Introduction to heavy flavour physics

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INTRODUCTION TO HEAVY FLAVOUR PHYSICS for MoriondQCD 2007 (..more on CP violation and CKM physics)

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This paper presents an introduction to the heavy flavour physics underlying some interesting results which will be presented at this conference. Special emphasis is put on measurements related to CP violation and the determination of the Unitarity Triangle parameters.

Keywords: Flavour Physics, CP Violation, CKM matrix, Unitarity Traingle, New Physics

1 Introduction

Accurate studies of the production and decays of beauty and charm hadrons are exploiting a unique laboratory for testing the Standard Model in the fermion sector, for studying QCD in the non-perturbative regime and for searching for New Physics (NP) through virtual processes. Furthermore the main objective of the elementary particle physics today is to search for evidence of physics beyond the Standard Model. The production of new particles is not the only way to search for. New particles can manifest themselves through virtual effects in decays of Standard Model particles such as B and D mesons and τ leptons. The effects due to the presence of NP are proportional to the ratio coupling/scale. If the scale is fixed (particles are discovered) precise measurements in the flavour sector allow to measure the couplings and so to have a knowledge on the flavour structure of the NP. On the other hand precise measurements could allow us to probe New Physics energy scales inaccessible at present and next-generation colliders. The "mot d'ordre" for this approach is precision.

In the last few years tremendous improvements have been achieved with the result of a precise determination of the CKM parameters and rare decays from B-factories together with new results from the Tevatron on B_s physics. Many additional measurements on B and D mesons properties (masses, branching fractions, lifetimes...) are necessary to constrain the Heavy Quark theories (Operator Product Expansion (OPE) / Heavy Quark Effective Theory (HQET) / Lattice QCD (LQCD)). The control of these theories is crucial for constraining the SM and looking for NP effects.

In the first part of this paper we show the new experimental results which are further constraining the Standard Model in the fermion sector, with emphasis on those which are the most sensitive to NP effects. We finally discuss the phenomenological impact of these measurements and we conclude on showing how to go on to try to use flavour physics as a very effective probe for NP.

2 Experimental results, mainly novelties as at Winter 2007.

Many new interesting results are presented to this conference, related to Unitarity Triangle (UT) angles, semileptonic and rare B decays and the recent evidence of the charm mixing. Few items are selected. Many others will be presented to this conference.

β *angle*. The mixing induced CP asymmetry, $a_{J\psi K_S}$, in $B^0_d \to J/\psi K_{S,L}$ decays allows to determine the angle β, with small theoretical uncertainties. The most recent measurements give a world average [1,2] $\sin(2\beta) = 0.675 \pm 0.026$. One of the two solutions : $\beta = (21.2 \pm 1.0)^\circ$ is consistent with the Standard Model. The determination of sin 2β gives so far the best determination of $\overline{\rho}$ and $\overline{\eta}$ parameters. New results on β are coming from the $B^0 \to D^0 h^0$ decay mode. The determination of β from these modes is not yet competitive with the previous one. Nevertheless together with $B \to J/\psi K\pi$ and $B \to D^* D^* K$ modes it helps in strongly disfavouring the solution of β corresponding to $(68.1 \pm 1.0)^\circ$.

α *angle*. The angle α can be obtained using the time-dependent analyses of $B^0 \to \pi^+\pi^-$, $B^0 \to \rho^+\rho^-$ and $B^0 \to (\rho\pi)^0$. In the absence of contributions from penguin diagrams, these decays give a measurement of $\sin 2\alpha$. Several strategies have been proposed to control this so-called "penguin pollution", which are mainly based on the use of an isospin analysis[3]. Measurements of branching fractions and CP asymmetries have been made in both the $B \to \pi\pi$ and $B \to \rho\rho$ systems [4].

To better constrain the penguin contributions the measurement of the branching fractions for the neutral modes is crucial. For this a very important result has been obtained from Babar measuring [5]: $Br(B^0 \to \rho^0\rho^0) = (1.07 \pm 0.33 \pm 0.19)\ 10^{-6}$. It is a 3.5σ evidence, and implies that the contributions from penguins in the $\rho\rho$ system are sizeable. Combining all the most recent results (including new results on $B \to \rho\pi$) we obtain $\alpha = [81, 111]^\circ U[159, 171]^\circ$ at 95% C.L. Selecting the SM solution: $\alpha = (93 \pm 8)^\circ$ [6].

γ *angle*. Various methods related to $B \to DK$ decays have been proposed to determine the UT angle γ [7], using the fact that a charged B can decay into a $D^0(\overline{D}^0)K$ final state via a $V_{cb}(V_{ub})$ mediated process. CP violation occurs if the D^0 and the $\overline{D}^0$ decay to the same final state. These processes are thus sensitive to the phase difference γ between V_{ub} and V_{cb}. Combining all the available measurements we get $\gamma = (82 \pm 20)^\circ$ with a π ambiguity [6]. The most precise results are coming from the Dalitz methods which consists in studying the interference between the $b \to u$ and the $b \to c$ transitions using the Dalitz plot of D mesons reconstructed into three-body final states. So far the only D^0 decay used was $D^0 \to K_s\pi^-\pi^+$. It will be important in future to control and reduce the error coming from the modelling of the D Dalitz decay. For this reason it is important to reconstruct other 3 bodies D decays . An important result from *BABAR* using the decay mode $D^0 \to \pi^- \pi^+ \pi^0$ gives $\gamma = (25 \pm 48)^\circ$.

$|V_{ub}|$. In a recent paper[8] it was observed that the determination of $|V_{ub}|$, using inclusive methods, was disfavoured by all other constraints at the 2.5σ level. This can come either from the fact that the central value of $|V_{ub}|$ from inclusive decays is too large, or from the smallness of the estimated error, or both. On the other hands $|V_{ub}|$ from exclusive decays has still large uncertainties. Moreover the problem has been recently worsened by the decrease of the value of $\sin(2\beta)$ determined by the direct measurements. At this conference new results are presented on both determinations. An interesting approach consists on using the universality of the shape function to link the spectrum (E_γ) of $B \to X_s \gamma$ decays with the one $(E_{lept.}, M_X)$ of $B \to X_u \ell \nu$ decays. Using the Babar data, it has been also shown that the value extracted for $|V_{ub}|$ is stable irrespective of the cuts on these observables and of the use of different theoretical approaches [9]. In general the most recent analyses confirm high value for $|V_{ub}|$ (for example $|V_{ub}|$=$(4.40 \pm 0.30(stat) \pm 0.47(syst) \pm 0.23(theo) 10^{-3}$ as quoted in[9]). This approach is interesting because part of the theoretical error is now absorbed in the statistical one.

Novelties also appeared on the exclusive analyses such as $(B \to \pi \ell \nu)$. The traditional solution to improve the S/B ratio was to cut on the quality of $p_{miss.}$ to have a good reconstruction for the neutrino. With the increase of the available statistics new analyses can be also performed with much worse S/B ratio (of about 0.1), keeping severe criteria on the identification of $\pi - \ell$ pair, but relaxing the criteria on p_{miss} and adjusting the cuts as a function of q^2. The results of that is an increase of more than a factor four in statistics. Babar has performed such analysis in 12 bins of q^2, obtaining $|V_{ub}|$=$(3.7 \pm 0.2 \pm 0.2^{+0.6}_{-0.4}(theo))10^{-3}$, which is the best single world determination of $|V_{ub}|$. The HFAG average [1] is $|V_{ub}|$=$(3.55 \pm 0.22^{+0.6}_{-0.4}(theo))10^{-3}$. To improve this determination more precise calculations of the form factors are needed.

β angle "with penguins".

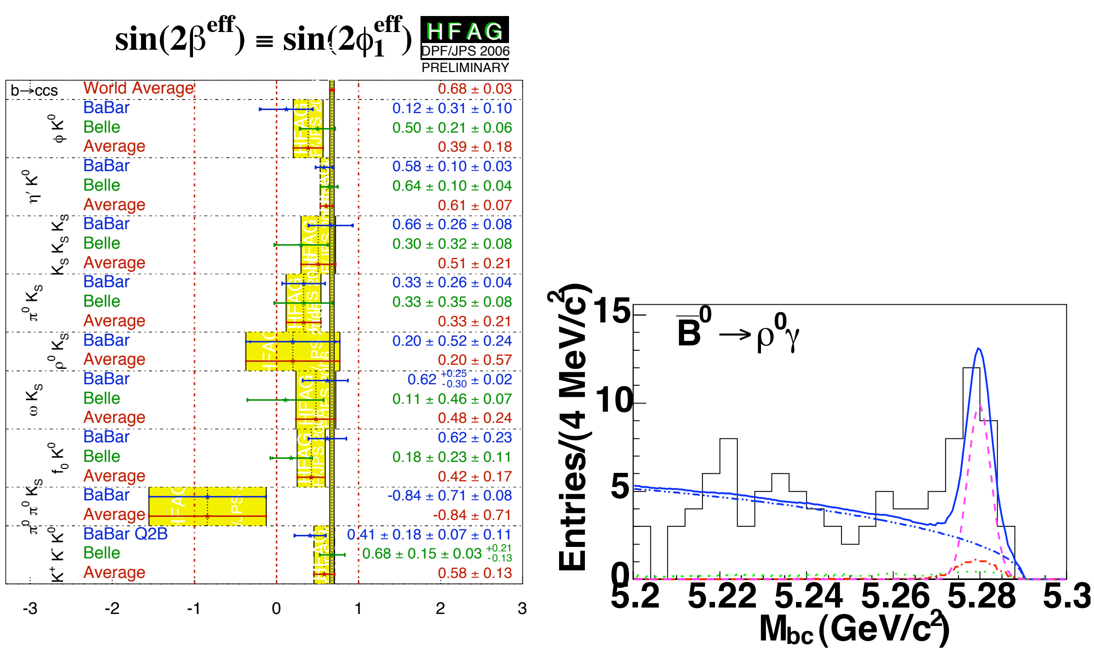

Figure 1: *Left plot : HFAG compilation of measurements of $sin(2\beta^{\rm eff})$ in decays dominated by $b \to s$ penguin amplitudes. Right plot : Signal for $B^0 \to \rho^0 \gamma$.*

Very interesting channels to search for New Physics effects in mixing-induced CP violation are those dominated by the $b \to s$ penguin transition [10]. In the SM the measurements of $sin2\beta$ should be approximately the same as the one measured with charmonium B decays up to hadronic corrections of $\sim$ 0.02–0.05 on $\sin(2\beta)$ (see, for example [11]). New Physics particles in the loops could produce significant deviation from Standard Model predictions. Quite few new results are presented at the winter conferences, with many channels now precisely measured : $B^0 \to \phi K^0$, and $B^0 \to K^0 \overline{K}^0 K^0$. For $B^0 \to \eta' K^0$. Each individual channel gives a result on $sin2\beta$ smaller then the SM one and a naive average gives : $sin2\beta_{eff.} = 0.53 \pm 0.05$ at about 2.5 σ from the SM value. The results are shown in Fig. 1.

Radiative decays. The radiative FCNC decays $b \to s\gamma$ and $b \to d\gamma$ are very sensitive probes of New Physics. The ratio of rates of $b \to d\gamma$ and $b \to s\gamma$ decays can be used to determine $|V_{td}/V_{ts}|$. The theoretically cleanest case is for the neutral modes, because weak annihilation contributes more significatively in the charged mode [12].

The current experimental world averages are $\mathcal{B}(B^0 \to \rho^0\gamma) = (0.91 \pm 0.19) \times 10^{-6}$ [13] and the signal for $B^0 \to \rho^0\gamma$ is shown in Fig. 1. From these results (using also the measured value of $\mathcal{B}(B^0 \to K^{*0}\gamma)$) we can extract $|V_{td}/V_{ts}| = 0.202 \pm 0.017(exp.) \pm 0.015(theo.)$. The theoretical error takes into account the ratio of $B \to V\gamma$ form factors and the remaining non-perturbative contributions [14].

Leptonic decays : $B \to \tau\nu$. Leptonic decay processes are described by annihilation diagrams and the rates of leptonic decays of the B^+ meson are proportional to $f_B^2 |V_{ub}|^2$, where f_B is the pseudoscalar constant. This channel is interesting because it is sensitive to New Physics and in particular to charged Higgs exchange in a scenario with large $\tan\beta$ [15].

Signals for $B^+ \to \tau^+\nu_\tau$ have been obtained [16], getting $B^+ \to \tau^+\nu_\tau = (1.31 \pm 0.48)\ 10^{-4}$, which compares with the value expected in SM of $B^+ \to \tau^+\nu_\tau = (0.85 \pm 0.13)\ 10^{-4}$ [8]. The experimental result has to be improved to become a significant test of new physics. Assuming the SM, the pseudoscalar constant can be extracted from this measurement to be $f_B = (237 \pm 37)$ MeV, which compares with $f_B = (189 \pm 27)$ MeV from lattice QCD calculations [8].

Evidence of D mixing. The highlight of the conference is the new result on charm mixing. *BABAR* finds evidence for oscillations in $D^0 \to K^+\pi^-$ with 3.9σ significance [17] by studying the proper-time distribution for Wrong Sign (WS) data ($D^0 \to K^+\pi^-$). The result is shown in Fig. 2.

Belle sees a 3.2σ effect in $D^0 \to K^+K^-$, with results using $D^0 \to K_S^0\pi^+\pi^-$ supporting the claim [18]. The world average of the mixing result gives [1] :

$$x_D = \left(8.5^{+3.2}_{-3.1}\right) \times 10^{-3} \qquad \text{and} \qquad y_D = \left(7.1^{+2.0}_{-2.2}\right) \times 10^{-3}.$$

where $x_D = \Delta M_D/\Gamma_D$ and $y_D = \Delta\Gamma_D/2\Gamma_D$. Contours in the (x_D, y_D) plane are shown in Fig. 2 The significance of the oscillation effect in the preliminary world averages exceeds 5σ.

This result suggests that charm mixing may be at the upper end of the range of Standard Model predictions. The interpretation of this result in terms of New Physics is limited by the theoretical uncertainty on the Standard Model prediction. Nevertheless interesting constraints on the mixing amplitudes and NP contributions have been already deduced [19]

3 Phenomenological impact

The recent results have further improved the determination of the UT parameters. Assuming the SM, in Fig. 3 we show the results of the new fit which includes all constraints.

The numerical results are : $\overline{\rho} = 0.164 \pm 0.029$; $\overline{\eta} = 0.340 \pm 0.017$

It is interesting to notice that the determination of the UT parameters from the measurements of CP violating quantities in the kaon (ϵ_K) and in the B sectors (UT angles) is now as precise as those obtained with the measurements of the sides (see Fig. 3)

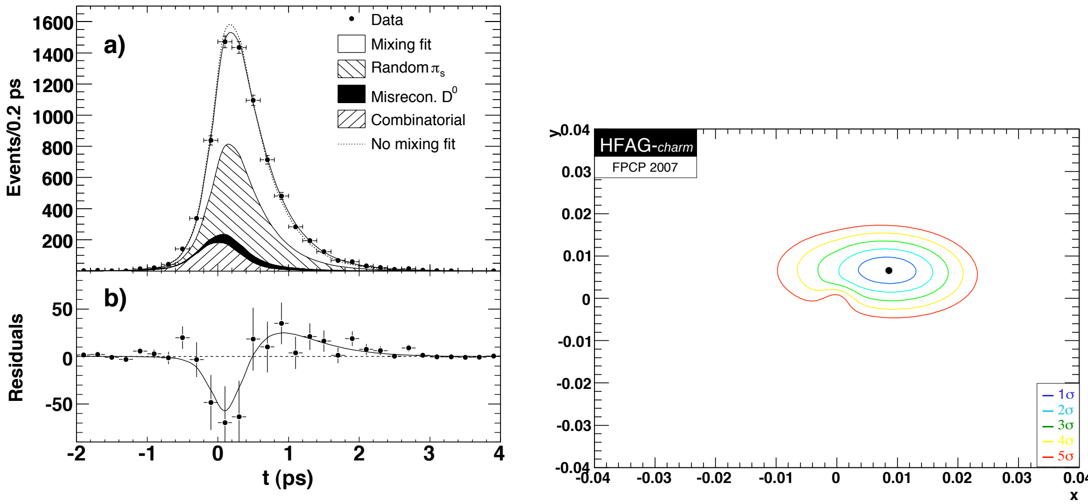

Figure 2: *Left plot : Babar result on D mixing. a) Projections of the proper-time distribution of combined* D^0 *and* $\bar{D}^0$ *WS candidates and fit result integrated over the signal region. The result of the fit allowing (not allowing) mixing but not CP violation is overlaid as a solid (dashed) curve. b) The points represent the difference between the data and the no-mixing fit. The solid curve shows the difference between fits with and without mixing. Right plot : likelihood contours in the* (x_D, y_D) *plane as obtained by HFAG*[1].

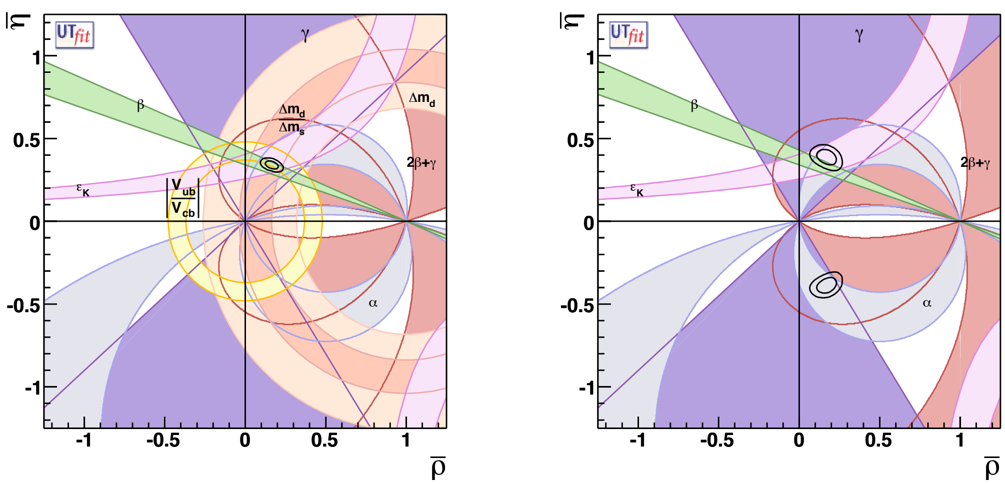

Figure 3: *Determination of* $\overline{\rho}$ *and* $\overline{\eta}$*. Left plot : constraints on* $|V_{ub}|\,/\,|V_{cb}|$, Δm_d, Δm_s, $|\varepsilon_K|$, β, γ, *and* α*. 68% and 95% total probability contours are shown, together with 95% probability regions from the individual constraints. Right plot : The contours at 68%, 95% selected by the measurements of* $|V_{ub}|/|V_{cb}|$, *Deltam*$_d$ *and* Δm_s *are compared to the bounds (at 95% probability) from the measurements of CP violating quantities in the kaon and in the B sectors.*

In addition the recent measurements performed at B factories and Tevatron allow for a simultaneous determination of the CKM parameters together with the NP contributions to $|\Delta F| = 2$ processes. In fact each of the mixing processes is described by a single amplitude and can be parameterized, without loss of generality, in terms of two parameters, which quantify the difference of the complex amplitude with respect to the SM one [20]. Thus, for instance, in the case of $B_q^0 - \bar{B}_q^0$ mixing we define

$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\rm eff}^{\rm full} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\rm eff}^{\rm SM} | \bar{B}_q^0 \rangle}\,, \qquad (q = d, s) \tag{1}$$

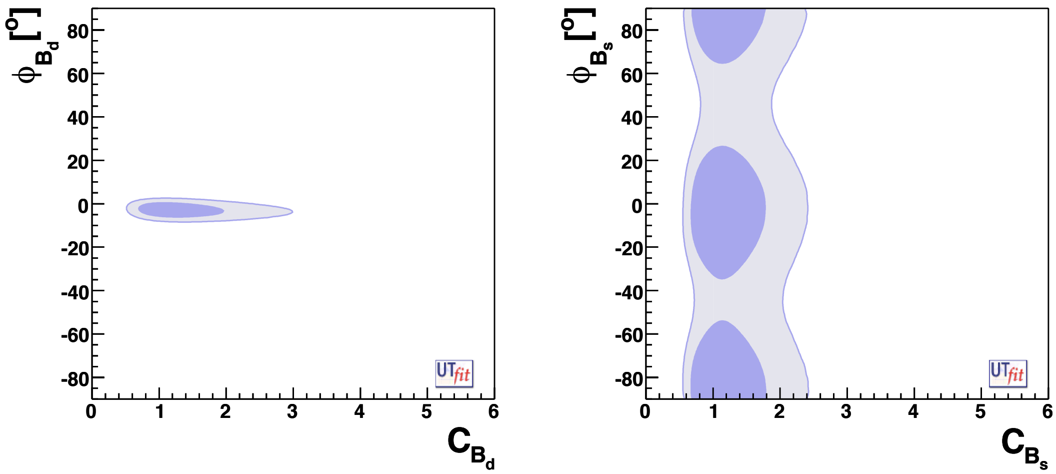

Figure 4: *The p.d.f.'s for ϕ_{B_d} vs. C_{B_d} (left) and ϕ_{B_s} vs. C_{B_s} (right). The darker and the lighter zones correspond respectively to 68% and 95% of the area.*

where $H_{\rm eff}^{\rm SM}$ includes only the SM box diagrams, while $H_{\rm eff}^{\rm full}$ includes also the NP contributions. In the absence of NP effects, $C_{B_q} = 1$ and $\phi_{B_q} = 0$ by definition.

The most important results are shown in Figs. 4 [22]. Two important conclusions can be drawn :

i) in the B_d sector we have already quite strong constraints on NP contributions which can be as large as the SM ones only if the SM and NP amplitudes have the same weak phase.

More generally we can conclude that NP should contribute no more than 20% with respect to the SM for a generic NP phase. In addition, the fit produces a nonzero central value for ϕ_{B_d} due to the difference in the SM fit between the angles and the side measurements.

ii) The measurement of Δm_s strongly constraints C_{B_s} which is now better known than C_{B_d}. ϕ_{B_s} starts to be constrained. This result is coming from several new measurements : the semileptonic asymmetry in B_s decays(A^s_{sl}, the dimuon charge asymmetry (A_{CH}), the measurement of the B_s lifetime from flavour-specific final states, the determination of $\Delta\Gamma_s/\Gamma_s$ from the time integrated analysis $B_s \to J/\psi\phi$ and the three-dimensional constraint on γ_s, the determination of $\Delta\Gamma_s$ and the phase ϕ_s of the B_s mixing amplitude from the time-dependent angular analysis of $B_s \to J/\psi\phi$ [21,22].

4 Conclusions and perspectives

Flavour physics is a very active research field. Many interesting results are presented at this conference: new and more precise determination of the UT angles, of $|V_{ub}|$, new results on radiative and purely leptonic decays which are very powerful instruments to look to NP... The highlight of the conference is the evidence of charm mixing. This result indicates that charm mixing is at the upper end of the range of Standard Model predictions and is already providing interesting constraints on the mixing amplitudes and NP contributions.

The Standard Model is still resisting against all these efforts to probe its validity limits. Nevertheless it has to be stressed that all the tests are at best at about 20% level. The next facilities can surely push these tests to a 1% or lower accuracy. In conclusions in Fig. 5 we show the regions on the $\bar\rho$-$\bar\eta$ plane selected by different constraints assuming the current measurement and precision expected at high luminosity B-factory (*Superb* is a B-factory collecting $75{\rm ab}^{-1}$) [23]. With the precision reached at *SuperB*, the current discrepancies would clearly indicate the presence of New Physics in the flavour sector !

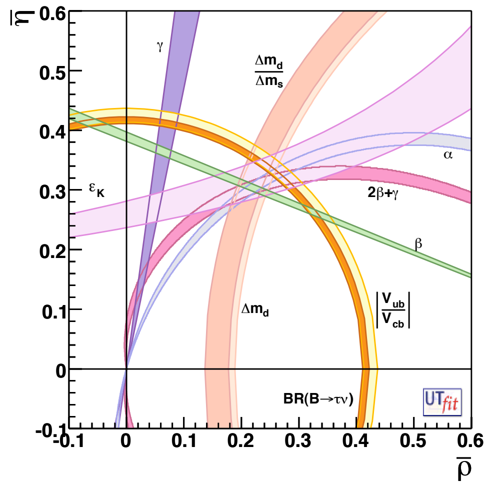

Figure 5: *Regions corresponding to* 95% *probability for* $\overline{\rho}$ *and* $\overline{\eta}$ *selected by different constraints, assuming present central values with errors expected at SuperB. .*

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