First results and prospects for the $\tau \to e + \alpha$(invisible) LFV decay at Belle II

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In its first year of operation, the Belle II experiment at SuperKEKB collected approximately 10 fb^{-1}at the $\Upsilon(4S)$ resonance, with about 100 fb^{-1} expected by the end of 2020. This results in a sizeable sample of τ pairs, enabling detailed studies including searches for Lepton-Flavor-Violating (LFV) decays. One of the first channels where competitive limits are expected is the $\tau \to e\alpha$ process, where alpha is an invisible Goldstone boson. Here, the currently best limit has been obtained by ARGUS with an integrated luminosity of 475 pb^{-1}. Belle II is expected to improve on this result with the data recorded. This contribution will discuss selected analysis details and present first preliminary results and the prospects for future larger data sets.

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1. Introduction

While the Standard Model (SM) has been extremely successful in describing most of the observed phenomena below the TeV scale, it does not provide an explanation for features such as the small, but non-zero neutrino masses; the mass structure of charged leptons and quarks; the hierarchy of their mixing angles; and the staggering scale difference between the strong CP phase and the Cabibbo-Kobayashi-Maskawa (CKM) one. Attempts to address these issues often incorporate new Goldstone or pseudo-Goldstone bosons, some of which induce charged Lepton Flavor Violation (LFV) [1–8].

We present a sensitivity study for the search of the $\tau \to e\alpha$ decay, where α is an undetected particle. The study is performed in a model-independent fashion, with minimal assumptions on the nature of the α. The current upper limit on this process, as reported by the ARGUS Collaboration [9], is $Br(\tau \to e\alpha)/Br(\tau \to e\nu\bar{\nu}) < 1.5\%$ at 95 % C.L. for a massless α.

2. Belle II Experiment

Belle II is a second-generation B factory experiment in Tsukuba, Japan, coupled to the SuperKEKB accelerator: an energy-asymmetric electron-positron collider designed to reach an unprecedented instantaneous luminosity of 8.0×10^{35} cm^{-2}s^{-1}. Over its lifetime, Belle II aims to record 50 ab^{-1} of data, a factor of 50 more than its predecessor Belle, enabling an extensive physics program [10]. Belle II recorded approximately 64 fb^{-1} of data at the $\Upsilon(4S)$ resonance in the almost-full detector configuration ("Phase III") since the first collisions in 2019; of this sample, 34.6 fb^{-1} was reprocessed and available for analysis at the time of this study.

The study uses Monte Carlo samples produced with the most up-to-date detector conditions and beam background simulations at the time. Standard Model samples are taken from official production streams; signal samples are generated with one τ (the signal) decaying to $e\alpha$ using a phase space model, while the other (the tag) decays according to the general KKMC tau decay table. We generate separate sets with α mass of 0, 0.5, 0.7, 1, 1.2, 1.4 and 1.6 GeV/c^2. These values correspond to the ones sampled in by ARGUS [9].

3. Reconstruction

We focus on events displaying a 1x3 topology. Candidate events are identified by having only one charged track in the signal side ("1-prong"); while the tag side tau decays into three charged tracks ("3-prong") according to the SM. This tag is mainly composed of the $\tau \to 3h\nu$ + neutrals decays, which are dominated by the $\tau \to 3\pi(n\pi^0)\nu$ channel.

Physics events, both signal and background, are reconstructed using charged tracks originating from the interaction region, defined as ($|dz| < 3.0$ cm, $|dr| < 1.0$ cm). Photon candidates are required to fall within tracking acceptance (in order to reject contributions from spurious charged particles) and to have either $E(\gamma) > 200$ MeV; or form a pair with $E(\gamma) > 100$ MeV and $115 < \mathrm{M} < 152$ MeV/c^2 - a neutral pion candidate.

In order to separate our events into signal and tag hemispheres, we define the thrust axis $\widehat{n}_{\text{trust}}$ such that the value V_{thrust},

$$V_{\text{thrust}} = \sum \frac{|\overrightarrow{p}_i^{\text{CMS}} \cdot \widehat{n}_{\text{thrust}}|}{\sum \overrightarrow{p}_i^{\text{CMS}}} , \tag{1}$$

is maximized. Here $\overrightarrow{p}_i^{\text{CMS}}$ is the momentum of each particle in the event in the center-of-mass (CMS) frame.

The hemisphere corresponding to the signal τ should contain a single electron track, with the three tracks in the other hemisphere constituting the τ tag decay products. The electron is identified by requiring E/p>0.8, where E is the energy deposited by the particle in the Belle II calorimeter. The orthogonal requirement E/p<0.8 is applied to the tag in order to select hadron tracks.

Exactly four tracks are used for event reconstruction; events with additional tracks are discarded. Furthermore, in order to reject non-τ events from misidentified $q\bar{q}$ continuum, we apply a vertex fit requirement on the 3-prong side as well as veto events containing γ or π^0 candidates.

4. Background Suppression

Further background suppression is implemented using a cut-based optimisation. Since the mass of the α particle is unknown, we optimise the selection using the irreducible SM τ-pair background. We focus on three key variables, applying the corresponding cuts:

1. The event thrust ($0.8 < thrust < 0.99$);
2. The visible energy in the CMS frame ($2.0 < E_{\text{vis}}^{\text{CMS}} < 9.9$ GeV); and
3. The invariant mass of the 3-prong system on the tag side ($0.48 < M_{\text{Inv}}^{3\pi} < 1.66$ GeV/c^2).

Their distributions are shown in Fig. 1 prior to the selection being applied .

5. Electron Spectrum

The $\tau \rightarrow e\alpha$ channel is a two-body decay. Therefore, if we were to observe the electron momentum in the τ rest frame, its spectrum would be composed of a sharp monochromatic peak at a value dependent on the α mass. However, in order to boost into the τ rest frame, knowledge of the flight direction of the τ lepton is required; this is neither directly measured, nor can it be reconstructed from the final state due to the presence of invisible neutrinos. Instead, one can approximate the momentum of the τ and boost into a τ *pseudo*-rest frame.

Two approaches have been considered in this study. In both cases we assume that in the CMS system the τ energy, E_τ, can be approximated with the collider beam energy E_{beam} up to initial-state radiative corrections:

$$E_\tau = E_{\text{beam}}. \tag{2}$$

In what we call the *ARGUS* method, we approximate the flight direction of the tag τ with the momentum vector of the 3-prong system, thus obtaining:

$$\hat{p}_\tau^{\text{signal}} = -\hat{p}_\tau^{\text{tag}} \approx -\frac{\vec{p}_{3\text{h}}}{|\vec{p}_{3\text{h}}|}. \tag{3}$$

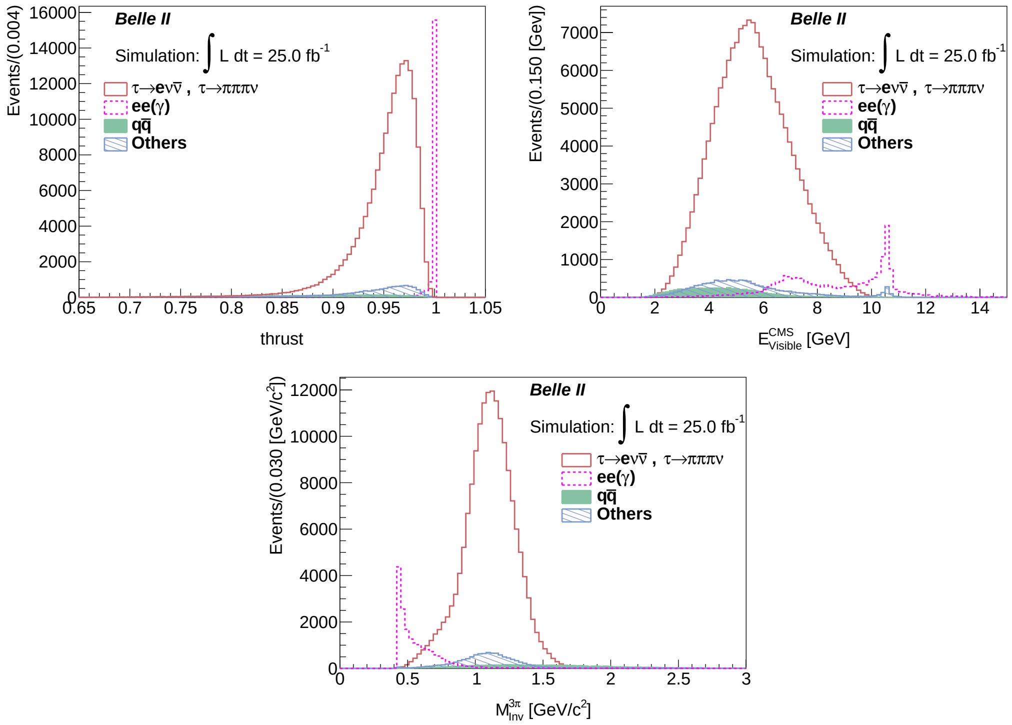

Figure 1: Event thrust (left), visible energy in the center of mass system (right) and invariant mass of the 3-prong system (bottom) for 1x3 τ-pair decays as well as other SM background sources.

This was the method used in [9]. Alternatively, one can approximate the flight direction of the signal τ using the reconstructed thrust vector:

$$\widehat{p}_\tau \approx \widehat{n}_{\text{thrust}}. \tag{4}$$

We call this the *thrust* method. Spectrum distributions for the two approaches are shown in Fig. 2; all selections discussed in previous sections are applied.

6. Sensitivity Estimate

Once the appropriate frame for the analysis is defined, the upper limit sensitivity is estimated with a template-based analysis using a modified frequentist method [11].

Independently of the chosen pseudoframe approximation x, data F can be modeled as:

$$F(x) = N_\alpha \times f_\alpha(x) + N_{e\nu\bar{\nu}} \times f_{e\nu\bar{\nu}}(x) + N_{\text{bkg}} \times f_{\text{bkg}}(x), \tag{5}$$

where N_i is the number of events corresponding to the i-th sample, and f_i are corresponding templates extracted from Monte Carlo. In our case it is useful to consider the relative branching fraction as our parameter of interest for the fit:

$$poi \equiv \frac{Br(\tau \to e\alpha)}{Br(e\nu\bar{\nu})} = \frac{\epsilon_{e\nu\bar{\nu}}}{\epsilon_\alpha}\frac{N_\alpha}{N_{e\nu\bar{\nu}}} \tag{6}$$

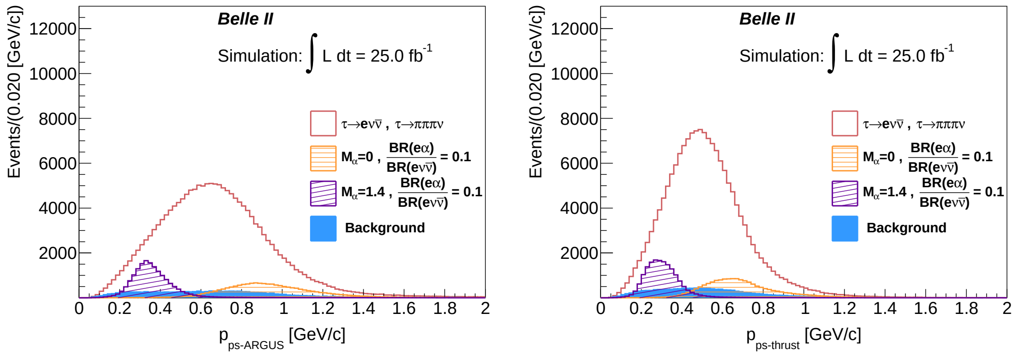

Figure 2: Distributions of the electron momentum in the τ pseudo-rest frame determined with the *ARGUS* method (left) and with the *thrust* method (right). The contributions shown are the SM $\tau \to e\nu\bar{\nu}$ decay; two example $\tau \to e\alpha$ simulations produced with $M_\alpha = 0$ and 1.4 GeV/c^2 respectively, normalised to $\mathcal{B}(\tau \to e\alpha)/\mathcal{B}(\tau \to e\nu\bar{\nu}) = 0.1$; and the remaining background from all other SM processes.

as several common uncertainties will cancel out. Here ϵ_i combines efficiencies and detector acceptances; we treat it as a nuisance parameter.

We therefore rewrite Eq. 5 as:

$$F(x) = \frac{\epsilon_\alpha}{\epsilon_{e\nu\bar{\nu}}} \times N_{e\nu\bar{\nu}} \times poi \times f_\alpha(x) + N_{e\nu\bar{\nu}} \times f_{e\nu\bar{\nu}}(x) + N_{\text{bkg}} \times f_{\text{bkg}}(x) \tag{7}$$

The values of N_i and ϵ_i used here are taken from simulation studies; in a final analysis, they would instead come from auxiliary measurements.

We perform the study under the conservative assumption of an integrated luminosity of 25 fb^{-1} treating simulated SM samples as pseudo-data, and estimate an upper limit sensitivity at the 95% CL. Systematic uncertainties are not included at this stage. The results are summarized in Tab. 1 and Fig. 3.

M(α) [GeV/c^2]	Argus (1995)	"Argus" method	"Thrust" method
0	0.015	0.0025	0.0016
0.5	0.017	0.0028	0.0025
0.7	0.024	0.003	0.0031
1.0	0.036	0.004	0.004
1.2	0.034	0.005	0.005
1.4	0.025	0.003	0.004
1.6	0.006	0.001	0.0009

Table 1: Current best published $Br(\tau \to e\alpha)/Br(e\nu\bar{\nu})$ upper limits [9] compared to the estimated sensitivity, for different values of the α mass.

7. Conclusion

In the current state of this study, the two approaches to approximating the τ pseudoframe display equivalent performance. In either case Belle II already shows the potential to improve the $\tau \to e\alpha$ measurement by approximately one order of magnitude; incorporating the full 2020 dataset

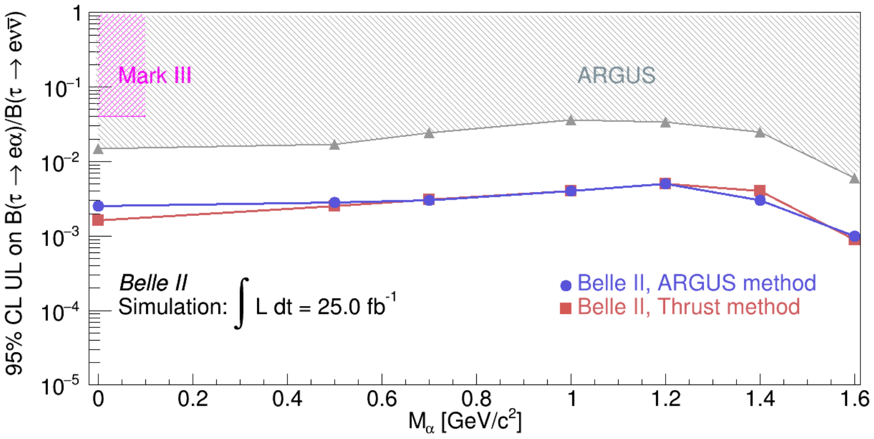

Figure 3: Estimated Belle II sensitivity to the $Br(\tau \to e\alpha)/Br(e\nu\bar{\nu})$ upper limit at 95% CL, assuming 25 fb^{-1} luminosity. Systematic uncertainties are not included. Previous measurements included for reference

will allow even further improvement. Studies are ongoing to refine the statistical methods, evaluate systematic uncertainties and incorporate the $\tau \to \mu\alpha$ channel.

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