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Direct searches for new physics at the $e^+ - e^-$ B-factories

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B-Factories are versatile machines which physics output shed light on many aspects of high precision physics in the last decade. In the following we will report about the most recent results in direct searches for new physics performed by BaBar and Belle collaborations. The results presented come from a wide range of topics from b-physics to τ physics, and bottomonium decay in new axion-like or higgs-like particles.

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1. Introduction

B-factories have been operating over the last ten years, with both BaBar and Belle [1] reaching record luminosities and recording the two largest samples of B meson and τ lepton decays ever recorded, consisting of data samples, taken around $\Upsilon(4S)$ resonance energy, of 486 fb^{-1} and 798 fb^{-1} respectively. The two collaborations recorded also data with different center of mass energies, broadening their reach for new physics: BaBar recorded 30 fb^{-1} around $\Upsilon(3S)$ resonance and 14 fb^{-1} around $\Upsilon(2S)$ in order to study in Υ decays; Belle recorded 121 fb^{-1} around the $\Upsilon(5S)$ resonance, making it possible to study B_s physics.

2. New Physics in B decays: $B \to K^{(\star)} \nu\bar{\nu}$

The Standard Model (SM) predicts small branching fractions (BF) for $B \to K^{(\star)}\nu\bar{\nu}$, with high precision: $\mathscr{B}(B \to K^{\star}\nu\bar{\nu}) = (6.8^{+1.0}_{-1.1}) \times 10^{-6}$ and $\mathscr{B}(B \to K\nu\bar{\nu}) = (4.7 \pm 0.7) \times 10^{-6}$ [2], which are below the present experimental sensitivity. On the other hand, many new physics (NP) models predict enhancements in the BF: the BF is expected to be 5 times larger if supersymmetric particles are present in loops, while decays with dark matter candidates in the final state (i.e. $B \to K^{(\star)}SS$, where S are WIMPS with mass less than two GeV) are expected to have BF up to an order of magnitude greater than SM prediction [3].

Both BaBar and Belle collaborations put limits on $B \to K^{(\star)}\nu\bar{\nu}$. Belle performed an analysis using a 492 fb^{-1} data-sample with a fully reconstructed B tagging method, reconstructing the tagging B from its hadronic decays. In order to reduce backgrounds particle identification (PID) was applied on K and πs coming from K_S, further selection was applied on the number of π^0 and on the unassociated neutral energy deposits. The main background consist of $b \to c$ transition, which is reduced selecting only Ks with large momenta; events with particles lost along the beam pipes are rejected using missing momentum and track polar angle information. Results [4] are shown in Tab. 1.

Table 1: Results for $B \to K^{(\star)}\nu\bar{\nu}$ searches at the B-Factories. Belle performed searches using only hadronic tagging, while for BaBar both SL and HAD tags were used for $B \to K^{\star}\nu\bar{\nu}$ searches: both results are presented, along with their combination. Upper Limits (UL) are shown in units of 10^{-5}.

Channel	Belle		BaBar			
	$\mathscr{L}$ (fb^{-1})	UL	$\mathscr{L}$ (fb^{-1})	UL (had)	UL (SL)	UL
$B \to K^{0\star}\nu\bar{\nu}$	491	34	413	11	18	8
$B \to K^{+(\star)}\nu\bar{\nu}$		14		21	9	
$B \to K^{0}\nu\bar{\nu}$	491	16	413		5.6	1.4
$B \to K^{+}\nu\bar{\nu}$		1.5			1.3	

BaBar made two separate analysis for $B \to K^{\star}\nu\nu$ [5], and for $B \to K\nu\nu$ [6]. $B \to K^{\star}\nu\nu$ analysis was made reconstructing the tagging B-meson both in its semileptonic decays (SL-tag) and hadronic decays (HAD-tag), the signal yield was obtained using a fit to the non associated neutral energy deposit in the SL-tag case, while a fit to a Neural Network output variable was used for HAD-tag sample. Since no selection is applied on neutrino kinematics the measurement this is the first model independent measurement for this BF. $B \to K\nu\nu$ search was made using only SL-tag, for $B^+ \to K^+\nu\nu$ along the full BF measurement, partial BF were measured for different momentum ranges of the K^+ ($p(K^+) < 1.5$ GeV$/c$ and $p(K^+) > 1.5$ GeV$/c$). Results are shown in Tab. 1.

3. Lepton Flavor Violation in τ decays

Lepton Flavor Violation (LFV) involving charged leptons has never been observed, and stringent experimental limits exist for both μ and τ decays, on the other hand results from ν oscillations show that LFV does indeed occur, although BF for charged leptons in SM have an expected rate of $\mathscr{O}(10^{-40})$. Many NP models predict BF larger than $\mathscr{O}(10^{-10})$, which are within present experimental sensitivities. An observation of LFV in τ decays would be a clear signature of NP, while improved limits provide further constraints on theoretical models.

Both BaBar and Belle performed searches for LFV in τ decays. In order to look for LFV, events with low charged multiplicity are selected, and the event space is divided in two non overlapping hemispheres bisecting the event space with a plane orthogonal to the thrust axis, passing through the interaction poing. Each track is assigned to the one of the two hemispheres depending on their direction. The two hemispheres are called the tag side (where SM τ decay is observed) and the signal side (where LFV decay product are expected). Both collaborations performed blind analyses, with background reduction obtained by using PID, kinematic information, and in some cases (as for BaBar $\tau \to \ell\gamma$ analysis) multivariate algorithms. The selection is optimized independently for each channel: BaBar collaboration optimized the selection in order to obtain the best expected UL, while Belle collaboration performed an optimization to get the best discovery significance for their analyzes. The number of expected background events in the blinded signal regions is extrapolated from unblinded sidebands, and the UL is measured using a modified frequentist approach that accounts for systematics errors. Results for the latest searches of LFV in τ decays are summarized in Tab. 2.

Table 2: Results for LFV searches in τ decays, luminosity, efficiency and UL is shown for each channel.

Belle					BaBar				
$\tau \to$	$\mathscr{L}$ (fb^{-1})	ε (%)	UL (10^{-8})		$\tau \to$	$\mathscr{L}$ (fb^{-1})	ε(%)	UL (10^{-8})	
$e^-e^+e^-$	782	6.0	2.7	[7]	$e^-e^+e^-$	468	8.6	297	[8]
$\mu^-e^+e^-$		9.3	1.8		$\mu^-e^+e^-$		8.8	2.2	
$\mu^+e^-e^-$		11.5	1.5		$\mu^+e^-e^-$		12.6	1.8	
$e^-\mu^+\mu^-$		6.1	2.7		$e^-\mu^+\mu^-$		6.4	3.2	
$e^+\mu^-\mu^-$		10.1	1.7		$e^+\mu^-\mu^-$		10.2	2.6	
$\mu^-\mu^+\mu^-$		7.6	2.1		$\mu^-\mu^+\mu^-$		6.6	3.3	
$e K_S$	671	10.2	2.6	[9]					
μK_S		10.7	2.3		$e\gamma$	516	3.9	3.3	[10]
$e K_S K_S$		5.8	7.1		$\mu\gamma$		6.1	4.4	
$\mu K_S K_S$		5.1	8.0						

4. Lepton Flavor Violation in Υ(2S) and Υ(3S)decays

BaBar recorded the largest samples of Υ(3S) and Υ(2S) decays (28.0 fb^{-1} and 13.6 fb^{-1} respectively). Υ(nS) decays have been used to search for LFV in $\Upsilon(\mathrm{nS}) \to \ell\ell'$ decay, which are as sensible as τ decays to NP. Four channels have been studied, looking at $e\tau$ and $\mu\tau$ final states for both Υ(3S) and Υ(2S). The LFV event signature is composed of one energetic lepton (either e or μ) and a τ reconstructed through leptonic or hadronic ($\tau \to \pi\pi^0(\pi^0)$) decays, the selection is partially common to the four channels with differences regarding mainly PID and τ-daughters kinematics. The main background is composed by BhaBha, μ-pairs, and τ-pairs. In order to calculate the BF an unbinned maximum likelihood fit was performed to determine signal and background yields, the discriminating variable is the ratio between the primary lepton (i.e. e or μ coming from Υ) momentum and the beam energy, different PDF were used for BhaBha and muon pairs, hadrons, and τ decays, the BF is calculated as $BF = N_{SIG}/(\varepsilon_{SIG} \times N_{\Upsilon(\mathrm{nS})})$. The main systematics uncertainties on BF measurement arise from the choice of the PDF shapes, due to the limited statistics in the selected sample. The results are reported in Tab. 3 [11].

Table 3: Results for LFV searches in Υ decays, systematical error is noted first followed by systematic error, the last column shows the improvement with respect to previous measurements made by CLEO collaboration. UL for $\Upsilon(2\mathrm{S}) \to e^{\pm}\tau^{\mp}$ and $\Upsilon(3\mathrm{S}) \to e^{\pm}\tau^{\mp}$ were measured for the first time

	$\mathscr{B}(10^{-6})$	UL (10^{-6})	Improvement
$\mathscr{B}(\Upsilon(2\mathrm{S}) \to e^{\pm}\tau^{\mp})$	$0.6^{+1.5+0.5}_{-1.4-0.6}$	< 3.2	First
$\mathscr{B}(\Upsilon(2\mathrm{S}) \to \mu^{\pm}\tau^{\mp})$	$0.2^{+1.5+1.0}_{-1.3-1.2}$	< 3.3	×5.5
$\mathscr{B}(\Upsilon(3\mathrm{S}) \to e^{\pm}\tau^{\mp})$	$1.8^{+1.7+0.8}_{-1.4-0.7}$	< 3.2	First
$\mathscr{B}(\Upsilon(3\mathrm{S}) \to \mu^{\pm}\tau^{\mp})$	$-0.80.2^{+1.5+1.4}_{-1.5-1.3}$	< 3.3	×3.7

5. Search for Higgs-like particle in Υ(2S) and Υ(3S) decays

Υ(nS) decays provide also a great probe in the searches for light Higgs and Axion-like particles through their decays. In fact Higgs mechanism, leading to electroweak breaking, predict an Higgs mass which is unstable after radiative corrections, two possible solution involving NP is the presence of a CP-odd Higgs singlet A^0, as predicted by Next to Minimal Supersymmetric SM [12] or an axion-like particle [13]. The former would solve the Higgs instability while the latter would provide a solution for the dark energy puzzle: so Υ(nS) could be of paramount importance two of the most sought-after answers in particle physics.

BaBar performed three different searches looking at the $\Upsilon(2\mathrm{S},3\mathrm{S}) \to \gamma A^0, A^0 \to \mu^+\mu^-$ [14], $\Upsilon(3\mathrm{S}) \to \gamma A^0, A^0 \to \tau^+\tau^-$ [15], and $\Upsilon(3\mathrm{S}) \to \gamma A^0, A^0 \to$ invisible [16]. Signal candidates for $\Upsilon(2\mathrm{S},3\mathrm{S}) \to \gamma A^0, A^0 \to \mu^+\mu^-$ are characterized by two charged tracks, of which at least one should be identified as a μ and one energetic photon, a kinematic fit of $\gamma\mu\mu$ is performed to further refine event candidate selection; a scan of $\mu\mu$ invariant mass is performed, looking for a peak resonance produced by an A^0, the background is estimated from data and accounts for all known resonances, the fit is performed in the $0.212\mathrm{GeV} < m_{A^0} < 9.3\mathrm{GeV}$ range by looking at 300 MeV-wide windows that are moved by 2-5 MeV steps, resulting in 1951 fitting points. The two τs, in $\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$ searches, are reconstructed through their leptonic decays: the event signature is then a pair of leptons along with an energetic photon, the main backgrounds come from radiative τ production and two-photon processes, and are reduced using 8 kinematic and angular variables, optimized for 5 different ranges of the photon energy E_γ. The search itself is performed looking for a signal, represented by a peak contribution of known width in the E_γ distribution over the $4.03\mathrm{GeV} < m_{A^0} < 10.30\mathrm{GeV}$ range, with simultaneous fit for the $\mathrm{ee}\gamma$, $\mu\mu\gamma$, and $\mathrm{e}\mu\gamma$ samples. $\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible is one of the most promising channels in SUSY scenarios with light LSP, the selection is focused on the search of a mono-energetic peak in the E_γ distribution, and relies on BaBar single photon trigger and neutral energy deposit quality, the search is performed for $m_{A^0} \leq 7.8\mathrm{GeV}$. We report in Tab. 4 the UL for all the searches performed by BaBar collaborations.

Table 4: Results for Higgs and Axion-like particle searches performed by BaBar collaboration.

	Energy Range	Upper Limit	
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	$0.212\mathrm{GeV} < m_{A^0} < 9.3\mathrm{GeV}$	$(0.26-8.3)\times 10^{-6}$	[14]
$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	$0.212\mathrm{GeV} < m_{A^0} < 9.3\mathrm{GeV}$	$(1.5-16)\times 10^{-5}$	[15]
$\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible	$m_{A^0} \leq 7.8\mathrm{GeV}$	$(0.7-31)\times 10^{-6}$	[16]

6. Conclusion

B-Factories have proved to be versatile machines for the searches for NP in over a decade, making it possible to measure,or at least set UL, with unprecedented sensitivities a wide array of rare processes. Many results were published in the last year and many more are to come in the near future in B physics, τ physics and Υ(nS) decays, which are going to shed more light on our understanding of SM and possibly on not yet discovered NP.

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