstructed in its signal decay mode. This procedure is referred to as "tagging", which significantly reduces backgrounds and allows one, in case of a hadronic tagging, to infer the kinematic of the signal B meson in the event.

The hadronic tagging uses a neural network to efficiently identify and rank tag B meson candidates. Around 2400 different hadronic decay channels are used, leading to a hadronic tagging efficiency of $\mathcal{O}(0.3\%)$. The semileptonic algorithm has an efficiency of $\mathcal{O}(1\%)$ and is often based mainly on the reconstruction of $B \to D^*\ell\nu$ decays because of their high purity.

3. Measurement of $|V_{cb}|$ and hadronic form factor parameters from $B \to D^*\ell\nu$ decays with hadronic tagging

Due to its high branching ratio, the $B \to D^*\ell\nu$ decay channel, with $\ell = e, \mu$, allows a precision measurement of the CKM matrix element $|V_{cb}|$. The study of the differential decay rates additionally allow to measure parameters of the hadronic form factors, that govern the non-perturbative strong decay dynamics:

$$\frac{\mathrm{d}^4\Gamma(B \to D^*\ell\nu)}{\mathrm{d}w\,\mathrm{d}\cos\theta_v\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\chi} = f(|V_{cb}|^2, \rho^2_{D^*}, R_1, R_2), \tag{3.1}$$

where w is the product of the two four-velocities of the B and D^* meson, that depends on the momentum transfer q^2. $\cos\theta_v$, $\cos\theta_\ell$ are the angles describing the decay of the D^* and the W respectively and χ is the angle between the two decay planes. These four kinematic variables fully describe the decay.

This analysis uses the full Belle data set and employs hadronic tagging, which allows to obtain a very pure sample of B -> D* l nu decays [1]. The projections of the four variables are shown in Figure 1.

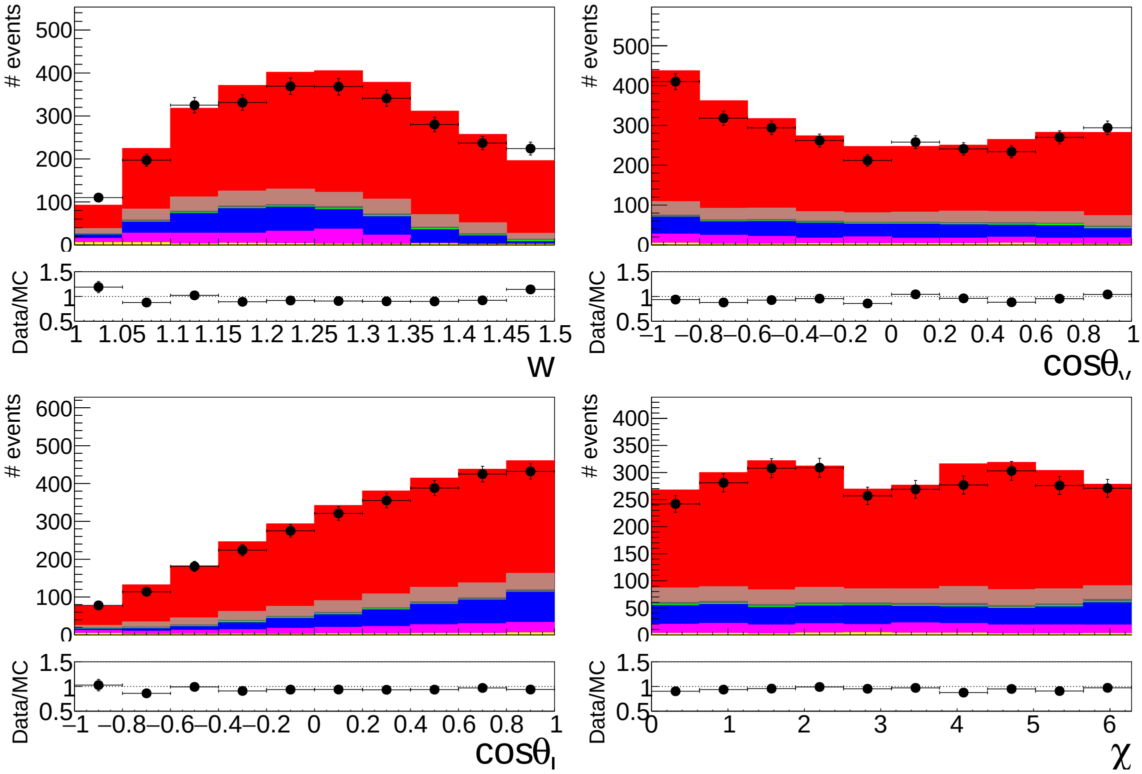

Figure 1: Raw reconstructed one-dimensional projections of the differential decay rate.

To separate the $B \to D^*\ell\nu$ signal from background, each bin of these kinematic distributions is fitted using an unbinned likelihood fit to the missing mass squared distribution. The missing mass squared is defined as:

$$m^2_{miss} = (p_{\Upsilon(4S)} - p_{tag} - p_{D^*} - p_\ell)^2, \tag{3.2}$$

where $p_{e^+e^-}$, p_{tag}, p_{D^*}, and p_ℓ denote the four-momenta of the centre-of-mass system, the tag-side B meson, the reconstructed D^* candidate, and the reconstructed lepton candidate respectively. For signal decays, this quantity corresponds to the mass of the neutrino and should peak around zero. For background a broad distribution is expected, which is smeared out towards positive m^2_{miss} values. The inclusive m^2_{miss}-distribution is shown in Figure 2.

The extracted signal yields are then fitted to the theory prediction of the CLN parametrisation [2] to extract the form factor parameters and $|V_{cb}|$. Tab 1 summarises the determined values and uncertainties and compares them to the world averages of [3].

Parameter	Measurement	World average
$\lvert V_{cb}\rvert \cdot 10^3$	37.4 ± 1.2	39.2 ± 0.7
$\rho^2_{D^*}$	1.04 ± 0.13	1.20 ± 0.03
R_1	1.38 ± 0.07	1.40 ± 0.03
R_2	0.86 ± 0.10	0.85 ± 0.02

Table 1: Result of the fit of differential decay rates to theory prediction using CLN parametrisation.

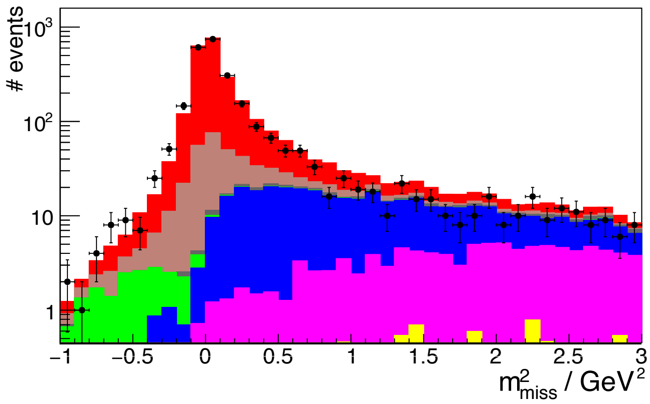

Figure 2: Inclusive m^2_{miss} distribution.

The spectra have additionally been unfolded to get results that are independent of the detector properties such as acceptance, efficiency and migrations. This has been done using the SVD formalism [4]. The results are shown in Figure 3 in comparison to the CLN theory prediction. These have been used in follow-up papers [5], [6], [7] to fit a different parametrisation of form factor parameters, the so called BGL parametrisation. This has been presented in a separate contribution [8].

4. Measurement of $\mathscr{R}(D^*)$ using a semileptonic tagging method

Semileptonic B meson decays with τ leptons in the final state are sensitive to new physics coupling to the third generation. For example, the presence of a charged Higgs boson, which is predicted by many extension of the SM, would change the ratio:

$$\mathscr{R}(D^*) = \frac{\mathscr{B}(B \to D^* \tau \nu)}{\mathscr{B}(B \to D^* \ell \nu)}, \tag{4.1}$$

from its SM value. Experimentally measuring ratios like Equation **??** is beneficial as many of the systematic uncertainties cancel and the prediction in the SM is independent of the CKM matrix element $|V_{cb}|$. It's value is predicted in the Standard Model to be $\mathscr{R}(D^*) = 0.252 \pm 0.003$ [9].

Recently, the Belle collaboration reported a new measurement of $R(D^*)$ using a semileptonic tagging approach [10]. For the tag-side, $B \to D^* \ell \nu$ decays are reconstructed. To keep background at an acceptable level, only neutral B-mesons were considered. The signal $B \to D^* \tau \nu$ decay is reconstructed using leptonic τ decay modes. To separate signal decays from the $B \to D^* \ell \nu$ normalisation mode, the angle between the B meson and the $D^* \ell$-system in the centre-of-mass frame is used:

$$\cos \theta_{B-D^*\ell} = \frac{2E_{beam}E_{D^*\ell} - m_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}. \tag{4.2}$$

where E_{beam} denotes the beam energy, $E_{D^*\ell}$, $M_{D^*\ell}$, and $|\vec{p}_{D^*\ell}|$ denote the energy, the mass and the absolute three-momentum of the visible $D^*\ell$ system, and m_B and $|\vec{p}_B|$ the mass and absolute

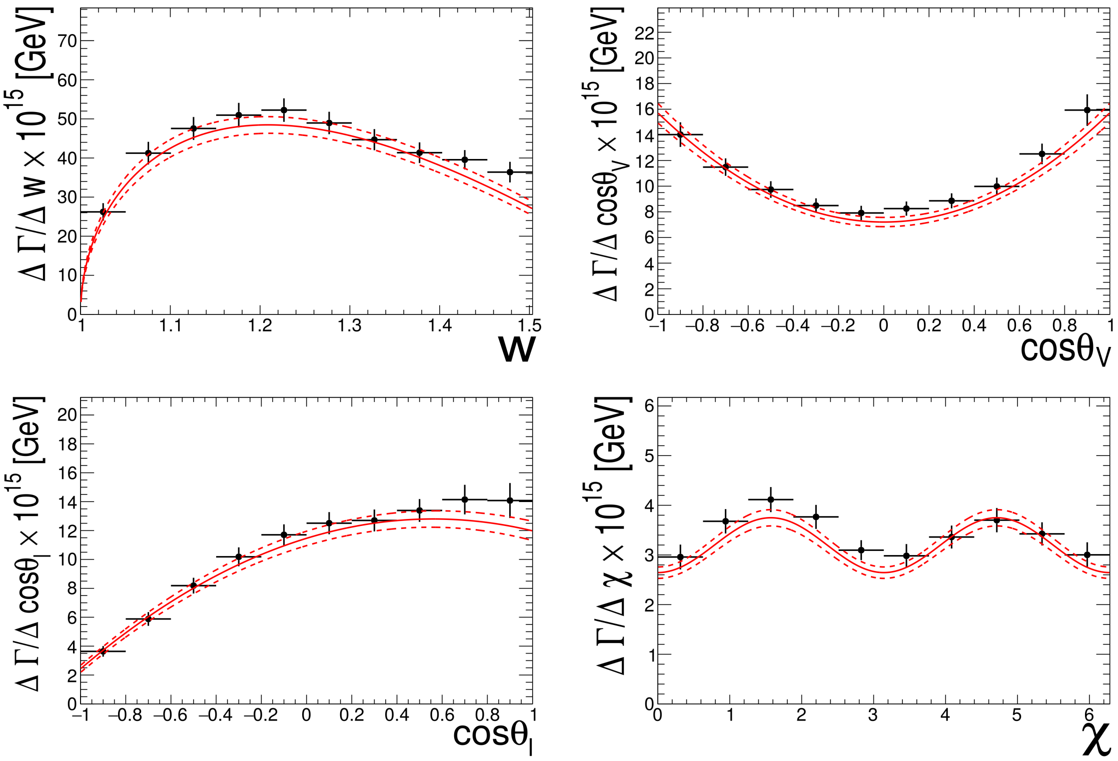

Figure 3: Unfolded kinematic distributions compared to the CLN theory prediction

three-momentum of the B-meson. The angle Equation 4.2 ranges from -1 and 1 for $B \to D^* \ell \bar{\nu}_\ell$ decays. Missing particles, like final state radiation photons or in the case of $B \to D^* \tau \nu$, additional neutrinos shift the distributions towards negative values. This allows for a good separation between normalisation and signal mode. Additional separation power can be gained by the variable E_{ECL}, which corresponds to unassigned neutral depositions in the calorimeter. For signal and normalisation mode no particles should be unassigned, but for backgrounds on average larger depositions are observed. Both variables are shown in Figure 4. The variables $\cos\theta_{B-D^*\ell}$ is combined with the $m^2_{\text{miss}} = (2E_{beam} - \sum_i E_i)^2 - |\sum_i \vec{p}_i|^2$ and the visible energy $E_{\text{vis}} = \sum_i E_i$ of each decay into a single classifier using a neural network approach.

The signal extraction is done using a two-dimensional binned likelihood fit to the neural network classifier and E_{ECL}. The value of $\mathscr{R}(D^*)$ is obtained via:

$$\mathscr{R}(D^*) = \frac{1}{2\mathscr{B}(\tau \to \ell \nu_\ell \nu_\tau)} \cdot \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \cdot \frac{N_{sig}}{N_{norm}} \tag{4.3}$$

where N_{sig} and N_{norm} and the fitted yields for signal and normalisation mode, and ε_{sig} and ε_{norm} are their reconstruction efficiencies, which are obtained from simulation. A value of $\mathscr{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$ is measured, which is in good agreement with the SM expectation. The measured central value is 1.6 σ above the expected value of $R(D^*)$.

The compatibility of this result with new physics has been tested in a model independent way

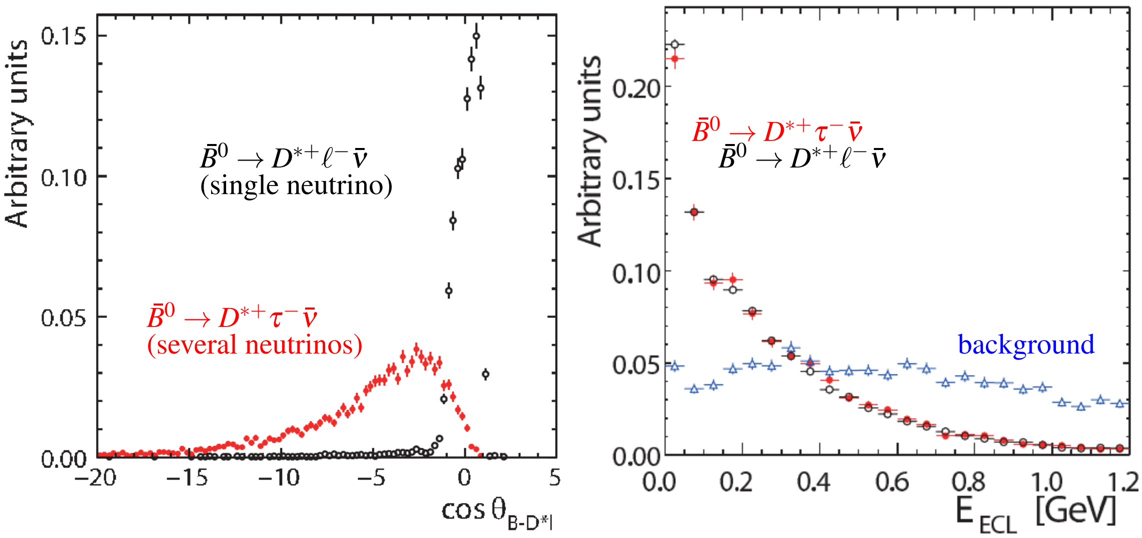

Figure 4: Distribution of the variable used for the separation of the signal and normalisation decay (left) and of the one used for the separation of signal and background (right).

using an effective Hamiltonian approach:

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[\mathcal{O}_{SM} + \sum_{\text{all}} C_X \mathcal{O}_X \right], \tag{4.4}$$

where $\mathcal{O}_X$ are all possible four-fermion operators, and C_X are the Wilson coefficients describing the coupling strengths to these operators. The analysis is repeated using simulated events with contributions from the operators $\mathcal{O}_X$ added one-by-one. From the comparison to data, the Wilson coefficients can be constrained. The results can be found in Tab. 2.

Models or operators	Parameters	Allowed regions (68% C.L.)
$\mathcal{O}_{S_1}$	C_{S_1}	$[-4.25, -3.09]$, $[+0.44, +1.57]$
$\mathcal{O}_{S_2}$	C_{S_2}	$[-1.56, -0.43]$, $[+3.12, +4.28]$
$\mathcal{O}_{V_1}$	C_{V_1}	$[-2.15, -2.03]$, $[+0.05, +0.15]$
$\mathcal{O}_{V_2}$	C_{V_2}	$[-0.17, 0.00]$, $[+1.83, +1.96]$
$\mathcal{O}_T$	C_T	$[-0.06, -0.01]$, $[+0.34, +0.39]$
R_2-type leptoquark	$C_T(= +C_{S_2}/7.8)$	$[-0.05, -0.01]$, $[+0.34, +0.38]$
S_1-type leptoquark	$C_T(= -C_{S_2}/7.8)$	$[-0.07, -0.01]$, $[+0.22, +0.28]$

Table 2: Constrains on different models set by constraining the Wilson Coefficients in an effective Hamiltonian.

5. Measurement of the τ lepton polarisation and $\mathscr{R}(D^*)$ in the $B \to D^*\tau\nu$ decay

Another variable that is sensitive to new physics is the τ lepton polarisation in the $B \to D^*\tau\nu$

decay, which is defined as:

$$P_\tau(D^*) = \frac{\Gamma^+(D^*) - \Gamma^-(D^*)}{\Gamma^+(D^*) + \Gamma^-(D^*)}, \tag{5.1}$$

where $\Gamma^\pm(D^*)$ is the decay rate of $B \to D^*\ell\nu$ with τ helicity $\pm\frac{1}{2}$. The polarisation is predicted in the Standard Model to be $P_\tau(D^*) = -0.497 \pm 0.013$ [11].

The polarisation has been measured from the forward backward asymmetry in the $B \to D^*\tau\nu$ decay using hadronic τ lepton decays [12]:

$$\frac{d\Gamma(D^*)}{d\cos\vartheta_{hel}} = \frac{\Gamma(D^*)}{2}\left[1 + \alpha P_\tau(D^*)\cos\vartheta_{hel}\right], \tag{5.2}$$

where $\cos\vartheta_{hel}$ is the angle between the hadron from the τ decay and the opposite W boson momentum in the τ rest-frame. The parameters α is sensitive to the reconstructed τ-decay mode in question. In leptonic τ decays the value of α is negligibly small. To probe the τ polarisation one needs to study hadronic τ decays and the presented analysis reconstructs such in the $\tau \to \pi\nu$ and $\tau \to \rho\nu$ modes.

The signal extraction is done in eight event categories divided into charged and neutral B mesons, the two τ lepton decay modes and two detector regions. The two detector regions are defined as forward ($\cos\vartheta_{hel} > 0$) and backward ($\cos\vartheta_{hel} < 0$). In a first step, the $B \to D^*\ell\nu$ normalisation is extracted from a fit to M^2_{miss} in a control sample. In a second step, a simultaneous likelihood fit is performed to the E_{ECL} distribution in all eight event categories.

The polarisation is measured to be $P_\tau(D^*) = \frac{2(N^F_{sig} - N^B_{sig})}{\alpha(N^F_{sig} + N^B_{sig})} = -0.38 \pm 0.51^{+0.21}_{-0.16}$. In addition, a value of $\mathscr{R}(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$ is measured. Both values are in good agreement with the SM expectation. Figure 5 shows both measurements and compares them to the world average of $R(D^*)$ and the SM expectations. The uncertainties are statistically dominated and there is great potential to reduce them with the future Belle II experiment.

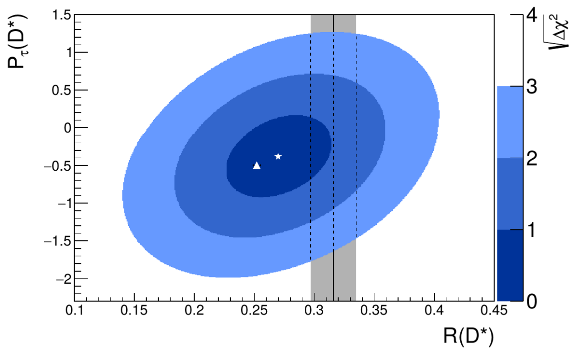

Figure 5: Comparison of the combined measurement of the τ lepton polarisation and $\mathscr{R}(D^*)$ with the prediction from the Standard Model.

6. Measurement of $B \to \eta^{(\prime)}\ell\nu$ decays

Accurate knowledge of $B \to \eta^{(\prime)}\ell\nu$ is important for inclusive measurements of the CKM matrix element $|V_{ub}|$ and could offer a future channel to measure $|V_{ub}|$ using exclusive decays. The measurement uses hadronic tagging. The η is reconstructed in the following decay channels: $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$. The η' final state is reconstructed using the $\eta' \to \eta\pi^+\pi^-$ channel with $\eta \to \gamma\gamma$. The signal is extracted using a binned likelihood fit to the M^2_{miss} distribution and the corresponding post-fit distributions are shown in Figure 6.

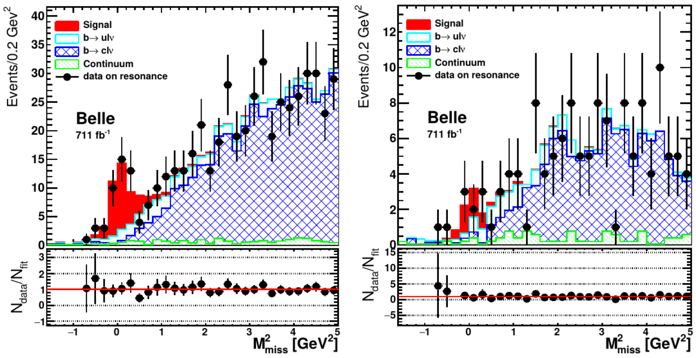

Figure 6: M^2_{miss} distributions for reconstructed events in the $B \to \eta\ell\nu$ (left) and $B \to \eta'\ell\nu$ (right) channels.

A branching fraction of $\mathscr{B}(B \to \eta\ell\nu_\ell) = (4.2 \pm 1.1 \pm 0.3) \cdot 10^{-5}$ is measured and a 90% limit of $\mathscr{B}(B \to \eta'\ell\nu_\ell) < 0.72 \cdot 10^{-4}$ is observed. The resulting branching fraction and the limit are compatible with previous results from BaBar and CLEO. The result is statistically limited and future measurements with Belle II will help reducing them significantly.

7. Search for purely leptonic $B \to \mu\nu$ decays

In the SM, the branching fraction of purely leptonic decays is extremely low due to CKM and helicity suppression. Such a suppression, however, might be absent in New Physics models, what makes the precision determination of these branching fractions a high priority. Precise measurements are challenging as the SM expectation is $\mathscr{B}(B \to \mu\nu) = (3.80 \pm 0.31) \cdot 10^{-7}$ [15]. For the first time, Belle reports a branching fraction for $B \to \mu\nu$ decays [14].

The shown analysis uses an untagged approach to retain a maximal signal efficiency. Events with one muon are reconstructed and it is assumed that all other particles in the event must belong to the second B meson in the decay. From this the beam-constrained mass, M_{bc}, and the energy difference ΔE are reconstructed according to:

$$M_{bc} = \sqrt{E^2_{\text{beam}} - \left(\sum_i \vec{p}^{\,*}_i\right)^2} \tag{7.1}$$

where i are all reconstructed particles, and

$$\Delta E = E_B - E_{\text{beam}} \tag{7.2}$$

Both variables are shown in Figure 7.

To suppress continuum background a cut on the thrust axis is used. The signal yield is obtained using a two-dimensional fit to the muon momentum in the centre-of-mass frame and a neural network classifier, trained to suppress the remaining background. In the B meson rest frame

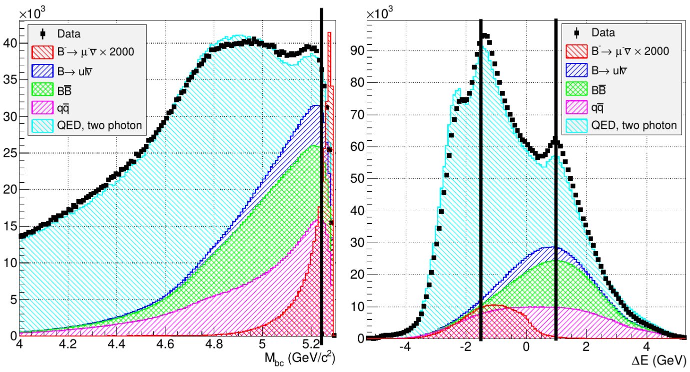

Figure 7: M_{bc} and ΔE distributions used to cut away background from the $B \to \mu\nu$ reconstruction.

the muon momentum would have a value of $m_B/2$ and this value is smeared due to the boost into the centre-of-mass frame. A positive signal with a significance of 2.4σ is observed and a limit of $\mathscr{B}(B \to \mu\nu) \in [2.9, 10.7]x10^{-}7$ is set at 90% CL. The result is compatible with the Standard Model expectation.

8. Conclusion

In summary, five recent results from the Belle experiment on semileptonic B meson decays have been reported. All results are compatible with the predictions from the Standard Model. All of the reported results are statistically limited and will be improved with the upcoming Belle II experiment.

References

[1] A. Abdesselam *et al.* [Belle Collaboration], arXiv:1702.01521 [hep-ex].

[2] I. Caprini, L. Lellouch and M. Neubert, Nucl. Phys. B **530** (1998) 153 doi:10.1016/S0550-3213(98)00350-2 [hep-ph/9712417].

[3] Heavy Flavor Averaging Group, EPS-HEP 2015

[4] A. Hocker and V. Kartvelishvili, Nucl. Instrum. Meth. A **372** (1996) 469 doi:10.1016/0168-9002(95)01478-0 [hep-ph/9509307].

[5] F. U. Bernlochner, Z. Ligeti, M. Papucci and D. J. Robinson, Phys. Rev. D **95** (2017) no.11, 115008 doi:10.1103/PhysRevD.95.115008 [arXiv:1703.05330 [hep-ph]].

[6] D. Bigi, P. Gambino and S. Schacht, Phys. Lett. B **769** (2017) 441 doi:10.1016/j.physletb.2017.04.022 [arXiv:1703.06124 [hep-ph]].

[7] B. Grinstein and A. Kobach, Phys. Lett. B **771** (2017) 359 doi:10.1016/j.physletb.2017.05.078 [arXiv:1703.08170 [hep-ph]].

[8] S. Schacht, P. Gambino, D. Bigi, EPS-HEP Talk, Venice, July 2017, https://indico.cern.ch/event/466934/contributions/2586301

[9] S. Fajfer, J. F. Kamenik and I. Nisandzic, Phys. Rev. D **85** (2012) 094025 doi:10.1103/PhysRevD.85.094025 [arXiv:1203.2654 [hep-ph]].

[10] Y. Sato *et al.* [Belle Collaboration], Phys. Rev. D **94** (2016) no.7, 072007 doi:10.1103/PhysRevD.94.072007 [arXiv:1607.07923 [hep-ex]].

[11] M. Tanaka and R. Watanabe, Phys. Rev. D **87** (2013) no.3, 034028 doi:10.1103/PhysRevD.87.034028 [arXiv:1212.1878 [hep-ph]].

[12] S. Hirose *et al.* [Belle Collaboration], Phys. Rev. Lett. **118** (2017) no.21, 211801 doi:10.1103/PhysRevLett.118.211801 [arXiv:1612.00529 [hep-ex]].

[13] C. BeleÃśo *et al.* [Belle Collaboration], Phys. Rev. D **96** (2017) no.9, 091102 doi:10.1103/PhysRevD.96.091102 [arXiv:1703.10216 [hep-ex]].

[14] Belle Collaboration, "Search for $B \to \mu\nu$ decays at the Belle experiment", July 2017, PRL journal publication in preparation

[15] Y. Amhis *et al.* [HFLAV Collaboration], Eur. Phys. J. C **77** (2017) no.12, 895 doi:10.1140/epjc/s10052-017-5058-4 [arXiv:1612.07233 [hep-ex]].