Missing Energy decays of a B meson at Belle II

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Summary. — We present recent results of missing energy decays of B-mesons based on data collected at the $\Upsilon(4S)$ resonance by the Belle II experiment. This report includes two key analyses focusing on τ over μ/e lepton universality. The first is the measurement of the branching-fraction ratio $R(D^*_{\tau/\ell}) = \mathcal{B}(\overline{B} \to D^*\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^*\ell^-\overline{\nu}_\ell)$ using hadronic tagging. The second is the first measurement of the inclusive ratio $R(X_{\tau/\ell}) = \mathcal{B}(\overline{B} \to X\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to X\ell^-\overline{\nu}_\ell)$. We also present the branching-fraction ratios $R(X_{e/\mu}) = \mathcal{B}(\overline{B} \to Xe^-\overline{\nu}_e)/\mathcal{B}(\overline{B} \to X\mu^-\overline{\nu}_\mu)$. Finally, we present a simultaneous measurement of the magnitude of the CKM matrix $|V_{ub}|$ using the semileptonic $b \to u$ transitions: $B^0 \to \pi^-\ell^+\nu$ and $B^- \to \rho^0\ell^+\nu$. All results are consistent with the corresponding Standard Model predictions.

1. – Introduction

In the Standard Model of particle physics, the electroweak force carriers interact equally with all three charged leptons (e, μ, and τ), a principle known as lepton universality (LU). Missing energy B-meson decays are particularly valuable for testing the Standard Model, as both experimental measurements and theoretical predictions can achieve high precision.

2. – The Belle II Detector, Experimental Data, and MC Simulations

The Belle II experiment, situated at the SuperKEKB collider in Tsukuba, Japan, primarily collects data at the $\Upsilon(4S)$ resonance to study B meson decays. The Belle II detector consists of several key components: the Vertex Detector (including a Pixel Detector (PXD) and a Silicon Vertex Detector (SVD)) for high-precision vertexing and tracking, the Central Drift Chamber (CDC) for momentum measurements, Time-Of-Propagation (TOP) counters and ring-imaging Cherenkov counters (ARICH) for particle identification, an Electromagnetic Calorimeter (ECL) for detecting electrons, photons, and neutral particles, and a Resistive Plate Chamber system (KLM) for muon and K_L detection.

The dataset used for these analyses comprises an integrated luminosity of 189 fb^{-1} collected from 2019 to 2021, except for the last analysis explained in Sec. **5**, where the luminosity is higher: $L = 364$ fb^{-1}. Experimental results are interpreted and compared with Standard Model predictions using Monte Carlo simulations, employing software packages such as EvtGen[4], Pythia[3], and KKMC[5]. The full detector responses and simulations are executed with Geant4, while data and Monte Carlo reconstructions are performed using the Belle II analysis software framework, `basf2` [6].

2˙1. *Full Event Interpretation:* ***FEI***. – The Full Event Interpretation (FEI) [8] is an algorithm used in the Belle II experiment to classify events into signal-side (the B decay) and tag-side (the other B produced in the event). It provides crucial details about B decays, such as event type (e.g., $q\bar{q}$, $\tau\tau$, or $B\overline{B}$), decay vertex, and the reconstructed four-momentum of the tag and signal B mesons. FEI employs Multivariate Classifiers for each decay channel and is trained on Monte Carlo data within the `basf2` software package. The method, used with a hadronic tagging approach, offers high purity but limited tagging efficiency compared to semileptonic tagging. In all the analyses presented here, the hadronic tagging method is employed.

3. – Measurement of $R(D^*_{\tau/\ell})$ with Hadronic Tag

The first lepton-flavor universality test presented here involves measuring the ratio $R(D^*_{\tau/\ell})$ [1], defined as $\mathcal{B}(\overline{B} \to D^*\tau^-\overline{\nu})/\mathcal{B}(\overline{B} \to D^*\ell^-\overline{\nu})$. For both the numerator and denominator, a single lepton is required in the final state to eliminate normalization effects via the ratio, causing the cancellation of numerous systematics. The τ is reconstructed only in its fully leptonic decays ($\tau \to \ell\nu\nu$). Leptons are identified using likelihood ratios.

Charge conjugation is implied in all physical processes, and natural units are utilized. The hadronic component of the B decay is reconstructed through specific decay chains, suppressing combinatorial background by imposing a requirement of no other charged particles in the event. The reconstruction uses $D^* \to D^+\pi^0$ and $D^* \to D^0\pi^0$ decay chains, each with 11 sub-decay modes.

Signal extraction is accomplished through a 2D maximum-likelihood fit in $E_{\rm ECL}$ and $M^2_{\rm miss}$. The former represents the sum of the energy deposits in the calorimeter not associated with either $B_{\rm tag}$ or $B_{\rm sig}$. The latter, $M^2_{\rm miss}$, is the squared magnitude of the missing 4-momentum. Fig. 1 illustrates the distributions of these variables for three different samples: the numerator of $R(D^*_{\tau/\ell})$, the denominator, and the main background $\overline{B} \to D^{**}\ell^-\nu$.

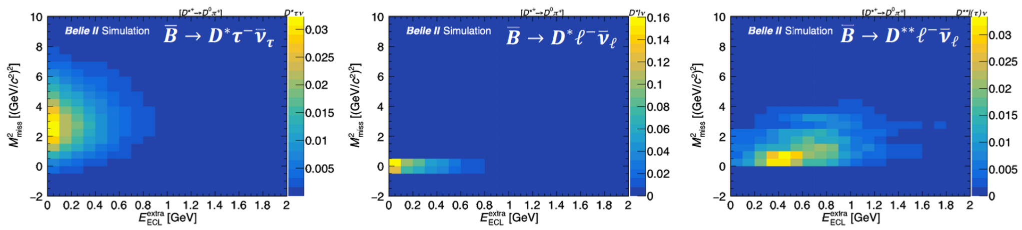

Fig. 1. – E_{ECL} vs $M^2_{\rm miss}$ distribution of three different samples. $\bar{B} \to D^*\tau^-\nu$ is on the left plot, $\bar{B} \to D^*\ell^-\nu$ is in the center, and $\bar{B} \to D^{**}\ell^-\nu$ is in the right plot.

To validate and correct shapes of the PDF used in the fit and normalizations, three control samples are employed. Background contributions from misidentified D mesons are corrected in distinct M^2_{miss} regions, using a sideband of the $\Delta M = M_{D^*} - M_D$ variable. A correction of 15 ± 7 MeV is applied to neutral cluster energies to address an observed excess at lower values in the control region with $M^2_{\mathrm{miss}} < 1$ GeV^2.

In the signal extraction fit, signal, normalization, and $\overline{B} \to D^{**}\ell^-\nu$ yields are left free, while background contributions from misidentified D mesons are constrained based on their calibration in the ΔM control region. Other backgrounds are fixed according to their predicted branching fractions.

The result obtained is

$$R(D^*_{\tau/\ell}) = 0.262^{+0.041+0.039}_{-0.035-0.032}$$

The main sources of systematic uncertainty are MC statistics and the E_{ECL} shape. Our result is consistent with both the Standard Model prediction and the world average [7].

4. – First Measurement of $R(X_{\tau/\ell})$ with Hadronic Tag

The study of the inclusive decay branching fraction ratio, denoted as $R(X_{\tau/\ell}) = \mathcal{B}(\overline{B} \to X\tau^-\overline{\nu})/\mathcal{B}(\overline{B} \to X\ell^-\overline{\nu})$ is another robust test of the Standard Model's assumption of heavy to light lepton universality. This ratio has been experimentally investigated for the first time at Belle II in [2].

Stringent lepton identification thresholds and rejection of specific hadron combinations mitigate fake lepton contributions and suppress secondary decays in the analysis. All remaining tracks and neutral ECL clusters are part of the hadronic system X, and its mass is denoted as M_X. Using the information on the X hadronic system, we can compute M^2_{miss}.

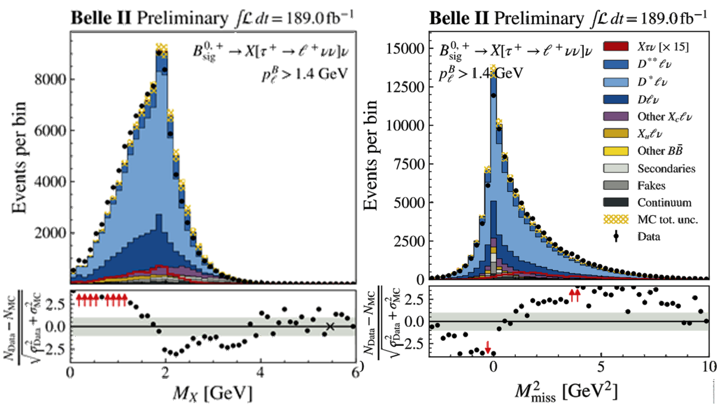

Fig. 2. – M_X (left) and M^2_{miss} (right) distributions before the corrections for $D \to K_L X$ are applied.

We observe a significant excess in low M_X and a deficit in the high range as shown in Fig. 2. This is mainly due to the incorrect modeling of $D \to K_L X$ decays. The disagreement is corrected with a proper data-driven reweighting, using a high-p_ℓ control region. Secondary and fake processes are reweighted in two-dimensional intervals of p_ℓ and M_X using the same-flavor control region, where both B had the same reconstructed flavor.

The signal is finally extracted using a two-dimensional binned maximum-likelihood fit in bins of the p_ℓ and M^2_{miss} variables.

We obtain

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016 \pm 0.036$$

The dominant systematic uncertainties are from the $D \to K_L X$ reweighting and the control region calibration.

5. – $|V_{ub}|$ measurement from simultaneous $B^0 \to \pi^- \ell^+ \nu_\ell$ and $B^+ \to \rho^0 \ell^+ \nu_\ell$ analyses

Finally, we present our recent analysis aimed at determining the magnitude of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{ub}|$. Our study focuses on simultaneous measurements of the decay channels $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$.
Our methodology involved the use of untagged measurements for both decay channels. By not employing flavor tagging, we simplify the experimental procedure and mitigate systematic uncertainties, thereby enhancing the precision of our measurements. In untagged analysis, the background suppression plays a very important role, since the number of events coming from the continuum $e^+e^- \to q\overline{q}$ is much higher than in the hadronic FEI analysis (as seen in the previous sections). The other predominant background is the $B \to X_c \ell \nu$ phenomenoun.
The final fit to obtain the yields and the $|V_{ub}|$ value is done using the variable M_{bc} and ΔE in q^2 bins. We conducted the evaluation of systematic uncertainties, considering factors such as detector efficiency, modeling of the signal and background, and uncertainties in external parameters.
Our results yield a precise value for $|V_{ub}|$, which is consistent with the current world averages and Standard Model predictions. The precise determination of $|V_{ub}|$ contributes to a more comprehensive understanding of the CKM matrix and provides a stringent test of the Standard Model.

6. – Summary and Future Prospects

These measurements represent significant steps towards precise testing of the Standard Model's lepton universality hypothesis. The results are currently in line with both the Standard Model and world averages. The Belle II experiment, leveraging the capabilities of the SuperKEKB collider, is expected to reduce systematic uncertainties in future measurements. This will be achieved through increased data volumes and improved theoretical models, including better understanding and incorporation of effects like $D \to K_L X$ decays. Future work includes extending these analyses to different decay channels, higher precision in lepton identification, and exploring other potential signs of new physics beyond the Standard Model.

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