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Measurements of electroweak penguin and lepton-flavour violating B decays to final states with missing energy at Belle and Belle II

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The Belle and Belle II experiments have collected a 1.2 ab^{-1} sample of $e^+e^- \to B\bar{B}$ collisions at a centre-of-mass energy corresponding to the $\Upsilon(4S)$ resonance. These data, with low particle multiplicity and constrained initial state kinematics, are an ideal environment to search for rare electroweak penguin B decays and lepton-flavour-violating B decays to final states with missing energy from neutrinos. Results from $b \to s\nu\bar{\nu}$ processes and their interpretation are presented. In addition, we present searches for the processes $B \to K^{*0}\tau^+\tau^-$. Finally, we present our search for the lepton-flavour violating decay $B^0 \to K^{*0}\tau^\pm\ell^\pm$, and $B^0 \to K^0_S\tau^\pm\ell^\pm$ where ℓ is an electron or muon.

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1. Introduction

Flavour-changing neutral currents (FCNC) are processes forbidden at tree level in the Standard Model (SM) and thus suppressed. The theoretical predictions in this sector are relatively precise. Therefore, these processes can serve as a probe to test the SM and potential access to New Physics (NP) if deviation from the SM predictions are observed.

Two particularly interesting categories of FCNC are the $b \to s\tau\ell$ and $b \to s\nu\bar{\nu}$ transitions. Several NP models couple differently with the three generations, and the coupling with the third one is often enhanced. Thus, τ lepton is a unique probe to test these models. In case also the second lepton is a τ ($b \to s\tau^-\tau^+$), the transition is allowed in the SM but strongly suppressed and an observation of the process will be the smoking gun of NP. In these proceedings we report the search for $B^0 \to K^{*0}\tau^+\tau^-$ decays [1] performed on the Belle II data. On the other hand, if the second lepton is a muon or an electron the process is lepton-flavuor violating (LFV) and is allowed only via neutrino mixing with an unmeasurable small rates. We report the searches of $B^0 \to K^0_S\tau^\pm\ell^\mp$ [2] and $B^0 \to K^{*0}\tau^\pm\ell^\mp$ [3] decays performed on the combined Belle and Belle II data. Finally, the $b \to s\nu\bar{\nu}$ transitions are allowed in the SM, with theory predictions more precise than $b \to s\ell^+\ell^-$ transitions. We report the search for $B \to X_s\nu\bar{\nu}$ decays performed on the Belle II data. In addition, we will describe a new reinterpretation technique and its application [4] on the $B^+ \to K^+\nu\bar{\nu}$ measurement [5] on Belle II data.

2. Belle II status and B-tagging techniques

Belle II [6] is the experiment of the SuperKEKB collider [7] at KEK, Japan. SuperKEKB is an asymmetric energy e^+e^- collider, which operates at centre-of-mass energy of 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ decays almost exclusively in $B\bar{B}$ pairs. Belle II between 2019 and 2022 (Run 1) collected about 400×10^6 $B\bar{B}$ pairs, equivalent to a integrated luminosity of 365 fb^{-1}. In the 2024 the Run 2 started and about 150 fb^{-1} have been collected so far. The Run 2 dataset is not used in the analyses described in these proceedings. The Belle II data sample can be combined with the 711 fb^{-1} sample of Belle experiment, to obtain a 1.1 ab^{-1} sample.

The clean environment and the well-known initial state produces ideal conditions to study rare B decays with missing energy in the final state. These decays are reconstructed using the B-tagging approach. In the exclusive B tagging one of the two B-meson (B_{tag}) is reconstructed in well known hadronic or semileptonic decay channels. Then, the B_{tag} and the knowledge of $\Upsilon(4S)$ initial state are used to infer information (kinematics, flavour, charge,...) on the second B-meson of the event which is reconstructed as the required signal (B_{sig}). This allows to recover the missing information from the neutrinos in the signal side. The Belle II main B-tagging algorithm is called Full Event Interpretation (FEI) [8]. It is a multivariate algorithm which uses a network of BDT to hierarchically reconstruct the B_{tag} starting from the tracks, vertices and calorimetric clusters of the events to identify the final state particles, the intermediate particles and finally identify the B meson. On the other hand, the inclusive B-tagging method reconstructs the signal B meson first and then interprets all the rest of information in the event as the second B. This approach guarantees higher reconstruction efficiency but a lower purity.

3. Lepton flavour violating $B \to K^{(*)}\tau\ell$ searches

The $B \to K^{(*)}\tau\ell$, $\ell = e, \mu$ transitions are lepton flavour violating (LFV) decays, forbidden in the SM. The lepton flavour conservation is not protected by any fundamental symmetry, and there are several NP models which predict LFV, introducing additional particles like Z' mediators or leptoquarks [9]. Moreover, the tensions in $b \to c\tau\nu$ [10] which imply Lepton Flavour Universality violation may be explained with NP models which predict LFV too. Finally, the recently observed tensions in $b \to s$ transitions [5] can be also explained with NP models which enhance LFV $B \to K^{(*)}\tau\ell$ at current sensitivity level [11].

The analysis strategy at Belle II for these class of decays exploits the τ recoil mass method. The hadronic B tagging is used to fully reconstruct the B_{tag} side of the event in hadronic decays with the FEI. Then, the $K^{(*)}$ and the charged lepton ℓ are reconstructed on the signal side. The τ is not explicitely reconstructed, but is indirectly identified constructing a recoil τ mass variable M_τ that exploit all the rest of the event information (B_{tag} and $K^{(*)}\ell$ system) :

$$M_\tau = [m_B^2 + M^2(K^{(*)}\ell) - 2(E_{\text{beam}}E_{K^{(*)}\ell} + |\vec{p}_{B_{\text{tag}}}||\vec{p}_{K^{(*)}\ell}|\cos\theta)]^{1/2}, \quad (1)$$

where m_B is the known B^0 mass; $M(K^{(*)}\ell)$, $E_{K^{(*)}\ell}$, $\vec{p}_{K^{(*)}\ell}$ are the mass, energy, and momentum of the system composed of the $K^{(*)}$ and ℓ, respectively; θ is the angle between $\vec{p}_{B_{\text{tag}}}$ and $\vec{p}_{K^{(*)}\ell}$. All the above quantities are defined with respect to the center-of-mass frame. The M_τ is used as a signal extraction variable. A parameteric fit is used to discriminate between the signal events which peaks at the τ mass, and background events which have a smooth distribution.

3.1 Search for $B^0 \to K^0_S\tau^\pm\ell^\pm$ decays

The search for $B^0 \to K^0_S\tau^\pm\ell^\pm$ decays [2] is performed on the combined Belle and Belle II datasets. The K^0_S is reconstructed in the $\pi^+\pi^-$ final state, with a purity above 98%. The τ is reconstructed requiring a track (t_τ) targeting the one-prong decays. In particular are identified the four channels $\tau \to e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, $\rho(\to \pi\pi^0)\nu$ which covers over 70% of the τ decays. Events with additional tracks in the rest of the events are vetoed to improve the purity. The signal events are identified by the combination of a K^0_S, a charged lepton ℓ and the track t_τ.

The residual dominant backgrounds are coming from $B\bar{B}$ events, and in particular from semileptonic $b \to c$ transitions. For the Same-Sign modes ($B^0 \to K^0_S\tau^-\ell^+$) the main background are $B \to D^{(*)}(\to K^0_S t^- X)\ell^+\nu$ decays, where the tracks from the D meson is misinterpreted as the τ decay track. For the Opposite-Sign modes ($B^0 \to K^0_S\tau^+\ell^-$) the correct sign configuration is reproduced by B^0 decays after mixing ($\bar{B}^0 \to D^{(*)+}\ell^-\bar{\nu}$). These backgrounds are reduced with an invariant mass cut on $m(K^0_S t_\tau)$. Additional invariant mass veto are applied for specific backgrounds like $B^0 \to K^0_S J/\psi(\to \ell^+\ell^-)$. The $B\overline{B}$ and continuum $q\overline{q}$ ($q = u, d, s, c$) backgrounds are further suppressed using a multivariate classifier based on Boosted Decision Tree (BDT). A dedicated BDT is trained for each of the four τ decay channels. The BDTs reject on average 90% of the background with a 90% signal retention. Several data control samples are used for the calibration of the efficiency. In particular, $B \to D^-\pi^+$ is used to calibrate the B_{tag} efficiency and $B^0 \to D^+_s D^-$ is used to calibrate the signal shape and BDT selection.

No significant signal is observed and thus upper limits (ULs) are set for the branching fractions ($\mathcal{B}$s) four channels, as reported in Table 1 (left). These are the first upper limits set in the $B^0 \to K^0_S\tau\ell$

channels. An example of the M_τ distribution and fit is shown in Fig. 1 (left). These limits are obtained using a signal efficiency evaluated from a simulated sample generated a with a three-body phase space model. However, efficiency distributions are provided as a function of the kinematic variables of the decay, to allow reinterpretation in different NP models. The main systematic uncertainties arise from the BDT selection, estimated on the $B^0 \to D_s^+ D^-$ control sample.

3.2 Search for $B^0 \to K^{*0}\tau^\pm\ell^\pm$ decays

The search for $B^0 \to K^{*0}\tau^\pm\ell^\pm$ decays [3] is performed similarly as the $B^0 \to K_S^0\tau^\pm\ell^\pm$ search. For brevity only the main differences are highlighted here. The signal is identified as the combination of a K^{*0} and a charged lepton ℓ. An additional track (t_τ) is required targeting the one-prong decay of the τ. However, no categorization based on the τ decay channel is performed and up to two additional tracks are allowed in the event. This inclusive τ reconstruction choices target a higher signal efficiency. The M_τ fit is performed simultaneously on the Belle and Belle II datasets without combining the reconstructed samples prior to the fit as is done in the $B^0 \to K_S^0\tau^\pm\ell^\pm$ search.

No significant signal is observed and thus ULs are set for the branching fractions ($\mathcal{B}$s) four channels, as reported in Table 1 (right). An example of the M_τ distribution and fit is shown in Fig. 1 (right). These are the first published limits of these channels obtained at B-factories and the first limit more in general for the electron channels[1]. The limits are obtained both using a three-body phase space model and with specific NP models. The resulting ULs are close of the phase-space ones. The efficiency distribution as a function of the kinematic variables of the decay are provided to allow further reinterpretations.

Table 1: Upper limits at 90% CL on the branching fractions for $B^0 \to K_S^0\tau^\pm\ell^\pm$ and $B^0 \to K^{*0}\tau^\pm\ell^\pm$ decays (from Ref. [2] and [3], respectively).

Decay mode	90% CL UL on $\mathcal{B}$
$B^0 \to K_S^0\tau^+\mu^-$	1.1×10^{-5}
$B^0 \to K_S^0\tau^-\mu^+$	3.6×10^{-5}
$B^0 \to K_S^0\tau^+e^-$	1.5×10^{-5}
$B^0 \to K_S^0\tau^-e^+$	0.8×10^{-5}

Decay mode	90% CL UL on $\mathcal{B}$
$B^0 \to K^{*0}\tau^+\mu^-$	2.9×10^{-5}
$B^0 \to K^{*0}\tau^-\mu^+$	6.4×10^{-5}
$B^0 \to K^{*0}\tau^+e^-$	4.2×10^{-5}
$B^0 \to K^{*0}\tau^-e^+$	5.6×10^{-5}

4. Search for $B \to K^{*0}\tau^+\tau^-$ decays

In the SM $\mathcal{B}(B \to K^*\tau^+\tau^-) = (0.98 \pm 0.10) \times 10^{-7}$ [13], beyond the current experimental reach. However, several NP models predict enhancements of these transitions. For instance NP models which accommodate lepton flavour universality tensions or $B^+ \to K^+\nu\bar{\nu}$ decays excess, also increase the $\mathcal{B}(B \to K\tau^+\tau^-)$ of several orders of magnitude [13].

The search for $B^0 \to K^{*0}\tau^+\tau^-$ decays [1] is performed on the Belle II dataset using the hadronic B-tagging method. Differently from $B \to K\tau\ell$ searches, the presence of two τ leptons spoils the possibility of having a peaking variable to extract the signal. The signal is reconstructed

[1] LHCb recently presented a preliminary result [12] which contains the most stringent ULs on the $B^0 \to K^{*0}\tau^\pm e^\pm$ decays

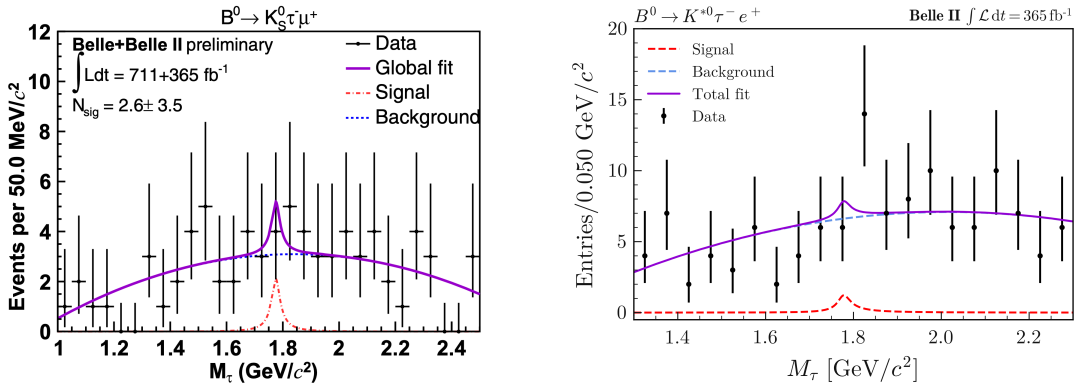

Figure 1: $M)\tau$ distribution and the fit results for $B^0 \to K^0_S \tau^- \mu^+$ on the combined Belle and Belle II data (left, from Ref. [2]) and for $B^0 \to K^{*0}\tau^- e^+$ on the Belle II data (right, from Ref. [3]).

targeting τ one-prong decays, reconstructing $\tau \to e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, $\rho(\to \pi\pi^0)\nu$ channels. The K^{*0} is reconstructed in the $K^+\pi^-$ channel. The signal candidates are subdivided in four categories according to the final state of the final states of the two τs: $\ell\ell$ (two leptonic decays), $\ell\pi$ (one leptonic and a pion prong), ρX (at least one $\tau \to \rho\nu$ decay) and $\pi\pi$ (two pion prongs). The main source of background are $B\bar{B}$ events, where the B_{tag} is properly reconstructed and the second B decays semileptonically. A BDT is trained for each category to discriminate between signal and the backgrounds. The main variables are the missing energy, the energy in the calorimeter not assigned to either B_{tag} or to the signal, the $q^2 = (p_{\tau^+} + p_{\tau^-})$, the invariant masses of the K^{*0} and each of the tracks from the τ decay.

The region of the BDT output between 0.4 and 1 is defined as signal region. The distribution of the BDT output $\eta(BDT)$ in this region is used as a fitting variable, performing a simultaneous binned maximum likelihood fit to the four categories. The fit results are shown in Fig. 2. The most sensitive is the $\ell\ell$ category. A 43 fb^{-1} sample collected at a center-of-mass energy 60 MeV below the $\Upsilon(4S)$ ("off-resonance") is used to calibrate the $q\bar{q}$ continuum background. A "same-flavour" control sample, with two B^0 or two $\bar{B}^0$ are identified because of mixing, is used to calibrate the $B^0\bar{B}^0$ background. The analysis is validated reconstructing $B^0 \to J/\psi K^{*0}$ events and replacing the tracks and the clusters from signal side with simulated $B^0 \to K^{*0}\tau^+\tau^-$ information, keeping the data B_{tag} and rest of event data information.

No significant signal is observed, thus an UL is set: $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8\times10^{-3}$ at 90% CL. This is a factor two improvement compared to the previous world's best limit by Belle [14], despite the sample used by Belle was two times larger. The main reasons of this improvement are the FEI efficiency, which is more performant than the B-tagging algorithm of Belle, and the use of the BDT.

5. Search for $B \to X_s\nu\bar{\nu}$ decays

The inclusive $\mathcal{B}(B \to X_s\nu\bar{\nu}) = (2.9\pm0.3)\times10^5$ in the SM [15]. The best UL for this branching fraction has been set by ALEPH collaboration [16] at 6.4×10^{-4} level. This analysis is part of the effort of Belle II of in-depth investigation of the $b \to s\nu\bar{\nu}$ sector, following the tension created by the evidence $B^+ \to K^+\nu\bar{\nu}$ decays [5]. In particular, the inclusive branching fraction is sensitive to different NP parameters compared to the exclusive $B \to K\nu\bar{\nu}$ [17].

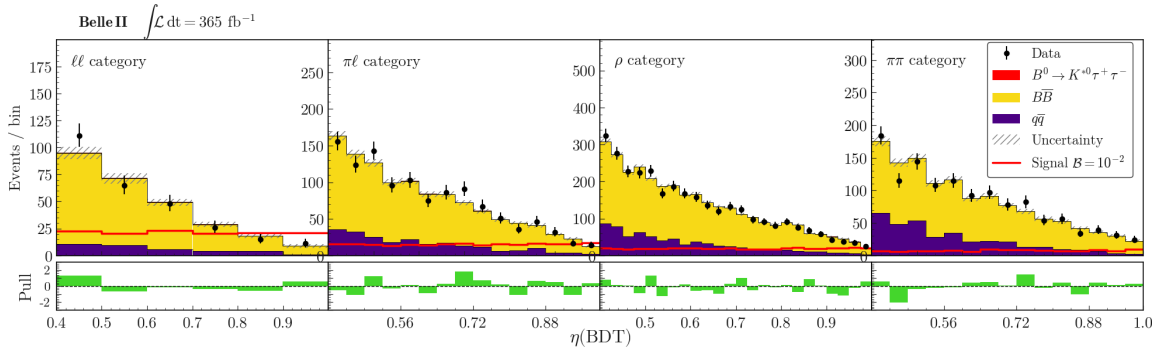

Figure 2: Distribution of $\eta(BDT)$ in the signal region for the four signal categories in data and post-fit prediction. The signal $B^0 \to K^{*0}\tau^+\tau^-$ fitted branching fraction is $(-0.15 \pm 1.01) \times 10^{-3}$. A scaled signal is overlayed. From Ref. [1].

The analysis is performed on the Belle II data sample using the hadronic B-tagging method. The signal is identified as the sum of 30 exclusive modes ($B \to Kn\pi$ with $n \leq 4$, $B \to 3K$, $B \to 3K\pi$). The backgrounds are suppressed with a BDT selection ($O(BDT) > 0.86$), where $O(BDT)$ is the BDT classifier output. The signal is extracted with a binned maximum likelihood fit to the bidimensional distribution of $O(BDT)$ and the invariant mass of the X_s system ($M(X_s)^{\text{reco}}$). The $q\bar{q}$ continuum background estimation is validated using the off-resonance sample. The $B\overline{B}$ background is validated using a sideband reverting the $O(BDT)$ cut and using an $M_{bc} = \sqrt{E^2_{\text{beam}} - \vec{p}^{\,2}_B}$ sideband.

No significant signal is observed, thus ULs in bin of $M(X_s)$ are set. At 90% CL $\mathcal{B}(B \to X_s\nu\bar{\nu}) < 2.5 \times 10^{-5}$ ($0 < M(X_s) < 0.6$ GeV), $< 1.0 \times 10^{-4}$ ($0.6 < M(X_s) < 1.0$ GeV), 3.5×10^{-4} (1 GeV $< M(X_s)$). The unrolled fitted distribution is shown in Fig. 3 (left). Combining all the invariant mass regions we obtain the UL $\mathcal{B}(B \to X_s\nu\bar{\nu}) < 3.6 \times 10^4$. This results are new world's best UL for this channel. The observed limits are compatible with the hadronic-tagged contribution to the measurement of the exclusive $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ [5]. The presented results are preliminary and current no reference is available.

6. $B^+ \to K^+\nu\bar{\nu}$ reinterpretation

The first evidence of $B^+ \to K^+\nu\bar{\nu}$ decays [5] has a 2.7σ tension with the SM, with a measured branching fraction about four times the expected one. This result received significant interest in the theory community, which provided several possible interpretations of the excess [11, 18, 19].

To facilitate the use of the Belle II results in a complete and correct way, a novel reinterpretation method has been developed [20]. The goal is to build a model-agnostic likelihood and reweight it to the desired model. Assuming q^2 to be the relevant kinematic variable of the model, and x to be the fitting variable, the central quantity is the number density $n(x) = L \int \varepsilon(x|q^2)\sigma(q^2)dq^2$, where L is the luminosity and ε the efficiency. Given a reference number density, like the SM one $n_0(x)$ we can obtain an alternative model number density reweighting it

$$n_1(x) = \sum_{q^2 \text{ bins}} n_{0,q^2}(x) w(q^2) \quad \text{with} \quad w(q^2) = \sigma_1(q^2)/\sigma_0(q^2). \tag{2}$$

We applied this method to the $B^+ \to K^+\nu\bar{\nu}$ analysis [4]. Here the fitting variable is $x = \eta(BDT2)\times q^2_{\rm rec}$ (the output of the selection BDT and the squared di-neutrino mass $q^2 = (p_B - p_K)^2$), while $n_0(x)$ is the SM signal. The result is reinterpreted in therm of Weak Effective Theory (WET) including dimension 6 operators. In this framework we introduce left (L) and right (R) scalar (S), vector (V) and tensor (T) Wilson coefficients, while in the SM only the $C_{\rm VL}$ coefficient is different from 0.

In Fig. 3 (right) the posterior distribution for each coefficient is shown. The WET signal has a significance of 3.3σ versus the background hypothesis only. Moreover, a non-zero tensor contribution and a larger vector contribution are preferred compared to the SM expectation. In addition, highest density credible intervals (the smallest possible credible intervals at a given probability) are provided. In conclusion, the main deliverables of this analysis are likelihood and the joint number density distribution of $B^+ \to K^+\nu\bar{\nu}$, together with the method and the tools to facilitate further reinterpretations.

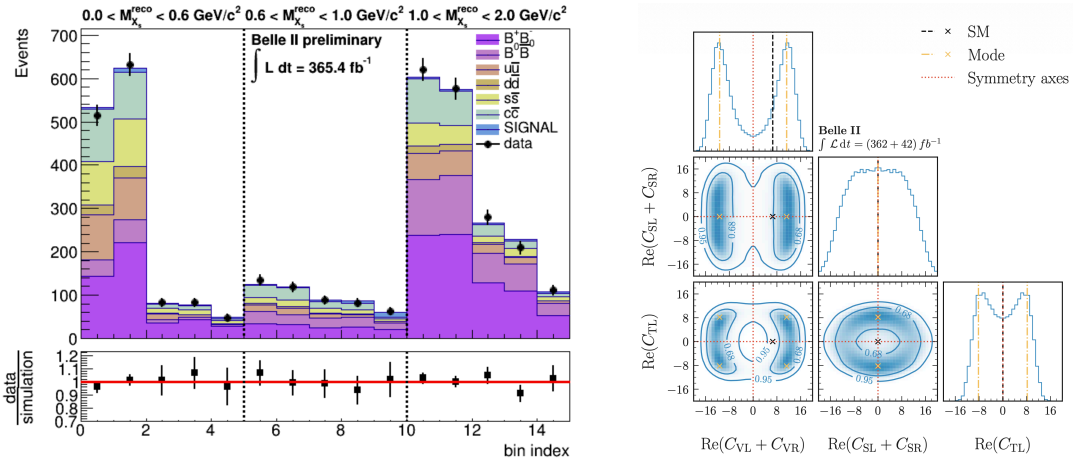

Figure 3: Unrolled post-fit distribution of the fit variables for $B \to X_s\nu\bar{\nu}$ search (left). Marginalized posterior for the Wilson coefficients included in the WET model as 1-dimensional (diagonal) and 2-dimensional (off-diagonal) sample density PDFs; the contours indicate the credible intervals; the SM and the posterior modes are highlighted (right, from Ref. [4])

7. Conclusion

Belle II is fully exploiting its unique sensitivity in channels with missing energy in the final state, on the 1.1 ab^{-1} Belle and Belle II combined dataset. Belle II is improving the upper limits in LFV $b \to s\tau\ell$ and $b \to s\tau^+\tau^-$ searches, exploiting better B-tagging performance and analysis tools. The $b \to s\nu\bar{\nu}$ investigation is ongoing, with a new world's best upper limit in the sum-of-exclusive $B \to X_s\nu\bar{\nu}$ search. A novel reinterpretation method is now available together with the number density for the $B^+ \to K^+\nu\bar{\nu}$ measurement, allowing the community to further test NP models.

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