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New results on B-physics

Cibrán Santamarina Ríos*
Departamento de Física de Partículas, Universidade de Santiago de Compostela, Santiago de Compostela
E-mail: cibran.santamarina@usc.es

A review of the most important recent results on B-physics produced by the B-factories, the Tevatron and the LHC experiments is presented.

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*Speaker.

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1. Introduction

The Standard Model (SM) [1] provides an overall description of particle physics up to the energy scales probed in experiments so far, namely hundreds of GeV. In spite of the phenomenological success, the SM is not satisfactory for some reasons. One relevant example is the origin of the matter-antimatter asymmetry in our universe. In 1967 A. Sakharov proposed three conditions for our universe to be primarily composed of matter [2]. One of them is the requirement of violation of the Charge-Parity (*CP*) symmetry. Some years later, in 1973 M. Kobayashi and T. Mashkawa proposed that *CP* violation (CPV) could be accomplished through the weak interaction if a third, at the time undiscovered, family of quarks existed [3]. They predicted the existence of the bottom and top quarks and the possibility that flavour transitions mediated by the weak force violated *CP* symmetry. Experimentally this can be probed in the weak decays of hadrons where CPV arises from a single phase in a quark mixing (CKM) matrix, testing the Yukawa couplings to the quarks.

The existence of the bottom and top quarks and CPV have been fully confirmed and Kobayashi and Mashkawa shared the 2008 Nobel prize for their work. However, the measured breakdown of *CP* is too little to account for the matter-antimatter asymmetry in the universe and a larger effect is still searched in transitions between different quark families. Furthermore, these reactions are particularly sensitive to New Physics (NP), especially in decays strongly suppressed in the SM.

History shows that studies in the flavour sector predicted the effects and provided limits on properties of particles before their direct discovery. An example of this is the discovery of kaon mixing and the suppression of $\mathscr{B}(K_L^0 \to \mu\mu)$ that was explained with the Glashow-Iliopoulos-Maiani (GIM) mechanism and led to anticipate the existence of the charm quark. Other phenomena in which flavour studies were visionary are: the limit on the top mass established from *B*-meson mixing and, more recently, the constraints on the parameter space in some supersymmetric models.

Other than the above, flavour physics could help to understand open questions in cosmology like the nature of dark matter or the problem of instability of the fundamental scale of the weak interactions, the Fermi scale, against radiative corrections (hierarchy problem). This can be done by measuring the decays of known particles seeking deviations from pure SM expectations that would reveal quantum effects of physics beyond the directly available energies at the LHC.

Whereas in the past there was significant activity studying kaon decays, the interest now is focused on the analysis of *B*-mesons, and also on *D*-mesons, Λ_c and Λ_b baryons. In this document we aim at reviewing some of the latest results produced in the analysis of *B*-meson decays.

2. Experiments

It is out of the scope of this document to make a historical review of the experiments of flavour physics. Instead the experiments that are producing the latest results will be briefly listed and the reader will be referred to the bibliography to get additional information.

The *B*-factories are colliders that produce $b\bar{b}$ pairs impacting e^+ and e^- resonating at Υ excited states, mainly $\Upsilon(4S)$. The $\Upsilon(4S)$ decays in more than 96% of the cases into a pair of $B\overline{B}$ mesons. There are two *B*-factories.

- The KEKB collider in Japan associated to the Belle experiment [4]. Belle stopped data-taking in June 2010 after collecting 711 fb^{-1} at the $\Upsilon(4S)$ resonance center-of-mass energy and 121 fb^{-1} at the $\Upsilon(5S)$ resonance center-of-mass energy [1]. An upgrade of this experiment (Belle-II) is foreseen to start running in 2014 or 2015.

- The PEP-II collider at SLAC (USA) producing interactions that were detected by the BaBar experiment [5]. BaBar stopped operation in April 2008 after storing 550 fb^{-1} of data, most of them (433 fb^{-1}) at the $\Upsilon(4S)$ resonance center-of-mass energy.

Both Belle and BaBar continue producing results with the analysis of the accumulated statistics.

Two other active actors are the CDF [6] and D0 [7] collaborations. They have also finished data taking after the Tevatron stopped its operation in September 2011. The B-mesons were produced in about 2 TeV center-of-mass proton-antiproton collisions of which the accelerator delivered more than 12 fb^{-1} to each experiment. The events were detected in multi-purpose barrel spectrometers producing the data that were and still are analyzed.

Three experiments performing measurements in the B-physics sector are currently taking data at the LHC, the proton-proton collider built at CERN (Switzerland): ATLAS [8], CMS [9] and LHCb [10]. ATLAS and CMS are general purpose detectors, while LHCb is a dedicated experiment for flavour physics. LHCb has collected about 1 fb^{-1} in 2011 at a center-of-mass energy $\sqrt{s} = 7$ TeV and about 2 fb^{-1} in 2012 at $\sqrt{s} = 8$ TeV. Running at an average luminosity of 4×10^{32} cm^{-2} s^{-1}, twice the design one, LHCb has to cope with a rate of about 120,000 $b\bar{b}$ pairs per second. This is possible thanks to an excellent decay time resolution, particle identification and an efficient trigger both for leptonic and hadronic final states.

3. Direct *CP* violation

Direct CPV can be revealed through the measurement of a different branching fraction for $B^0_{(s)}$ and $\overline{B}^0_{(s)}$ meson decays. This is produced by the interference of two diagrams leading to the same final state. The canonical example is: $\overline{B}^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$. Quantitatively this difference is given by the asymmetry

$$A_{CP}(B^0 \to K\pi) = \frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}, \tag{3.1}$$

for which LHCb provides the most precise single measurement: $A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011(stat.) \pm 0.008(syst.)$ [12]. Also in this reference, the same A_{CP} asymmetry is, for the first time, measured for B^0_s to be $A_{CP}(B^0_s \to K\pi) = 0.27 \pm 0.08(stat.) \pm 0.02(syst.)$.

Another direct evidence of CPV appears in rare non-resonant $B^\pm \to \pi^\pm h^+ h^-$ and $B^\pm \to K^\pm h^+ h^-$ decays (here $h = K$ or $h = \pi$). One example is the observation of large asymmetries comparing the K^+K^- invariant mass spectrum (between 1.2 and 2 GeV$^2/c^4$) of $B^+ \to K^+K^+K^-$ to its CP-conjugated mode ($B^- \to K^-K^+K^-$). This effect, that was first reported by the BaBar collaboration in 2007 [13] and which LHCb has fully confirmed [14], has not yet a clear theoretical explanation but points to some interesting hadronic dynamics that could generate direct CPV.

[1] The decay of $\Upsilon(5S)$ permits B^0_s meson decay studies.

4. Measurement of γ

Among the parameters that probe CPV, one of them, the CKM γ angle, is only known in direct measurements to a precision of 16%, $\gamma = (68^{+10}_{-11})^{\mathrm{o}}$ [30], achieved analyzing both tree and penguin decay modes. Processes with large penguin contributions are thought to be more sensitive to NP whereas tree–level diagrams are dominated by SM processes. A measurement using pure tree–level processes produces a cleaner extraction of γ. Of course penguin-sensitive γ measurements are also very important because discrepancies with tree–level dominated determinations would point to NP.

The decays that are sensitive to γ are those that experience $b \to c$ and $b \to u$ interference (therefore involving the V_{ub} and V_{cb} CKM matrix elements). This includes $B \to D^0 h$ channels, where h is either a kaon or a pion.

There are three standard ways to obtain the γ angle in $B \to D^0 h$ decays. The GLW strategy proposes to extract γ when the D^0 decays to CP eigenstates [15, 16] as $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$. Complementary, the ADS method exploits the interference between the Cabibbo favoured and doubly Cabibbo suppressed decay modes of the neutral D mesons to final states such as $K\pi$ that are not CP eigenstates [17]. Finally, the GGSZ approach proposes the use of self-conjugate three-body D decays, such as $K^0_S\pi^+\pi^-$ and $K^0_S K^+K^-$ to access γ from examination of the Dalitz plot [18].

The recent $B \to D^0 K$ LHCb results combining the three methods produce an independent clean measurement of $\gamma = (71.1^{+16.1}_{-15.2})^{\mathrm{o}}$. Also, for the first time information from $B \to D\pi$ decays is included, the best-fit value of the combined result being $\gamma = 85.1^{\mathrm{o}}$ with limits of $\gamma \in [43.8, 101.5]^{\mathrm{o}}$ at 95% confidence level (CL) [19].

5. *CP* violation and mixing

An alternative way to detect CPV is via the effect of $B^0_q - \overline{B}^0_q$ mixing. Mixing is a consequence of the mass operator not commuting with the flavour operator. Therefore B-meson flavour eigenstates are not mass eigenstates. This effect produces matter-antimatter oscillations that evolve according to a Schrödinger–like equation

$$i\frac{d}{dt}\begin{pmatrix} |B^0_q\rangle \\ |\overline{B}^0_q\rangle \end{pmatrix} = \begin{pmatrix} M - i\Gamma/2 & M_{12} - i\Gamma_{12}/2 \\ M^*_{12} - i\Gamma^*_{12}/2 & M - i\Gamma/2 \end{pmatrix} \begin{pmatrix} |B^0_q\rangle \\ |\overline{B}^0_q\rangle \end{pmatrix}. \tag{5.1}$$

After diagonalizing, the mass eigenstates can be expressed as a linear combination of the flavour eigenstates: $|M_L\rangle = p|B^0_q\rangle + q|\overline{B}^0_q\rangle$ and $|M_H\rangle = p|B^0_q\rangle - q|\overline{B}^0_q\rangle$, where L and H indicate high and low mass eigenstates respectively[2]. There is CPV in mixing if $|p/q| \neq 1$. The frequency of the oscillations depends on the mass eigenvalue difference $\Delta m_q = M_H - M_L$.

5.1 Measurement of time-dependent *CP* violation

If both meson and anti-meson decay to the same final state f their time-dependent decay rates are

[2] The subscript q indicates if a d or an s quark applies.

$$\Gamma(B_q \to f) = \mathcal{N}_f |A_f|^2 e^{-\Gamma_q t} \left[(1+|\lambda_f|^2)\cosh\left(\frac{\Delta\Gamma_q}{2}t\right) + (1-|\lambda_f|^2)\cos(\Delta m_q t) + \right.$$
$$\left. 2\mathrm{Re}(\lambda_f)\sinh\left(\frac{\Delta\Gamma_q}{2}t\right) - 2\mathrm{Im}(\lambda_f)\sin(\Delta m_q t) \right], \quad (5.2)$$

$$\Gamma(\overline{B}_q \to f) = \mathcal{N}_f |\overline{A}_f|^2 e^{-\Gamma_q t} \left[(1+|\overline{\lambda}_f|^2)\cosh\left(\frac{\Delta\Gamma_q}{2}t\right) + (1-|\overline{\lambda}_f|^2)\cos(\Delta m_q t) + \right.$$
$$\left. 2\mathrm{Re}(\overline{\lambda}_f)\sinh\left(\frac{\Delta\Gamma_q}{2}t\right) - 2\mathrm{Im}(\overline{\lambda}_f)\sin(\Delta m_q t) \right], \quad (5.3)$$

where $\mathcal{N}_f$ is a common, time-independent, normalization factor, $A_f = \langle f|B_q^0\rangle$, $\overline{A}_f = \langle f|\overline{B}_q^0\rangle$, $\lambda_f = (q/p)(\overline{A}_f/A_f)$ and $\overline{\lambda}_f = 1/\lambda_f$. The decay rates into CP-conjugate final states, $\overline{f}$, are obtained with $\mathcal{N}_{\overline{f}} = \mathcal{N}_f$ and the substitutions $A_f \to A_{\overline{f}}$ and $\overline{A}_f \to \overline{A}_{\overline{f}}$, $\lambda_f \to \lambda_{\overline{f}}$ and $\overline{\lambda} \to \overline{\lambda}_{\overline{f}}$.

The Δm_q oscillating terms in (5.2) and (5.3) is evident. Additionally, there are hyperbolic terms with a time constant depending on the difference of the decay widths of the mass eigenstates, $\Delta\Gamma_q = \Gamma_L - \Gamma_H$. Outside the brackets appears an exponential term with decay constant, $\Gamma_q = (\Gamma_L - \Gamma_H)/2$.

With equations (5.2) and (5.3) the time dependent asymmetry of finding a B_q^0 or a $\overline{B}_q^0$ meson decaying into a given final state f can be constructed. It is usually parametrized as

$$A_{CP}(t) = \frac{A_f^{dir}\cos(\Delta m_q t) + A_f^{mix}\sin(\Delta m_q t)}{\cosh(\frac{\Delta\Gamma_q}{2}t) - A_f^{\Delta\Gamma_q}\sinh(\frac{\Delta\Gamma_q}{2}t)}, \quad (5.4)$$

where A_f^{dir} and A_f^{mix} are the direct and mixing CP violating amplitudes. These amplitudes were measured in decays of the B^0 meson into $\pi^+\pi^-$ pairs with results summarized in 2010 by the HFAG: $A_{\pi\pi}^{dir} = 0.38 \pm 0.06$ and $A_{\pi\pi}^{mix} = -0.65 \pm 0.07$ [20]. LHCb has widened these studies by measuring for the first time the amplitudes for $B_s^0 \to K^+K^-$: $A_{KK}^{dir} = 0.02 \pm 0.18(stat.) \pm 0.04(syst.)$ and $A_{KK}^{mix} = 0.17 \pm 0.18(stat.) \pm 0.05(syst.)$ [21]. A measurement of $A_{\pi\pi}^{dir} = 0.11 \pm 0.21(stat.) \pm 0.03(syst.)$ and $A_{\pi\pi}^{mix} = -0.56 \pm 0.17(stat.) \pm 0.03(syst.)$ is also reported therein. This analysis can also contribute to the determination of γ [22].

5.2 Determination of ϕ_s

In the absence of direct CPV $|\lambda_f| = 1$ and eq. (5.4) simplifies into

$$A_{CP}(t) = \frac{\mathrm{Im}(\lambda_f)\sin(\Delta m_q t)}{\cosh\left(\frac{\Delta\Gamma_q}{2}t\right) - \mathrm{Re}(\lambda_f)\sinh\left(\frac{\Delta\Gamma_q}{2}t\right)}. \quad (5.5)$$

Within the SM $\lambda_f = \eta_{CP} e^{-i\phi_q}$ where η_{CP} is the CP eigenvalue of the final state and ϕ_q the weak phase, that depends on the CKM matrix elements.

An example where ϕ_s can be precisely measured is the study of $B_s^0 \to J/\psi\phi$ decays. This is a vector-vector final state, consequently a mixture of CP-odd and CP-even components, that can be separated using an angular analysis. The LHCb result is the most precise measurement available

Experiment	SM prediction [23, 24]	LHCb [25]	D0 [26]	CDF [27]	ATLAS [28]	CMS [29]
ϕ_s [rad]	-0.036 ± 0.002	-0.001 ± 0.105	-0.55 ± 0.38	$[-0.12, 0.6]$	0.22 ± 0.42	-
$\Delta\Gamma_s$ [ps^{-1}]	0.087 ± 0.021	0.116 ± 0.019	0.163 ± 0.035	0.068 ± 0.027	0.053 ± 0.022	0.048 ± 0.024

Table 1: Summary of ϕ_s and $\Delta\Gamma_s$ latest measurements from different experiments.

and also agrees with the SM calculation. Other than ϕ_s this analysis also supplies a value for $\Delta\Gamma_s$. A summary of results from various experiments is shown in Table 1.

LHCb has combined its results from $B_s^0 \to J/\psi\phi$ with those from $B_s^0 \to J/\psi f_0(980)(\to \pi\pi)$. This mode was discovered by LHCb in February 2011 and promptly confirmed by Belle, CDF and D0. The analysis of the LHCb 2011 data gives $\phi_s^{B_s^0 \to J/\psi f_0(980)} = -0.02 \pm 0.17(stat.) \pm 0.02(syst.)$. The combination of both channels gives the most precise determination of $\phi_s = -0.002 \pm 0.083(stat.) \pm 0.027(syst.)$ [25].

5.3 *CP* violation in mixing

Another manifestation of *CP* violation appears when two *CP* conjugate processes $B_q^0 \to \overline{f}$ and $\overline{B}_q^0 \to f$ have different decay rates as a consequence of mixing.

A particular example is given by the charge asymmetry in decays containing a muon in its final state, defined as

$$a_{\rm sl}^q = \frac{\Gamma(\overline{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\overline{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)}, \tag{5.6}$$

where again q is to be substituted by d or s. The $a_{\rm sl}^q$ is directly related to $\Delta\Gamma_q$ and Δm_q described in the previous section through

$$a_{\rm sl}^q = \frac{\Delta\Gamma_q}{\Delta m_q} \tan\phi_{12}, \tag{5.7}$$

with $\tan\phi_{12} = -arg(-\Gamma_{12}/M_{12})$, where $M_{12} - i\Gamma_{12}/2$ is the off-diagonal element of the mass matrix in eq. (5.1).

The SM predicts a tiny value of both: $a_{\rm sl}^d = (-4.1 \pm 0.6) \times 10^{-4}$ and $a_{\rm sl}^s = (1.9 \pm 0.3) \times 10^{-5}$ [30], whereas the D0 collaboration finds $a_{\rm sl}^d = (0.68 \pm 0.45 \pm 0.14) \times 10^{-2}$ [31], analyzing $B^0 \to D^+(\to K\pi^+\pi^-)\mu^-\nu$, and $a_{\rm sl}^s = (-1.12 \pm 0.74 \pm 0.17) \times 10^{-2}$, analyzing $B_s^0 \to D_s(\to \phi\pi^+)\mu^-\nu$ [32]. These two measurements are complemented with the determination of the inclusive asymmetry of events containing two positively or two negatively charged muons

$$A_{\rm sl}^b = \frac{N_{b\bar{b}}^{++} - N_{b\bar{b}}^{--}}{N_{b\bar{b}}^{++} + N_{b\bar{b}}^{--}}, \tag{5.8}$$

that in the absence of mixing $(t = 0)$ would be zero. $A_{\rm sl}^b$ is a linear combination of $a_{\rm sl}^d$ and $a_{\rm sl}^s$

$$A_{\rm sl}^b = C_d a_{\rm sl}^d + C_s a_{\rm sl}^s. \tag{5.9}$$

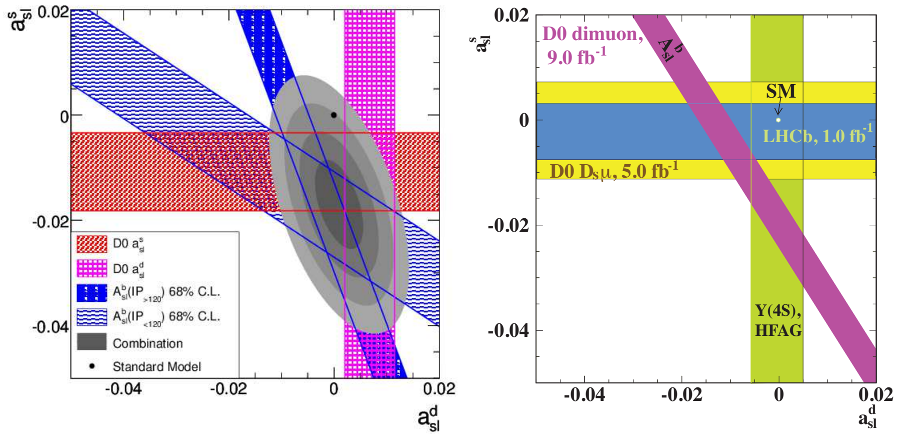

Figure 1: Left: Experimental results on $a^d_{\rm sl}$ and $a^s_{\rm sl}$ from the D0 collaboration compared to the SM prediction. **Right:** Experimental results on $a^d_{\rm sl}$ and $a^s_{\rm sl}$ from the LHCb, D0, BaBar and Belle collaborations.

The experimental determination and combination of $a^d_{\rm sl}$, $a^s_{\rm sl}$ and $A^b_{\rm sl}$ by D0 is in 3σ tension with the mentioned SM prediction (see Fig. 1). On the contrary, LHCb obtains $a^s_{\rm sl} = (-0.24 \pm 0.54(stat.) \pm 0.33(syst.)) \times 10^{-2}$ [33] and the B-factories $a^d_{\rm sl} = (-0.05 \pm 0.56) \times 10^{-2}$[20, 34, 35, 36] which are in agreement with the SM prediction. All results are summarized in Figure 1. We can conclude that this is an intriguing measurement that will need some follow-up in the near future.

6. Rare decays

A different strategy to search for NP phenomena is to study deviations of SM suppressed modes. This allows clear experimental access to decay rates or other observables very sensitive to NP. These systems can be described by an Operator Product Expansion Hamiltonian of the form (see [43] for additional details)

$$\mathscr{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i \mathscr{O}_i + C'_i \mathscr{O}'_i) + h.c., \tag{6.1}$$

where $C_i^{(\prime)}$ are the Wilson coefficients. Contributions from physics beyond the SM to the observables can be described by deviations in the Wilson coefficients.

In the following the latest results in some of these searches, as well as their consequences for different models of physics beyond the SM are briefly summarized.

6.1 $B^0 \to K^{*0}\mu^+\mu^-$

The $B^0 \to K^{*0}\mu^+\mu^-$ decay in the SM can only occur through diagrams involving loops. This implies a SM branching ratio of $\mathscr{B}(B^0 \to K^{*0}\mu^+\mu^-) = (1.06 \pm 0.10) \times 10^{-6}$ [37].

The angular distributions of this decay are mostly determined by the magnetic ($\mathscr{O}_7$), vector and vector-axial ($\mathscr{O}_9$,$\mathscr{O}_{10}$) operators. An example is the distribution of the forward-backward asymmetry as a function of the invariant mass squared of the two muons: q^2. An event is said to be forward if the angle between the negative muon momentum and the B^0 momentum is less than $\pi/2$ in the

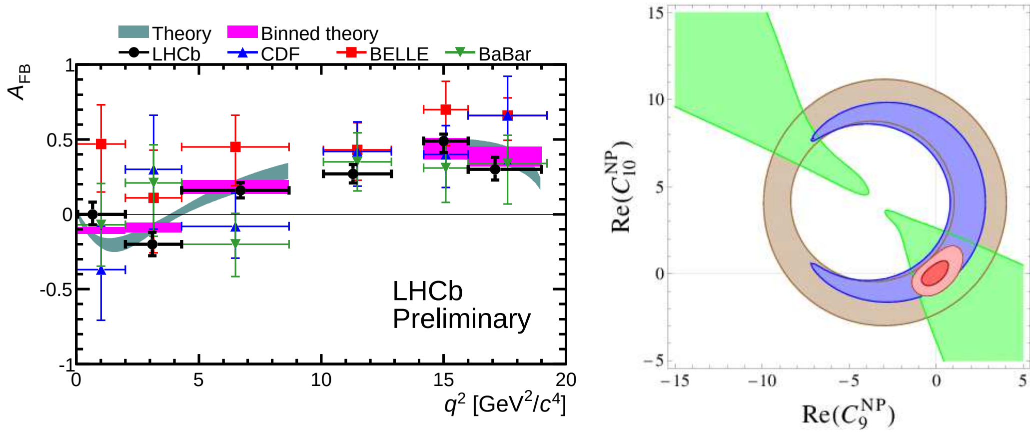

Figure 2: Left: Forward-Backward asymmetry A_{FB} distribution as a function of the dimuon invariant mass q^2. The SM prediction and results for different experiments are displayed. Taken from [42]. **Right:** Individual 2σ constraints in the C_9 and C_{10} Wilson coefficients complex plane, coming from $B^0 \to X_s \ell^+ \ell^-$ (brown), $B^0 \to X_s \gamma$ (yellow), $A_{FB}(B^0 \to K^* \mu^+ \mu^-)$ (green) and $\mathscr{B}(B^0 \to K^* \mu^+ \mu^-)$ (blue), as well as combined 1 and 2σ constraints (red). This is an example of the impact of the $B^0 \to K^* \mu^+ \mu^-$ results. Taken from [43], where additional information can be found.

center-of-mass system of the two muons. Otherwise the event is backward. The SM predicts a negative value for A_{FB} for small values of q^2 whilst the B-factories [38, 39], and in a lesser extent CDF [40], hinted a positive value although with large uncertainties. The results of LHCb in 2011 elucidated this puzzle showing good agreement with the SM prediction and restricting the parameter space for NP [41]. An update of the analysis also measured, for the first time, the zero crossing point where $A_{FB}(q^2) = 0$ at $q^2 = (4.9^{+1.1}_{-1.3})[\mathrm{GeV}^2/c^4]$ [42]. The result of the measurements and its consequences in some of the Wilson coefficients are shown in Fig. 2.

6.2 $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

The $B_s^0 \to \mu^+\mu^-$ decay is strongly suppressed in the SM due to the GIM mechanism and helicity conservation. The most precise calculations in the SM give a prediction of $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$ [44]. This decay is very sensitive to NP with new scalar and/or pseudoscalar interactions and therefore highly interesting to probe models with extended Higgs sector. In particular some of the SUSY models, such as CMSSM and NUHM1, predict an enhancement of this decay. Other possibilities that could produce deviations from the SM are extra dimensions, little Higgs or Technicolor.

By the time of the Charged Higgs conference the latest public results were upper limits in the branching fraction of: $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ at 95% CL [45] from LHCb, $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 7.7 \times 10^{-9}$ from CMS [46] and $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 2.2 \times 10^{-8}$ from ATLAS [47]. The combination of these results is: $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 4.2 \times 10^{-9}$ at 95% CL [48].

This result already produced tight constraints in the parameter space of the tested models [49]. However, on the 12th of November 2012 the LHCb collaboration presented at the Hadron Collider Particle Symposium in Kyoto the first measurement of the branching fraction of the $B_s^0 \to \mu^+\mu^-$ decay $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$ with a signal significance of 3.5σ [50], see Fig. 3.

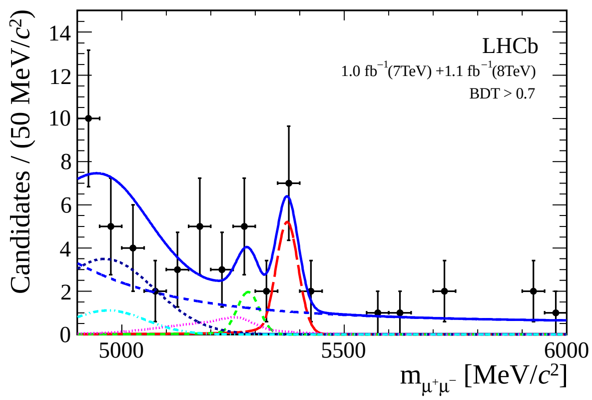

Figure 3: Invariant mass distribution of selected LHCb $B_s^0 \to \mu^+\mu^-$ candidates. The result of the spectrum fit is overlaid (solid blue line) and the different components detailed. Taken from [50].

The $B^0 \to \mu^+\mu^-$ decay is even more suppressed in the SM $\mathscr{B}^{SM} = (1.07 \pm 0.10) \times 10^{-10}$ [44]. The most up-to-date result of its branching fraction: $\mathscr{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ at 95% CL is also found in ref. [50]. The tightest constraint for this channel, pending on including this LHCb update, is the combination of the LHC experiments $\mathscr{B}(B^0 \to \mu^+\mu^-) < 8.1 \times 10^{-10}$ at 95% CL [48].

7. Tree-level W mediated B-meson decays containing a $\tau\nu$ pair

7.1 $\sin(2\beta)$ versus $B \to \tau\nu$

The u and $\bar{b}$ valence quarks of a B^+ meson annihilate in the SM producing a virtual W^+ boson. This W^+ may subsequently decay into a charged lepton and its corresponding neutrino. The branching fraction of such a process depends on the mass of the lepton as

$$\mathscr{B}(B \to \ell\nu) \propto m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right). \tag{7.1}$$

This means that the largest branching fraction is the one containing the heaviest lepton τ, that is of the order of $\sim 10^{-4}$. This reaction is very sensitive to the possibility of a decay mediated by a charged Higgs. This appears not only in supersymmetric models but also in simple extensions of the SM like the Two Higgs Doublets Models (2HDM). The branching fraction is also proportional to $|V_{ub}|^2$, one of the CKM matrix elements, and as $|V_{ub}|$ is intimately related to $\sin 2\beta$, being β one of the angles of the unitary triangle, the experimental results are often presented in a $\sin 2\beta$ versus $\mathscr{B}(B \to \tau\nu)$ plot. The summary of experimental results as of winter 2011 showed a 3σ tension with the SM prediction [53] therefore suggesting that either $\mathscr{B}(B \to \tau\nu)$ is too high or $\sin(2\beta)$ too low. The enhanced branching fraction is not explained by the latest improvements in the determination of the B decay constant f_B, that has achieved better than 10% precision in Lattice QCD [51] but goes in the opposite direction of a charged Higgs contribution, therefore creating an intriguing enigma. However, the updated results presented by the Belle collaboration in the summer of 2012 [52] are compatible with the SM and considerably reduce the world average tension to 1.6σ. These changes are achieved after considering the sample of hadronic τ decays and

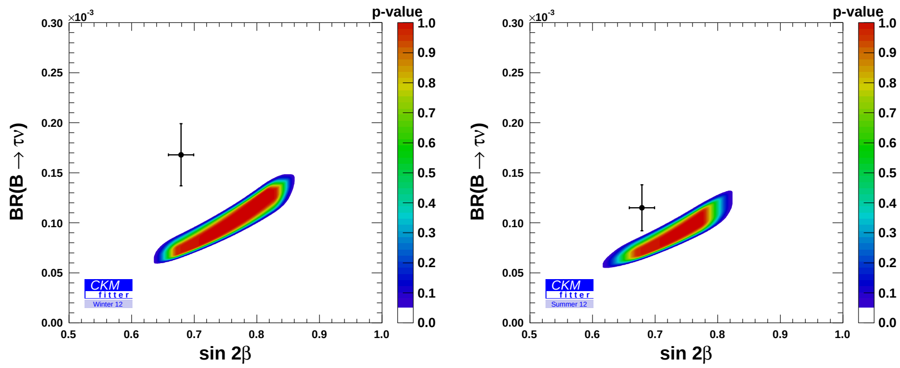

Figure 4: Left: $\sin 2\beta$ vs. $\mathscr{B}(B \to \tau\nu)$ in winter 2012. **Right:** $\sin 2\beta$ vs. $\mathscr{B}(B \to \tau\nu)$ after summer 2012. Both figures from [53].

improving the treatment of systematic effects. An update of the results on this channel is expected from the BaBar collaboration that would shed additional light on the topic.

7.2 $B \to D^{(*)}\ell\nu$ decays

The $B \to D^{(*)}\ell\nu$ decays are also mediated by a virtual W but in this case is a $b \to c$ transition rather than a $b \to u$ transition involved. Nevertheless, the reaction would be very sensitive to the existence of charged Higgs playing the role of the mediator in the decay. This would appear clearly in a measurement of the branching fraction ratios

$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}\ell\nu)}, \tag{7.2}$$

where l indicates the sum of τ, μ and e. The latest results from the BaBar collaboration [54] give: $R(D) = 0.440 \pm 0.071$ and $R(D^*) = 0.332 \pm 0.029$ that exceed the SM predictions of $R(D) = 0.297 \pm 0.017$ and $R(D^*) = 0.252 \pm 0.003$[55] by 2.0σ and 2.7σ. The combination of these results, including their correlation, excludes the possibility of both the measured $R(D)$ and $R(D^*)$ agreeing with the SM predictions at the 3.4σ level. Moreover, the type-II-2HDM model predicts $R(D) = R(D^*) = \tan\beta/m_H$ where $\tan\beta$ is the ratio of the vacuum expectation value between the two Higgs doublets and m_H is the mass of the charged Higgs. The BaBar results are not compatible with this model for any value of $\tan\beta$ and m_H.

8. Conclusions

Numerous high quality measurements have been made available by the experiments in the physics of the b–quark in the last year. These studies are allowing to explore higher energy scales than direct particle searches.

So far the Standard Model is enduring the tests and for some channels we are about to enter in a precision regime where new challenges await in the quest for finding answers to some of the unknowns yet to be understood in nature.

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