PROCEEDINGS OF SCIENCE

Semileptonic at B-factories ($R(D)$, $R(D^\star)$)

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Recently, the measurements of $R(D)$ and $R(D^\star)$, $R(D^{(\star)}) = \mathscr{B}\left(B \to D^{(*)}\tau\nu\right) / \mathscr{B}\left(B \to D^{(*)}\ell\nu\right)$, at the B-factories showed a significant tension with the Standard Model (SM). Here, a new analysis of $R(D^\star)$ using a semileptonically tagged sample by the Belle collaboration is presented. The new result of $R(D^*) = 0.302 \pm 0.030(\mathrm{stat}) \pm 0.011(\mathrm{sys})$ is compatible with the previous measurements by Belle, *BABAR* and LHCb and increases the tension with the SM to 4σ. A study of $B \to D^{(*)}\pi\pi\ell\nu$ by *BABAR*, which allows for better constraints on the semileptonic B-meson background in $R(D)$ and $R(D^\star)$ analyses, is shown. They find a value of $\mathscr{B}\left(B \to D^{(*)}\pi\pi\ell\nu\right) = 0.51^{+0.30}_{-0.15}\%$. Furthermore, *BABAR* studied the decay $B \to D^*\pi\pi\pi$ which is also an important background, especially when it comes to analyses with hadronic τ final states. Their analysis yields $\mathscr{B}(B \to D^*\pi\pi\pi) = (7.37 \pm 0.11 \pm 0.31) \cdot 10^{-3}$.

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1. Introduction

We present a preliminary result for $R(D^\star)$ from the Belle experiment as well as the related results for $\mathscr{B}\left(B \to D^{(*)}\pi\pi\ell\nu\right)$ and $\mathscr{B}\left(B \to D^{(*)}\pi\pi\pi\right)$ (preliminary) from *BABAR*.

To reduce systematic effects in studies of semileptonic B decays with τ leptons, usually the ratio

$$R(D^{(\star)}) = \frac{\mathscr{B}\left(B \to D^{(*)}\tau\nu\right)}{\mathscr{B}\left(B \to D^{(*)}\ell\nu\right)}, \tag{1.1}$$

is considered. Measurements of $R(D)$ and $R(D^\star)$ have been performed previously by Belle, *BABAR* and LHCb [3, 4, 5] using hadronically tagged events. The measurements yield higher values of $R(D)$ and $R(D^\star)$ than expected from the Standard Model of particle physics (SM). The world averaged value by HFAG excludes the SM at 3.9σ [1]. To understand this tension with the SM and to constrain possible contribution from New Physics (NP) beyond the SM, further analyses are needed to reduce the uncertainty on $R(D)$ and $R(D^\star)$. Belle has performed a new analysis of $R(D^\star)$ using a semileptonically tagged sample. The semileptonic tag allows for high statistics and an statistically independent sample to the hadronically tagged sample of the previous measurement. The preliminary result is discussed in Sec. 2.

All analyses rely on the understanding of backgrounds, e. g. feeddown from higher excited charmed mesons, which may mimic the signal. Whereas the 1P states (so-called D^{**} mesons) have been measured in $D^*\pi$ and $D\pi$ final states, the heavy 2S states have not yet been measured. This may explain the gap between the inclusive and exclusive branching fractions of semileptonic B decays. The measurement of the $B \to D^{(*)}\pi\pi\ell\nu$ state gives valuable insight and helps to constrain the structure of the excited charmed mesons. Details on this analysis can be found in Sec. 3.

The study of $R(D)$ at a hadron collider experiment like LHCb, will require a fuller understanding of other backgrounds. An example is the decay $B \to D^{(*)}\pi\pi\pi$, which may fake the signal signature, especially when analysing hadronic final states of the τ lepton. Alternatively, it might be used as a normalisation mode in such analyses. The discussion of this preliminary result is given in Sec. 4.

2. Semileptonically tagged $R(D^\star)$ at Belle

Belle reports a measurement of $R(D^\star)$ using semileptonically tagged events of the full $711\,\mathrm{fb}^{-1}$ data set. The difficulties arise, compared to the hadronically tagged analysis by Belle and *BABAR*, from the additional neutrino on the tag side. The measurement covers only $R(D^\star)$ because of poor background rejection in the case of $R(D)$. For the same reasons we use only the D^* semileptonic mode on the tag side. In case of a $B \to D\ell\nu$ tagging and/or normalisation mode, the possible feeddown of excited charmed mesons is difficult to control.

The $R(D^\star)$ signal is extracted in a 2D fit to the output of a neural net classifier and the so-called E_{ECL} variable. The latter is the sum of the residual energies in the electromagnetic calorimeter, after subtracting all energy deposition used in the signal and tag reconstruction. The neural net was trained to separate $B \to D^*\tau\nu$ from the $B \to D^*\ell\nu$ normalisation mode. Input variables are the cosine of $\theta_{BD^\star\ell}$ which is the estimated angle between the direction of the signal B and a single invisible neutrino. Thus, for signal events this observable is expected to be incompatible with the numerical range of the cosine. The other two variables are the squared missing four-momentum ("missing mass") and the visible mass in the event. All variables have in common that they separate the signal from the normalisation mode through the multi-neutrino signature of the signal.

The 2D maximum likelihood fit is carried out with three floating components: signal, normalisation mode and $B \to D^{**}\ell\nu$ backgrounds. The remaining backgrounds are fixed to their predictions from Monte-Carlo simulations (MC). The probability density functions (PDFs) are obtained from MC. Post-fit plots of the neural net output and E_{ECL} in the signal and normalisation mode enhanced network output regions are shown in Fig. 1.

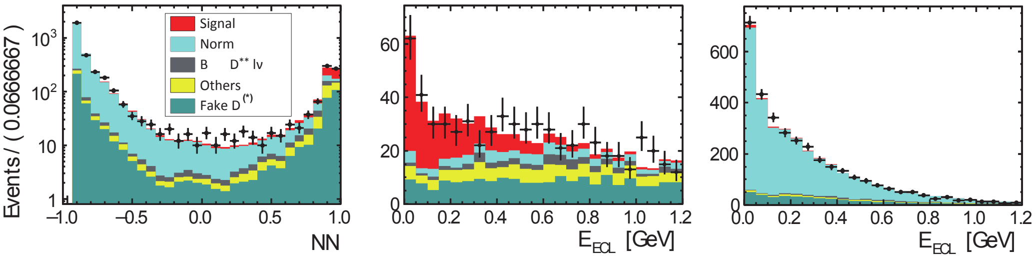

Figure 1: Plots for the extraction of the $B \to D^*\tau\nu$ signal and normalisation mode. The neural net spectrum (left) shows the full data set, while the E_{ECL} plots show the signal (center, NN> 0.8) and normalisation mode (right, NN< 0.8) enhanced samples separately. Taken from Ref. [6]

The preliminary fit yields

$$R(D^*) = 0.302 \pm 0.030(\mathrm{stat}) \pm 0.011(\mathrm{sys}), \tag{2.1}$$

which is compatible with previous hadronically tagged measurements, cf. Fig. 2. The uncertainty on the world averaged $R(D^*)$ is slightly reduced, resulting in a 4σ deviation of $R(D^{(*)})$ from the SM expectation [2]. The result has been analysed with respect to NP contributions. Tested models are those for a charged Higgs contribution from a type II two-Higgs-doublet-model (2HDM) and leptoquarks. The tests are performed with background-subtracted data in the momentum distributions of the signal lepton and D^*, which are compared to the model expectations from MC by χ^2 tests. While the lepton momentum spectrum does not show significant differences between the assumed models, the charmed meson spectrum does. It clearly disfavours the leptoquark model in the non-SM like parameter space with a p-value of 1.4%. The dataset cannot discriminate SM and 2HDM, as both models yield similar p-values of 37.6% and 37.9%, respectively.

A more detailed description of the analysis and the NP discussion can be found in Ref. [6].

3. Measurement of $\mathscr{B}\left(B \to D^{(*)}\pi\pi\ell\nu\right)$ at BABAR

Studying complex decay modes like $B \to D\tau\nu$ relies on the modelling of background decays, in particular the semileptonic B decays into charmed mesons. Decays of excited charmed mesons, like the D^{**}, can mimic missing momentum in $B \to D^{**}\ell\nu$ ($\ell = e, \mu$) decays and thus mimic the decay of the heavy τ. Another challenge is that the inclusive $b \to c\ell\nu$ rate which exceeds the measured exclusive rates. There is a gap between the inclusive and exclusive branching fractions of $1.51 \pm 0.26\%$ which needs to be filled up in MC simulations. To further investigate

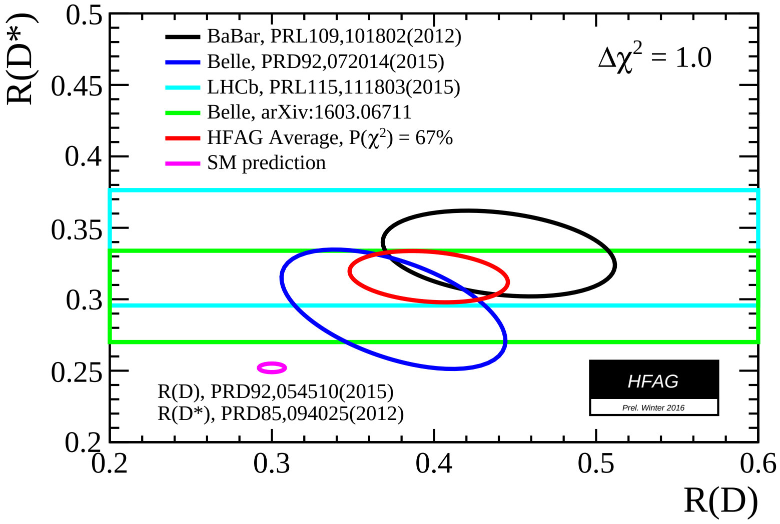

Figure 2: Combination of $B \to D^{(*)}\tau\nu$ measurements by the HFAG group including the new Belle semileptonic tag analysis. Taking the correlations of $R(D)$ and $R(D^{(\star)})$ in to account, the SM prediction is incompatible by 4σ. Taken from Ref. [2].

this inclusive-exclusive gap, *BABAR* performed an analysis of $B \to D^{(*)}\pi\pi\ell\nu$. The analysis uses a hadronically tagged sample of the whole $424\,\mathrm{fb}^{-1}$ *BABAR* data set. The signal is reconstructed as $B \to D^*\pi^+\pi^-\ell\nu$ and $B \to D\pi^+\pi^-\ell\nu$. In case of the latter decay, background from $B \to D^*\pi\ell\nu$ is suppressed with a veto on $\Delta m = m^*_D - m_D$. The signal MC was generated without assumptions on the production process of the pion pair, i. e. over the whole allowed phase-space. Possible production via, e. g. , $\rho \to \pi\pi$ are taken into account when extrapolating from the measured $\pi^+\pi^-$ to isospin averaged $\pi\pi$ final state. The signal is measured relative to the well studied $B \to D^{(*)}\ell\nu$ decays. Backgrounds are suppressed by a Fisher discriminat which is based on event shape variables and properties of the tag candidate. For the signal extraction fit, the observable $U = E_{\mathrm{miss}} - p_{\mathrm{miss}}$ is calculated from the missing energy and momentum in the event, respectively. This variable peaks at zero for single neutrino events and discriminates events with lost particles. In contrast to the previously mentioned m^2_{miss}, U is less sensitive to the exact modelling of the missing energy and thus the decay dynamics.

The signal is extracted separately for B^+ and B^0 as well as the D and D^* final states. Taking isospin averages into account, the total signal branching fraction yields

$$\mathscr{B}\left(B \to D^{(*)}\pi\pi\ell\nu\right) = 0.51^{+0.30}_{-0.15}\%. \tag{3.1}$$

For the final states, this is the first observation of $B \to D^0\pi\pi\ell\nu$ and evidence for $B \to D^+\pi\pi\ell\nu$ and $B \to D^{*+}\pi\pi\ell\nu$. A detailed description can be found in Ref. [7].

4. Measurement of $\mathscr{B}(B \to D^*\pi\pi\pi)$ at BABAR

In addition to the usually studied decays of $B \to D^{(*)}\tau\nu$ with leptonic τ decays, the hadronic τ decays are of great interest. They offer the opportunity of statistically independent data sets and

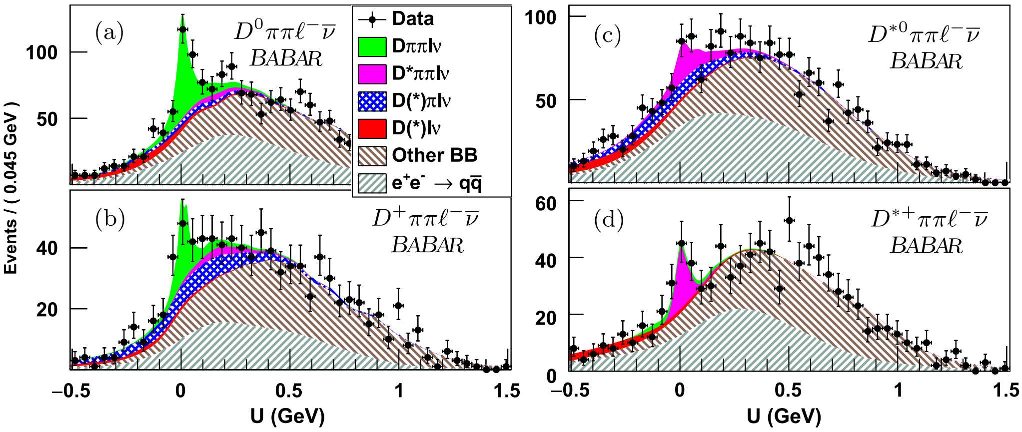

Figure 3: Signal extraction plots of the separate final states for $B \to D^{(*)}\pi\pi\ell\nu$ at *BABAR*. Taken from Ref. [7].

allow for advanced measurements such as τ polarisation. However, a pure hadronic signal selection brings up new challenges in the background modelling, as hadronic B decays can mimic signal events through undetected particles. It is even more challenging for hadron collider experiments like LHCb, where the missing energy is not available.

One of the obvious backgrounds is $B \to D^{(*)}\pi\pi\pi$, as it can mimic the signal easily in case of $\tau \to 3\pi$ or due to lost pions.

The *BABAR* analysis uses an untagged sub-sample of the whole *BABAR* data set. The D^* is reconstructed in the $K\pi$ channel and backgrounds are subtracted after a fit to the beam energy substituted mass $m_{\mathrm{es}} = \sqrt{E^2_{\mathrm{CMS}}/4 - p^2_B}$. The remaining spectrum of the 3π invariant mass is shown in Fig. 4.

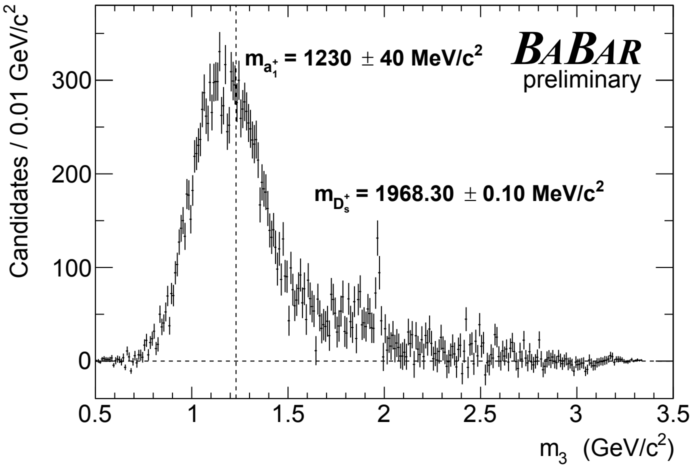

Figure 4: The final background subtracted spectrum of the 3π mass m_3. Taken from Ref. [8].

Clearly visible is the peak of the a_1, which is a bit shifted from the expected central value for yet unknown reasons. Also visible is a peak of 3π production through a D_s meson. The impact of these double charmed events is quite small and estimated by subtracting the MC prediction for double charmed events. The preliminary branching fraction is calculated to

$$\begin{aligned} \mathscr{B}\left(B \to D^{*}\pi\pi\pi\right)_{B\to D^{*}D_s\text{vetoed}} &= (7.26 \pm 0.11 \pm 0.31)\cdot 10^{-3} \\ \mathscr{B}\left(B \to D^{*}\pi\pi\pi\right) &= (7.37 \pm 0.11 \pm 0.31)\cdot 10^{-3}. \end{aligned} \tag{4.1}$$

5. Conclusions and Outlook

The question for possible NP contribution in semileptonic B decays with τ final states is still open. The recent semileptonic tagged analysis by Belle is compatible with the previous hadronic tagged measurements of $R(D^{\star})$ and results in a slightly more significant deviation from the SM. The origin of this deviation still needs to be investigated as the measurements disfavour the leptoquark but not the 2HDM-II model.

Measuring the backgrounds is an important step to improve our knowledge about $R(D)$ and $R(D^{\star})$. Here, we presented the measurement of $B \to D^{(*)}\pi\pi\ell\nu$ which also helps to understand the composition of the inclusive semileptonic B decays as a whole. The final result of the yet preliminary measurement of the $B \to D^{*}\pi\pi\pi$ will be important for future analyses involving the hadronic τ decays.

In the future, analyses like inclusive $B \to X_c\tau\nu$, which is not yet measured at one of the B factories, may emerge as a valuable cross-check to the excesses in $B \to D^{(*)}\tau\nu$. Furthermore, studies of $B \to D^{*}\pi\tau\nu$ or even $B \to D^{**}\tau\nu$ are important to better understand the results in the τ sector.

However, the Belle II detector will surpass the current experiments. With its huge expected data set of $50\,\text{ab}^{-1}$ and improved tracking and particle identification, it will significantly reduce the statistical and some systematic uncertainties.

References

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