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Recent results from the BaBar experiment

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Summary. — We present some of the most recent results from the analysis of the full dataset collected by the BaBar experiment. They include searches for rare decays in the charm sector, the first evidence for the $h_b(1S)$ bottomomium state and results from the analysis of the data collected above the $\Upsilon(4S)$ mass.

PACS 13.25.Ft – Decays of charmed mesons.
PACS 13.20.Fc – Decays of charmed mesons.
PACS 13.20.Gd – Decays of J/Ψ, Υ, and other quarkonia.
PACS 13.20.He – Decays of bottom mesons.

1. – BaBar dataset

The BaBar experiment has run at the PEP-II b factory from 1999 to 2008. Most of the data ($430\,\text{fb}^{-1}$) have been collected at a center-of-mass (CM) energy corresponding to the $\Upsilon(4S)$ resonance mass. This sample allows to study B physics but also charm and tau properties, given the high cross section for the $c\bar{c}$ and $\tau^+\tau^-$ production from the e^+e^- initial state. Other CM energy regions have been investigated, resulting in $30.2\,\text{fb}^{-1}$ and $14.5\,\text{fb}^{-1}$ collected at the $\Upsilon(3S)$ and $\Upsilon(2S)$ mass, respectively. Those events, other than increasing the statistics of the $c\bar{c}$ and $\tau^+\tau^-$ samples, have been used for charmonium and bottomomium spettroscopy studies. Moreover, an energy scan above the $\Upsilon(4S)$ mass, has provided events in which also B_s mesons are produced.

2. – Charm physics

2˙1. *Search for* $D^0 \to \gamma\gamma$. – The $D^0 \to \gamma\gamma$ decay is mediated by a flavour changing neutral current which cannot happen through a tree level diagram in the Standard Model (SM). Moreover it is subject to an additional suppression due to the GIM mechanism. In the SM, short- and long-distance contributions sum up to give a branching fraction ($\mathcal{B}$) of the order of 10^{-8} [1], where the long-distance terms are dominant. In the Minimal Supersymmetric Standard Model the $\mathcal{B}$ can be enhanced by up to a factor 200 with respect to the SM prediction, thanks to gluino exchange [2]. From the experimental point of view, BaBar has performed the analysis using $407.5\,\text{fb}^{-1}$ [3]. Events with reconstructed

$D^* \to D^0\pi^+$ decays are selected and the $D^0 \to \gamma\gamma$ and $D^0 \to K_S\pi^0$ final states are searched for. The second is used as normalization channel in order to reduce systematic effects in common with the signal channel. The signal yield is extracted from a fit to the $\gamma\gamma$ invariant-mass distribution and three contributions are accounted for: correctly reconstructed signal events, combinatorial $\gamma\gamma$ pairs surviving the selection criteria, and $D^0 \to \pi^0\pi^0$ final states in which part of the neutral energy is lost. The resulting fitted signal yield is -6 ± 15 and is used to set an upper limit on the process under study. The main systematic uncertainties affecting the branching fraction upper limit are due to differencies between Monte Carlo simulation and data on the modelling of the photon reconstruction efficiency and on the distribution of the selection variables. Considering statistical and systematic uncertainties, the resulting upper limit on $\mathcal{B}(D^0 \to \gamma\gamma)$ is 2.4×10^{-6}, a factor of 10 improvement with respect to the pervious measurement [4]. Moreover, given that the $D^0 \to \pi^0\pi^0$ is the main background contribution to the $\gamma\gamma$ final state, its $\mathcal{B}$ has also been measured: $\mathcal{B}(D^0 \to \pi^0\pi^0) = (8.4 \pm 0.5) \times 10^{-4}$ with a 40% improvement on the precision with respect to previous analyses [4].

2·2. *CP violation measurement in* $D^+ \to K_S\pi^+$. – Violation of the CP symmetry in the charm sector is expected to be small in the SM but can be enhanced in several new physics models. In the $D^+ \to K_S\pi^+$ decay, the SM expected CP asymmetry is: $\mathcal{A}_{CP} = \frac{\Gamma(D^+\to K_S\pi^+)-\Gamma(D^-\to K_S\pi^-)}{\Gamma(D^+\to K_S\pi^+)+\Gamma(D^-\to K_S\pi^-)} = (-0.332 \pm 0.006)\%$ [4] and is mainly due to $K^0 - \bar{K}^0$ mixing. The experimental measurement is very challenging: since the CP effect is small, a high statistic sample and a good control of the systematic effects are needed. The main contribution to those is related to the detector-induced asymmetry which is carefully studied using a very high statistic control sample from data. The BaBar analysis is performed on $469\,\text{fb}^{-1}$ [5]. A signal yield, consisting of $(807 \pm 1) \times 10^3$ events, is extracted from a maximum likelihood fit to the $K_S\pi$ invariant-mass distribution. The CP asymmetry is extracted from the signal yield asymmetry $\mathcal{A} = \frac{N_{D^+}-N_{D^-}}{N_{D^+}+N_{D^-}}$, being N_{D^+} (N_{D^-}) the fitted number of D^+ (D^-) candidates. The latter asymmetry includes contribution from the CP asymmetry $\mathcal{A}_{CP}$, the forward-backward asymmetry in the $e^+e^- \to c\bar{c}$ process $\mathcal{A}_{FB}$ due to $\gamma^* - Z^0$ interference and high-order QED processes, and the detector-induced asymmetry. The third component is subtracted following a data-driven approach, the first two are determined simultaneously. They can be written as a function of the cosine of the polar angle of the D candidate in the CM frame $\cos\theta^*_D$ as:

$$\mathcal{A}_{CP}(|\cos\theta^*_D|) = \frac{\mathcal{A}(+|\cos\theta^*_D|) - \mathcal{A}(-|\cos\theta^*_D|)}{2}\,, \tag{1a}$$

$$\mathcal{A}_{FB}(|\cos\theta^*_D|) = \frac{\mathcal{A}(+|\cos\theta^*_D|) + \mathcal{A}(-|cos\theta^*_D|)}{2}\,. \tag{1b}$$

Splitting the $\cos\theta^*_D$ range in 10 bins, the forward-backward asymmetry as a function of $\cos\theta^*_D$ is measured; the $\mathcal{A}_{CP}$ central value, which does not depend upon this angular variable, is computed using a χ^2 minimization to a constant in the $|\cos\theta^*_D|$ range. The resulting CP measurement is $\mathcal{A}_{CP} = (-0.44 \pm 0.13 \pm 0.10)\%$ where the first error is statistic and the second systematic. The dominant contributions to the latter term arise from the contamination from K, e, μ in the control sample used to determine the detector-induced asymmetry. This introduces a small bias due to different selection and PID performancies for oppositely charged leptons and kaons. This measurement represents the most precise determination of a CP-violating quantity in the charm sector.

TABLE I. – *Signal yields, branching fractions, and decay constants for the leptonic D_s decays. The first uncertainty is statistical and the second systematic.*

Decay	Signal yield	$\mathcal{B}(D_s \to \ell\nu_\ell)$	f_{D_s} (MeV)
$D_s^- \to e^-\bar{\nu}_e$	$6.1 \pm 2.2 \pm 5.2$	$< 2.3 \times 10^{-4}$	
$D_s^- \to \mu^-\bar{\nu}_\mu$	275 ± 17	$(6.02 \pm 0.38 \pm 0.34) \times 10^{-3}$	$265.7 \pm 8.4 \pm 7.7$
$D_s^- \to \tau^-\bar{\nu}_\tau(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$	408 ± 42	$(5.07 \pm 0.52 \pm 0.68) \times 10^{-2}$	$247 \pm 13 \pm 17$
$D_s^- \to \tau^-\bar{\nu}_\tau(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	340 ± 32	$(4.91 \pm 0.47 \pm 0.54) \times 10^{-2}$	$243 \pm 12 \pm 14$

2˙3. *Leptonic D_s decays.* – Leptonic D_s decays happen through an annihilation and their decay rate is given by: $\Gamma(D_s \to \ell^-\nu_\ell) = \frac{G_F^2|V_{cs}|^2 m_{D_s}}{8\pi}(1 - \frac{m_\ell^2}{m_{D_s}^2})^2 m_\ell^2 f_{D_s}^2$. Such processes may be used to measure the D_s decay constant f_{D_s} in order to test the SM predictions. Prior to this measurement, the experimental estimation was 3 σ away from the theoretical one. The analysis has been performed by BaBar using a sample of 469 fb^{-1} [6]. An inclusive sample of D_s candidates is searched for in the recoil of a $DKX\gamma$ system from an $e^+e^- \to DKXD_s^*$ process, with $D_s^* \to D_s\gamma$, and being X a system of additional pions produced in the fragmentation. An ensamble of $(67.2 \pm 1.5) \times 10^3$ D_s candidates is determined by a binned fit to the distribution of the recoil mass. The leptonic final states are then searched for requiring one additional charged tracks identified as electron or muon plus missing energy associated to the undetected neutrino(s). The amount of missing energy allows to distinguish between tauonic and lighter lepton final states. The $D_s \to \tau\nu_\tau$ yield is determined from a fit to the neutral energy in the event not associated to the $DKX\gamma$ system. This quantity is expected to peak at zero for correctly reconstructed events since the only missing particle in the event should be a neutrino. The $D_s \to \ell\nu_\ell$ yields, being here $\ell = e, \mu$, are determined from a fit to the missing mass defined as $m_{miss}^2(DKX\gamma\ell) = (p_{e^+} - p_{e^-} - (p_D + p_K + p_X + p_\gamma + p_\ell))^2$. The results of the analysis in terms of signal yield, branching fraction and f_{D_s} measurement are reported in table I. For the electronic channel, no evidence for signal is found and an upper limit on the branching fraction at 90% confidence level is set. The combined measurement for the D_s decay constant is $f_{D_s} = (258.6 \pm 6.4 \pm 7.5)$ MeV. Using this measurement, the HFAG group computed an averaged experimental value of $f_{D_s} = (257.3 \pm 5.3)$ MeV [7] which is 1.6 σ away from the latest theoretical estimation from the HPQCD Collaboration [8].

3. – Bottomomium spettroscopy: first evidence for $h_b(1S)$

The $h_b(1S)$ bottomomium state is expected to be the axial vector partner of the already measured $\chi_{bJ}(1P)$ states [4]. An observation of the $h_b(1S)$ state allows to test the spin dependence of the $q\bar{q}$ potential which, in the non-relativistic approximation, predicts a mass splitting between the ^3P_J and $^1P_1$ hadrons close to zero. The $h_b(1S)$ should be produced in $\Upsilon(3S)$ decays, in association with a neutral pion, and then it is expected to dominantly decay in a $\eta_b\gamma$ final state. BaBar has reported the first evidence for the $h_b(1S)$ state using 28 fb^{-1} collected at the $\Upsilon(3S)$ mass [9]. From the experimental point of view a $\gamma\gamma$ pair compatible with coming from a π^0 is searched for in $e^+e^- \to \Upsilon(3S)$ events. An additional photon associated to a high multiplicity hadronic decay of the η_b is used to select h_b candidates. Such photon is expected to be monochromatic in the h_b

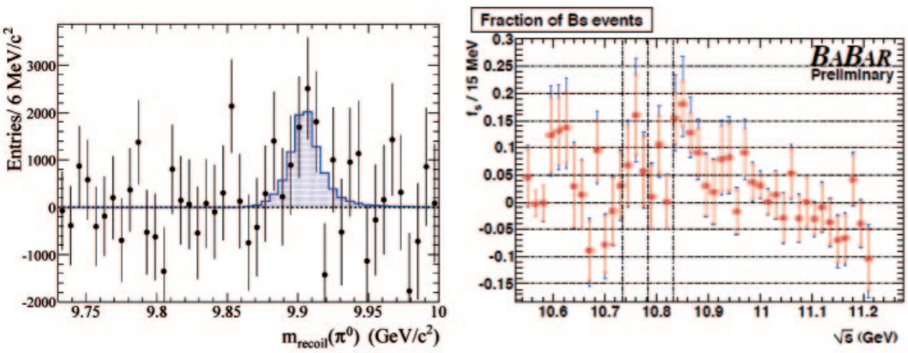

Fig. 1. – (Colour on-line) Left: $h_b(1S)$ search, the $m_{recoil}(\pi^0)$ spectrum after subtracting background; the shaded histogram represents the signal function resulting from the fit to the data (dots). Right: semileptonic B_s decays, f_s as a function of the CM energy; each point is associated to two error bars in the y-axis: the small one (red) corresponds to the statistical error only, while the big one (blue) incorporates the systematic uncertainties also.

rest frame and, given the h_b mass as the spin-weighted center of gravity of the $\chi_{bj}(1P)$ states, should have an energy around 490 MeV in the e^+e^- CM frame. Photons from π^0 decays are the main source of background for γ from the $h_b \to \eta_b\gamma$ decay. To reject them, each monochromatic photon is paired to another γ in the event and if the invariant mass of this pair is consistend with being produced in a π^0 decay the photon is rejected. A fit to the distribution of the mass recoiling against the π^0, $m_{recoil}(\pi^0)$, is used to extract the signal yield. Figure 1 (left panel) shows the background subtracted distribution for $m_{recoil}(\pi^0)$. The resulting fitted signal yield consists of $N_{sig} = (9154 \pm 2804 \pm 1082)$ events, establishing a 3.0 σ significance for signal evidence. The signal excess corresponds to a mass of $m_{h_b} = (9902 \pm 4 \pm 1)\,\mathrm{MeV}/c^2$ and to a mass splitting between the ${}^3P_J$ and ${}^1P_1$ of $\Delta M_{HF} = (2 \pm 4 \pm 1)\,\mathrm{MeV}/c^2$; both values are in agreement with the expectations.

4. – Above $\Upsilon(4S)$: semileptonic B_s decays

While B_d semileptonic (SL) decays have been extensively studied, semileptonic B_s decays are poorly known. A precise measurement of the branching ratio of such processes would be also useful for LHCb studies of B_s decay modes, whose measurement may be normalized to the inclusive SL branching fraction [10]. BaBar has exploited a dataset of $4.1\,\mathrm{fb}^{-1}$ collected above the $\Upsilon(4S)$ resonance to simultaneously measure the $\mathcal{B}(B_s \to X\ell\nu_\ell)$ and the B_s production rate f_s [11]. This is done by estimating the inclusive yield of ϕ mesons and ϕ meson + lepton and using the following relations:

$$(2a)\qquad N_{b\bar{b}} = R_b\left[f_s\varepsilon_{B_s} + (1-f_s)\varepsilon_{B_d}\right],$$

$$(2b)\qquad N_{\phi} = R_b\left[f_s\mathcal{P}(B_s\bar{B}_s \to \phi X)\varepsilon_{B_s,\phi} + (1-f_s)\mathcal{P}(B_d\bar{B}_d \to \phi X)\varepsilon_{B_d,\phi}\right],$$

$$(2c)\qquad N_{\phi,\ell} = R_b\left[f_s\mathcal{P}(B_s\bar{B}_s \to \phi\ell\nu_\ell X)\varepsilon_{B_s,\phi\ell} + (1-f_s)\mathcal{P}(B_d\bar{B}_d \to \phi\ell\nu_\ell X)\varepsilon_{B_d,\phi\ell}\right],$$

being R_b the ratio between the $e^+e^- \to b\bar{b}$ and $e^+e^- \to \mu^+\mu^-$ cross-sections; $\varepsilon_{B_s(B_d)}$ the efficiencies for selecting a B_s (B_d) candidate, $\varepsilon_{B_s(B_d),\phi}$ the efficiencies for selecting a ϕ in a B_s (B_d) final state, and $\varepsilon_{B_s(B_d),\phi\ell}$ the efficiencies for selecting a $\phi\ell$ pair in a B_s (B_d) final state; $\mathcal{P}$ the probability of having a $B\bar{B}$ final state containing a ϕ or a $\phi\ell$ pair. Combining eqs. (2b) and (2c), f_s as a function of the beam energy can be extracted; $\mathcal{P}(B_s\bar{B}_s \to \phi\ell\nu_\ell X)$ depends on $\mathcal{B}(B_s \to X\ell\nu_\ell)$, that can be extracted from eq. (2c), once f_s is determined. The number of B hadron events in eq. (2a) is computed by subtracting the amount of $e^+e^- \to q\bar{q}$ ($q = u, d, c, s$) events estimated from data control sample to the events passing the trigger. The inclusive ϕ (eq. (2b)) and $\phi\ell$ (eq. (2c)) yields are extracted from a fit to the KK and $KK + \ell$ invariant-mass distributions, respectively. This procedure allows to measure the SL B_s branching fraction as $\mathcal{B}(B_s \to X\ell\nu_\ell) = \left(9.9^{+2.6}_{-2.1}\,{}^{+1.3}_{-2.0}\right)\%$ where the first error is statistical and the second systematic. Figure 1 (right panel) shows the results for the f_s measurements as a function of the CM energy which are in agreement with the results reported by the Belle [12] and Cleo [13] Collaborations.

5. – Conclusions

Even if BaBar has ended its data taking in 2008, the data analysis is still very active and final results on the full dataset and with the final version of the reconstruction code are ongoing. Some of the most recent results have been discussed, showing improvements with respect to the existing measurements in the charm and B_s sectors along with the first evidence for the bottomomium state $h_b(1S)$.

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