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Flavour physics and beyond the Standard Model Higgs bosons

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Flavour physics plays a key role in the search for physics beyond the Standard Model. The indirect searches for new Higgs bosons performed at LHCb and the B-factories complement the direct searches performed by ATLAS and CMS. This document presents an overview of the experimental results in flavour physics in the search for new Higgs bosons.

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1. Introduction

The Standard Model (SM) of particle physics is an extremely successful theory explaining the available measurements of branching fractions and charge-parity asymmetries in the flavour sector of quarks performed at the accelerators around the world. However, this is considered an effective theory, valid only at low energies, since it does not explain phenomena such as dark matter or the matter-antimatter asymmetry observed in the universe. At higher energies, new physics phenomena are predicted to emerge.

In the search for physics beyond the SM (BSM), there are two complementary approaches: high-energy (or direct) approach and high-precision (or indirect) approach. Direct searches are performed at the highest available energies and aim at producing and detecting new heavy particles. Indirect searches focus on precision measurements of quantum-loop-induced processes. Accurate theoretical predictions are available for the heavy quark sector in the SM. It is therefore an excellent place to search for new phenomena, since any deviation from these predictions can be attributed to contributions from BSM physics.

In the SM, transitions between fermions of different flavour are possible via the charged current weak interaction. The study of these transitions is the goal of Flavour Physics. Flavour changing neutral currents (FCNC) are forbidden at lowest order, but are allowed in higher order processes. Since new particles can contribute to these loop diagrams, such processes are highly sensitive to contributions from BSM physics.

In the following, a few examples of flavour physics results are presented with special focus on the search for new Higgs bosons.

2. Tests of lepton universality

Lepton universality is one of the ingredients of the Standard Model of particle physics. This requires that the coupling between the three families of leptons and the gauge bosons is independent of the lepton flavour. However, models extending the SM may contain additional interactions involving enhanced couplings, specially to the third generation of leptons, that would violate this principle.

The B meson decay $B^+ \to K^+ l^+ l^{-1}$, where l represents either a muon or an electron, is a flavour-changing neutral current process. In the SM, this is highly suppressed, since it proceeds via loop (penguin and box) diagrams. This makes the branching fraction of $B^+ \to K^+ l^+ l^-$ decays highly sensitive to the presence of new particles that could enter into the loop. Lepton universality can be tested by measuring the ratio $R(K) \equiv \mathscr{B}(B^+ \to K^+ \mu^+ \mu^-)/\mathscr{B}(B^+ \to K^+ e^+ e^-)$. In the SM, this ratio is expected to be equal to 1, with negligible uncertainties. Previous measurements performed by BaBar and Belle [1][2] are consistent with unity with a precision of $20\% - 50\%$. The most recent LHCb measurement [3], performed in the dilepton invariant mass squared range $1 < q^2 < 6$ GeV^2/c^4, is found to be $R(K) = 0.745^{+0.090}_{-0.074}$(stat) $\pm$ 0.036(syst), compatible with the SM prediction within 2.6 standard deviations.

Another important place to search for lepton universality violation is semileptonic B hadron decays to the third generation of leptons. The presence of additional charged Higgs bosons can have

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[1] B mesons are mesons containing a b quark. Charge conjugation is implied throughout the text.

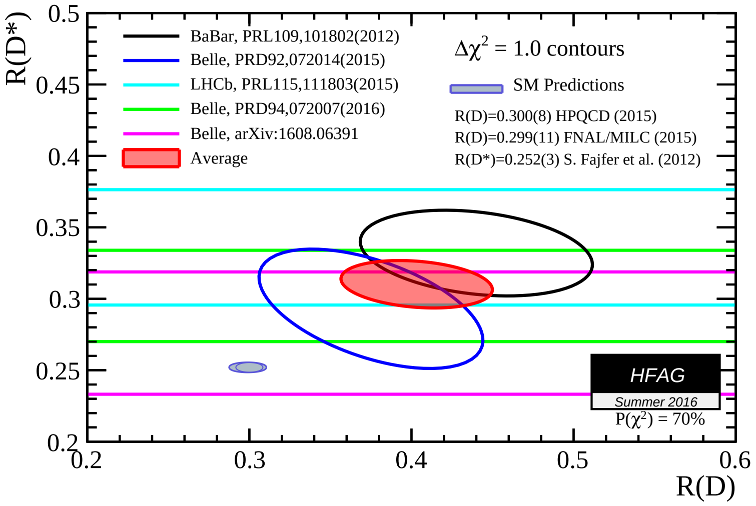

Figure 1: Measurements and average of $R(D^*)$ vs $R(D)$, and comparison with the SM prediction. This figure has been has been taken from the HFAG [11] web page.

a significant effect on the rate of the semitauonic decay $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ [4]. Semitauonic B meson decays have been observed by the BaBar, Belle and LHCb collaborations. BaBar reported measurements [5][6] of the ratios of branching fractions $R(D^*) \equiv \mathscr{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathscr{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$ and $R(D^*) \equiv \mathscr{B}(\overline{B}^0 \to D^{+}\tau^-\overline{\nu}_\tau)/\mathscr{B}(\overline{B}^0 \to D^{+}\mu^-\overline{\nu}_\mu)$ that shows deviations of 2.7σ and 2.0σ, respectively, from the SM predictions [7]. More recently, LHCb [8] and Belle [9][10] have performed additional measurements of $R(D^*)$, being all systematically over the SM expectation, as can be seen in figure 2. The combination of all the available measurements of $R(D)$ and $R(D^*)$ shows an interesting tension with the SM of 3.9σ [11].

3. Measurement of B^0 and B^0_s oscillation frequency

An example of FCNC process is the neutral meson mixing, where neutral mesons can transform into their antiparticles. Particle-antiparticle oscillations have been observed in the $K^0-\overline{K}^0$, $B^0-\overline{B}^0$, $B^0_s-\overline{B}^0_s$ and $D^0-\overline{D^0}$ systems, the frequency of $B^0_s-\overline{B}^0_s$ oscillations being the highest. The observed particle and antiparticle states $B^0_{(s)}$ and $\overline{B}^0_{(s)}$ are linear combinations of the mass eigenstates B_H and B_L with masses m_H and m_L and decay widths Γ_H and Γ_L, respectively. The $B^0_{(s)}$ oscillation frequency is equivalent to the mass difference $\Delta m_{d(s)} = m_H - m_L$. The parameter $\Delta m_{d(s)}$ is sensitive to new virtual particles entering into the mixing loop. The precision on the measurement of the oscillation frequency for the B^0 and B^0_s systems is already much better than the SM prediction. LHCb has recently measured $\Delta m_s = (17.768 \pm 0.023 \pm 0.006) ps^{-1}$ [12] and $\Delta m_d = (0.5050 \pm 0.0021 \pm 0.0010) ps^{-1}$ [13], using $B^0_s \to D^-_s\pi^+$ and $B^0 \to D^{(*)}\mu^+\nu_\mu$ decays, respectively. The oscillations can be seen in figures 2 and 3. These results are compatible with the SM expectations $\Delta m^{SM}_s = (16.3 \pm 1.1)$ ps^{-1} and $\Delta m^{SM}_d = (0.566^{+0.035}_{-0.043})$ ps^{-1} at the level of 1.3σ and 1.4σ, respectively.

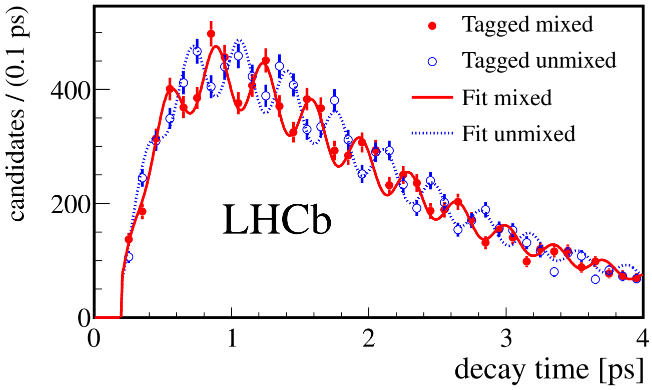

Figure 2: Decay time distribution for B_s^0 mesons tagged as mixed (different flavour at decay and production; red) or unmixed (same flavour at decay and production; blue). The points correspond to data, and the model with the lines.

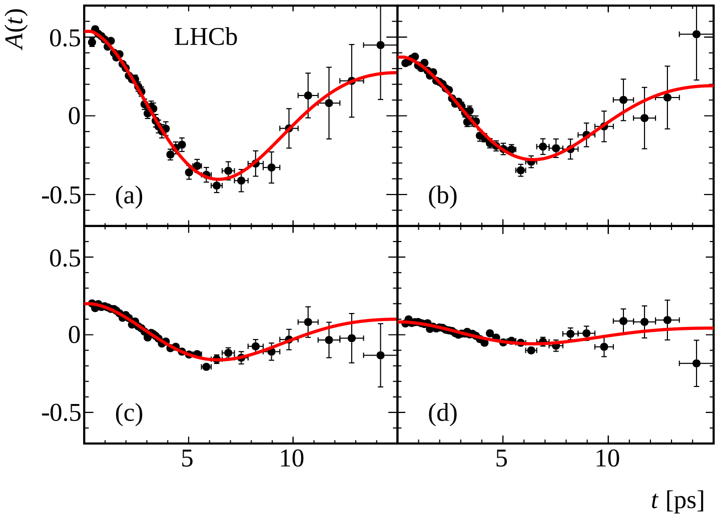

Figure 3: Mixing asymmetry projections, as defined in [13], in four tagging categories for $B^0 \to D^{*-}\mu^+\nu_\mu X$ decays.

4. Photon polarisation in radiative B_s^0 decays

In the SM, photons emitted in $b \to s\gamma$ transitions are produced predominantly with a left-handed polarisation, with a small right-handed component proportional to the ratio of the quark masses, m_s/m_b. In many extensions of the SM, the right-handed component can be enhanced, leading to observable effects in mixing-induced CP asymmetries and time-dependent decay rates of radiative B^0 and B_s^0 decays. Measurements of the time-dependent CP asymmetries in radiative heavy meson decays have been performed by the BaBar and Belle collaborations in the B^0 system only [11]. The production of polarised photons in $b \to s\gamma$ transitions was observed for the first time at LHCb by studying the up-down asymmetry in $B^+ \to K^+\pi^-\pi^+\gamma$ decays [14]. All these measurements are found to be in agreement with the SM predictions. Recently, also at LHCb, photon polarisation has been studied for the first time in the B_s^0 system using $B_s^0 \to \phi\gamma$ decays [15]. The invariant mass distribution of $B_s^0 \to \phi\gamma$ decays is shown in figure 4. This study results in $\mathscr{A}^\Delta = -0.98^{+0.46+0.23}_{-0.52-0.20}$, where $\mathscr{A}^\Delta$ is a parameter related with the ratio of right- and left-handed photon amplitudes. This result is in agreement with the SM expectation $\mathscr{A}^\Delta_{SM} = 0.047^{+0.029}_{-0.025}$ [16] at the level of 2 standard deviations.

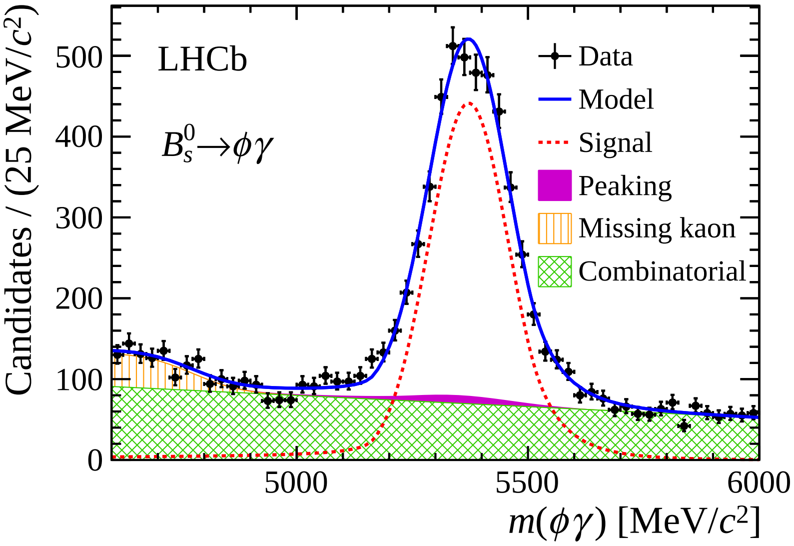

Figure 4: Fit to the $\phi\gamma$ invariant mass distribution for $B_s^0 \to \phi\gamma$ candidates.

5. Rare decays

Rare decays are important places in the search for new bosons. For instance, charged Higgs bosons can modify the branching fraction of $B^- \to \tau^-\overline{\nu}_\tau$, $B^0_{(s)} \to \mu^+\mu^-$ and $B^0_{(s)} \to \tau^+\tau^-$ decays.

The experimental world average value for the $B^- \to \tau^-\overline{\nu}_\tau$ branching fraction is $\mathscr{B}(B^- \to \tau^-\overline{\nu}_\tau) = (1.06 \pm 0.19) \times 10^{-6}$ [11], which is compatible with the SM at the level of 1 standard deviation. Also, new Higgs bosons could enhance the branching fractions of $B^0_{(s)} \to \mu^+\mu^-$ and $B^0_{(s)} \to \tau^+\tau^-$. A combined analysis of CMS and LHCb data [17] resulted in the first observation of the $B_s^0 \to \mu^+\mu^-$ decay and the first evidence of $B^0 \to \mu^+\mu^-$. In figure 5, the $\mu^+\mu^-$ invariant mass for $B^0_{(s)} \to \mu^+\mu^-$ decays is shown. The measured branching fractions are $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ and $\mathscr{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$, which are compatible with the SM at the 1.2σ and 2.2σ level, respectively. The comparison between the measurement and the SM prediction is shown in figure 6. Finally, for the $B^0_{(s)} \to \tau^+\tau^-$ decay, the SM predicts $\mathscr{B}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-8}$ and $\mathscr{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-7}$. The $B^0_{(s)} \to \tau^+\tau^-$ decay has been studied by LHCb [19], finding no evidence for the decay (see figure 7), and setting as upper limits $\mathscr{B}(B_s^0 \to \tau^+\tau^-) < 3.0 \times 10^{-3}$ and $\mathscr{B}(B^0 \to \tau^+\tau^-) < 1.3 \times 10^{-4}$ at 95% confidence level.

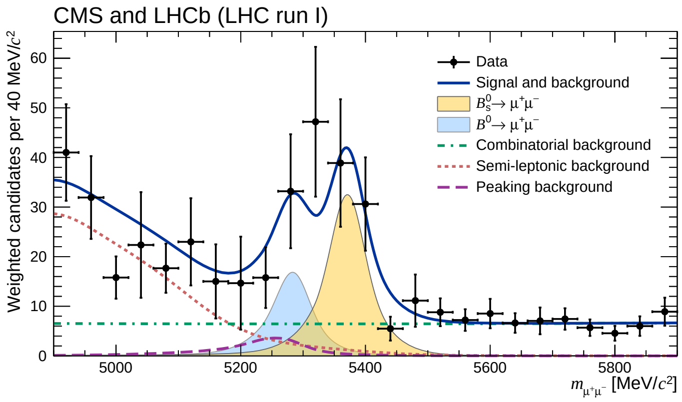

Figure 5: $\mu^+\mu^-$ invariant mass distribution for $B^0_{(s)} \to \mu^+\mu^-$ candidates using data from CMS and LHCb experiments.

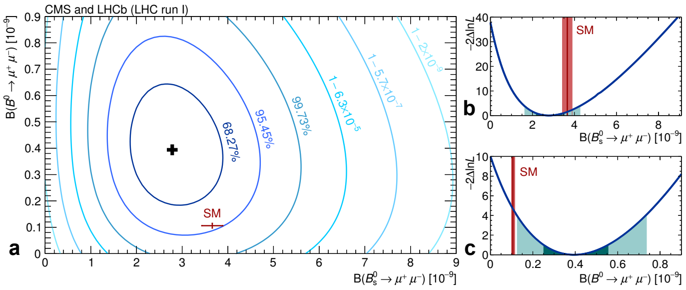

Figure 6: Likelihood profiles for the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ measured branching fractions from a combined analysis of CMS and LHCb data. The SM prediction is shown in red.

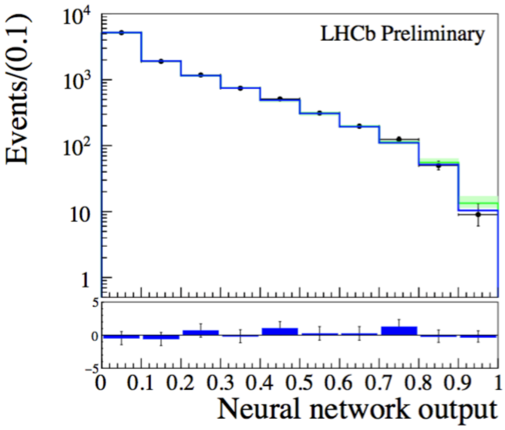

Figure 7: Distribution of a Neural Network output used in the $B^0_{(s)} \to \tau^+\tau^-$ LHCb analysis. Black points correspond to data. The total fit result is shown in blue, and the background component in green. The signal component cannot be shown as it has a negative yield.

6. Summary

In this document, some examples of measurements related with flavour physics and the prediction of new Higgs bosons are presented. A few interesting tensions with the SM arise. For instance, $R(D^{(*)})$ and $R(K)$ show a discrepancy at the level of 3.9 and 2.6 standard deviations, respectively. The precise measurement of these and other flavour physics observables is crucial since they strongly constrain new physics models. Another remarkable example is the sensitivity to very rare decays, such as the $B_{(s)} \to \mu^+\mu^-$ mode, that has reached the 10^{-10} level and will continue to improve with the new LHC run-2 data, the LHCb upgrade and the start of the Belle-II data taking (expected in 2018-2019).

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