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Semileptonic and leptonic decays with τ at the Belle II experiment

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Semileptonic and leptonic decays with τ are a stringent test of the Standard Model and an excellent probe for new physics. In this talk, an overview of the status of such measurements at the Belle II experiment is given. Future prospects for several golden semitauonic channels are also discussed.

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1. Introduction

Recent measurements of semileptonic and leptonic decays with τ by the $B-$factories [1] [2] and LHCb [3] have shown a consistent deviation, averaged to be 3.1 σ from the Standard Model expectation [4]. This has sparked the interest of the experimental and theoretical particle physics community and various predictions on the nature and type of new physics interactions that could lead to this B-anomaly have also followed. One of the goals of the Belle II experiment is to perform precision measurements in the semitauonic sector and eventually determine whether indeed there are new physics contributions present.

2. The Belle II experiment

The Belle II experiment is a B meson factory located in Tsukuba, Japan based on the SuperKEKB accelerator complex. Electrons and positrons are collided at a center-of-mass (CM) energy of 10.58 GeV, consistent with that of an $\Upsilon(4S)$ meson, which then decays almost instantly into a $B\bar{B}$ pair. Belle II is an upgrade of its predecessor Belle, with a target integrated luminosity of 50 ab^{-1}, which is 50× the size of the Belle data set. This large data set will be used for a rich physics program in the B, τ, charm sector and much more. Data taking at Belle II has started in March 2019 and has currently reached a total integrated luminosity of 218 fb^{-1} and will proceed in the next year, before the first upgrade planned for Belle II in 2023. The collected data set will be used to confirm the current B-anomalies and to present first novel results in the semi-tauonic sector. The planned measurements include: $R(D)$ and $R(D^*)$, $R(X)$, and $B \to \tau\nu$.

3. Tools for semitauonic measurements

3.1 Full Event Interpretation

Semileptonic and leptonic measurements involve neutrinos which do not leave a signature in the Belle II detector and can only be accounted for as missing energy. One of the main tools measuring these decays at Belle II is B-tagging. This involves the exclusive reconstruction of one of the two B mesons, referred to as the B_{tag}, in the decay $\Upsilon(4S) \to B\bar{B}$ via hadronic or semileptonic modes. The remaining information in a collision event is then attributed to the other B in the event, referred to as B_{sig} on which the semitauonic search is done. The $B-$tagging approach is ideal for events with neutrinos, since any missing energy in the event can be attributed to the B_{sig}. A novel $B-$tagging approach has been developed at Belle II, referred to as the Full Event Interpretation (FEI), and is based on a multivariate algorithm and a hierarchal reconstruction approach [5]. The FEI employs over 200 Boosted Decision Trees to reconstruct more than 1000 B decay chains, in both semileptonic and hadronic modes. The output of the FEI is a signal probability which separates between correctly reconstructed and misreconstructed B candidates, as shown in Fig. **??**. Compared to previous B-tagging at Belle, a 30-50% improvement in efficiency is achieved with the FEI. Currently, the hadronic FEI is calibrated to correct for data-MC differences using the inclusive channel $B \to X\ell\nu$. The calibration is implemented by determining the ratio of the data to Monte Carlo (MC) simulation after using hadronic B-tagging and selecting $B \to X\ell\nu$ channel[6].

3.2 Lepton Identification

Semileptonic decays with taus involve lower momentum leptons $\ell = e$ or μ which result from the corresponding τ daughter decay. Belle II has global particle identification (PID) based on almost all detector subsystem inputs. The performance of the PID has been evaluated in bins of the polar angle using standard candle processes. In addition, one of the main issues with PID is the high mis-identification rate at low momenta, $p < 1\,\mathrm{GeV}/c$. Currently, an updated PID technique based on a Boosted Decision Tree has been developed, with variables related to the shape of the electromagnetic shower related to the lepton. This BDT approach improves the separation between leptons and hadrons and decreases the mis-idetification rate for electrons by a factor of 10 and can be readily used for semitauonic decays.

3.3 E_{ECL}

E_{ECL} is a key variable for many semi-leptonic and missing energy analyses, such as $B \to D^*\tau\nu$. It is defined as the sum energy of all neutral clusters in the event after the full signal selection is applied. For properly reconstructed semileptonic events, E_{ECL} should ideally peak at zero, while background events with additional energy deposits due to misreconstructed neutral or charged particles will have a distribution peaking at higher values of E_{ECL}. However, due to the high level of beam backgrounds at Belle II, E_{ECL} peaks away from zero even for properly reconstructed semileptonic events. To correct for this, a multi-variate approach is developed, which employs shower shape variables to separate between energy deposits resulting from real photons and those that are related to beam backgrounds. The shower shapes of energy deposits resulting from beam backgrounds are isolated using $e^+e^- \to \mu^+\mu^-$ data events, while those resulting from true photons are obtained using simulated $B\bar{B}$ events. The multivariate (MVA) approach results in a beam background probability for each energy deposit to be assigned as resulting from beam backgrounds or true photons. A reasonable cut on this output results in an E_{ECL} distribution that is properly peaking at 0 for signal $B \to D^*\ell\nu$ events as shown in Fig. 1.

4. $R(D)$ and $R(D^*)$

The measurement of $R(D^{(*)})$ is one of the high priority analyses for Belle II. It is given by the ratio of the semitauonic B decay to its lighter lepton counterparts:

$$R(D^{(*)} = \frac{B \to D^{(*)}\tau\nu}{B \to D^{(*)}\ell\nu} \tag{1}$$

where here = e or μ. Currently, there are 3 planned measurements of $R(D^{(*)})$: i) with hadronic tagging and leptonic τ decays, ii) with hadronic tagging and hadronic τ decays, iii) semileptonic tagging and leptonic τ decays. Here, the hadronic τ decays refer to :$\tau \to \pi, \rho\nu$ while the clean leptonic decays refer to $\tau \to e\tau_e\tau_{\nu_\tau}, \tau \to \mu\tau_\mu\tau_{\nu_\tau}$. The advantage with the leptonic τ decays $R(D^{(*)}$ is that the numerator and denominator have the same final state, which allows for many systematic uncertainties to cancel. The latter is referred to as the normalization mode and its corresponding branching fraction has been measured in preparation for the $R(D^{(*)})$ measurement. $\mathcal{B} \to D^{(*)}\ell\nu$ has been measured using 34.6 of Belle II data. After applying the hadronic FEI algorithm, a $D^{(*+)}$

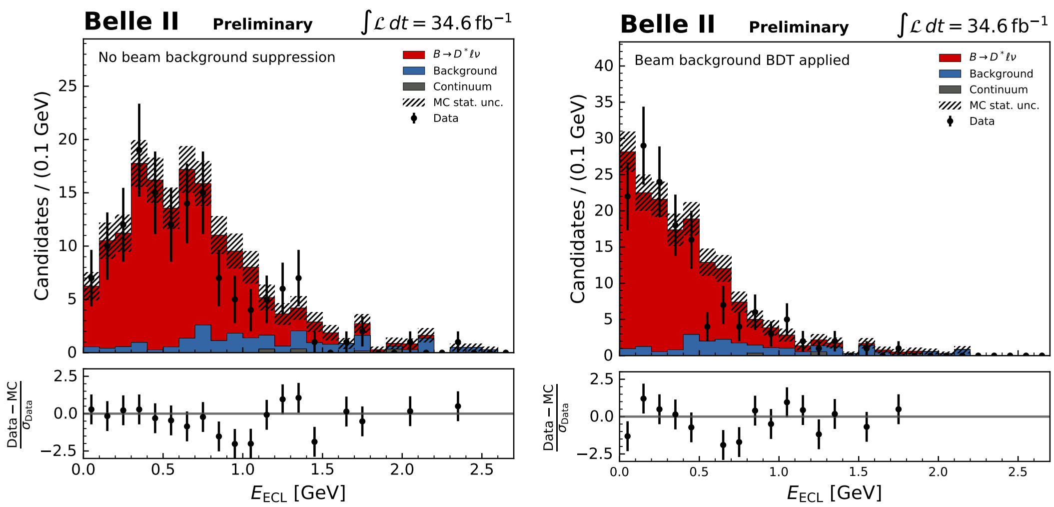

Figure 1: The E_{ECL} distribution after full reconstruction of both B mesons without (left) and with (right) the removal of beam background contributions with a cut on the MVA.

candidate is reconstructed using a soft pion π_s and $D^0 \to K^-\pi^+$ and a lepton with momentum> 1 GeV/c. The signal yield is then extracted from a fit to $m^2_{miss} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p^*_D - p_\ell)^2$, shown in Fig. 2. The resulting branching fraction is determined to be in agreement with the current world average and thus provides validation for the Belle II data and analysis chain. Currently, the $R(D^{(*)})$ analyses are developing multivariate algorithms to suppress the leading background contributions from semileptonic $B \to D^{**}\ell nu$ backgrounds and hadronic B decays. The initial plan is to confirm the B-anomaly with 0.5 ab^{-1}. The increase in the size of the Belle II dataset will considerably decrease the total uncertainty of $R(D^{(*)})$, especially since dedicated measurements of the $B \to D^{**}\ell\nu$ backgrounds are also planned. In addition, observables such as the τ polarization will also be measured in the near future, along with differential angular distributions that can shed further light on the source of this B-anomaly.

5. $R(X)$

Another unique measurement in the semitauonic sector is $R(X)$, which is defined as the ratio of the inclusive rates: $\mathcal{B}(B \to X\tau\nu)$ to the lighter lepton counterparts: $B \to X\ell\nu$. This inclusive rate can only be measured by B-factories such as Belle II and can provide complementary information on the current B-anomaly. The most recent measurement of $R(X)$ is by LEP [7] in 2001. The current Belle II measurement will use hadronic tagging and leptonic τ decays. After B_{tag} reconstruction, a lepton is identified using PID algorithms and the remaining information in the collision event is attributed to the X system in $B \to X\tau(\to \ell\nu_\ell)\nu_\tau$. Effective particle identification for low momentum leptons, which result from the τ decay, is critical and thus the BDT approach mentioned in 3.2 will improve the target precision. Furthermore, the measurement of $R(X)$ is highly sensitive to the modeling of semileptonic signal and background processes. Currently, dedicated studies are underway to better understand any modeling differences and to ensure agreement between data and

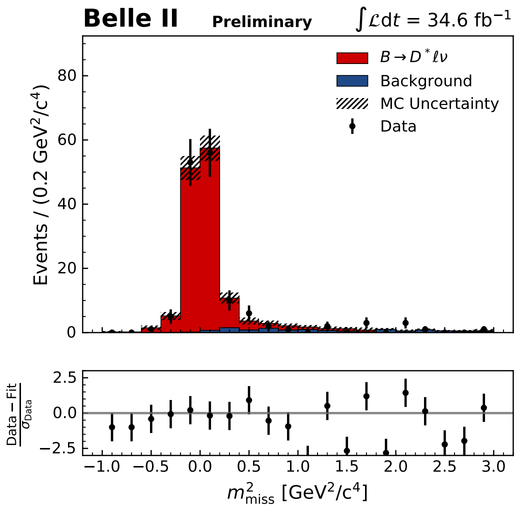

Figure 2: The fitted m^2_{miss} distribution for the normalization channel, $B^0 \to D^*\ell\nu$, in $R(D^{(*)})$ analyses.

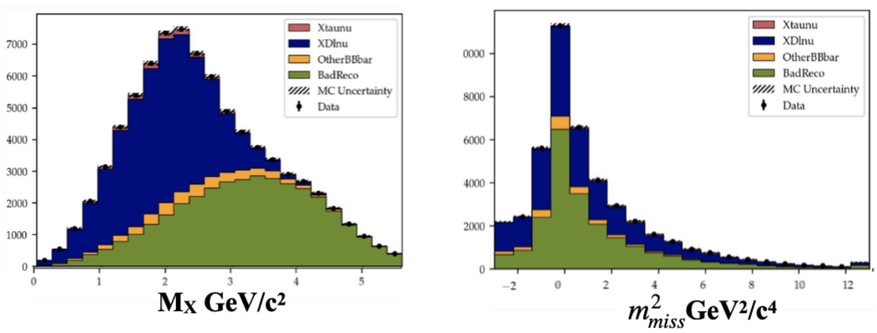

Figure 3: (Left) Distribution of M_X and (right) m^2_{miss} in $B \to X\tau(\to \ell\nu_\ell)\nu_\tau$ with simulated data.

simulation in quantities like M_X, the mass of the X system and the corresponding m^2_{miss} as shown in Fig. 3. The first measurement of $R(X)$ is planned with 500 fb^{-1} of Belle II data.

6. $B \to \tau\nu$

Another high priority measurement for the Belle II experiment is $\mathcal{B}(B \to \tau\nu_\tau)$. This is an important channel that can provide orthogonal information on $|V_{ub}|$. The larger Belle II data set will allow an unprecedented precision in this channel. Currently, the first Belle II measurement of $\mathcal{B}(B \to \tau\nu_\tau)$ will employ hadronic tagging with leptonic τ decays. After B_{tag} reconstruction, a lepton is identified and collision events with additional charged particles or energy deposits are excluded. Continuum events, where $e^+e^- \to q\bar{q}$ and q=u,d,s, or c ,are suppressed using event shape variables such as R2, the ratio of the second to zeroth Fox-Wolfram moment[8]. Optimization of the selection criteria to optimize the signal to background separation in key variables is currently in place. Furthermore, agreement between data and simulation is confirmed in key variables such as E_{ECL} and $E_{miss} + cp^*_{miss}$, as shown in Fig. 4, where the latter is defined as the sum of the missing energy and momentum in a collision event.

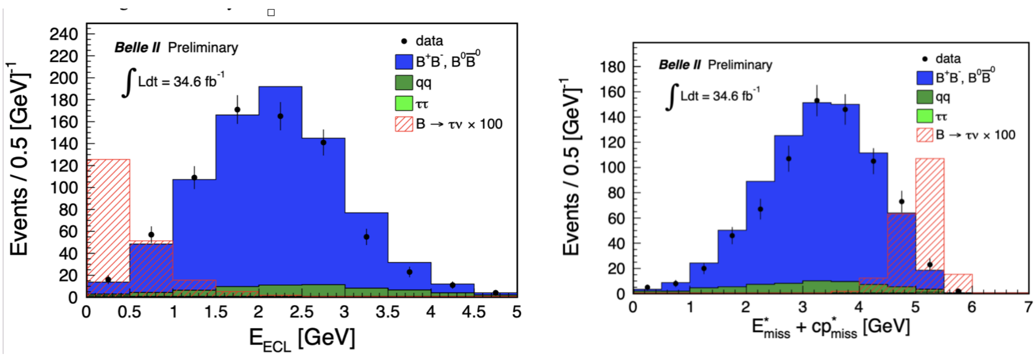

Figure 4: Left

7. Conclusion

In conclusion, Belle II is preparing for a range of results for semileptonic and leptonic decays with tau leptons. A set of software tools have been developed to improve the precision of these target measurements. Combined with the planned increase in the size of the Belle II data set, these measurements will shed more light on the current B-anomaly and other critical components in the hunt for physics beyond the SM .

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