Sensitivity to New Physics in the B-Sector

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Abstract. Cosmological arguments suggest that physics beyond the Standard Model, so-called New Physics, is needed to explain the matter-antimatter asymmetry of the universe by providing extra sources of CP-violation. Precision measurements of CP-violation and rare decays in the B-sector offer a very promising way to detect such contributions. After an introduction to the basic phenomenology of CP-violation measurements, the generic signatures for New Physics are presented. Finally some of the current results from the B-factories and the prospects for LHC are discussed.

1 Introduction

Experimental evidence suggests that all hadronic matter of the universe, up to the most distant galaxies, is made of matter rather than antimatter. Neither are significant amounts of annihilation radiation observed, as would be expected from the boundary between matter- and antimatter dominated regions, nor have studies of cosmic rays found any evidence for primordial anti-Helium left over from the Big Bang. This is a very surprising result, since in the Big Bang matter and antimatter were initially created in equal amounts.

The necessary conditions to explain the matter dominance of the universe were first outlined by Sakharov [1]. He showed that the fundamental interactions require C- and CP-violation, baryon-number violation and that the universe must have passed through a phase of thermal non-equilibrium. In principle all these ingredients are realized in Standard Model (SM) based Big Bang cosmology: C- and CP-violation exist in the CKM-sector of the Standard Model, and baryon-number violation via sphalerons can occur during a first order phase transition in the early universe.

Unfortunately, quantitative calculations show that the SM-Higgs particle is too heavy to generate the required phase transition. In addition, the amount of CP-violation is too small to explain the matter dominance of the universe. The fact that extra sources of CP-violation are needed suggests to look for signs of New Physics (NP) in precision measurements of CP-violation. Here the B-sector offers the highest sensitivity.

2 CP-Violation Measurements

CP-violation is conveniently measured by a so-called CP-asymmetry, $A_{CP}$, which for an initial state $x$ decaying into a final state $y$ is defined through

$$A_{CP} = \frac{\Gamma(x \rightarrow y) - \Gamma(x \rightarrow \bar{y})}{\Gamma(x \rightarrow y) + \Gamma(x \rightarrow \bar{y})}.$$  \hspace{1cm} (1)

The quantities $\Gamma(\cdot)$ and $a(\cdot)$ denote the partial widths, and $a(\cdot)$ the corresponding decay amplitudes. An important class are mixing-induced asymmetries of decays into a CP-eigenstate $y = y \epsilon - y \epsilon$. Here the final state can be reached in two ways: either by direct decay with amplitudes $a_D(x \rightarrow y \epsilon)$ and $a_D(x \rightarrow y \epsilon)$, or by mixing transitions with amplitudes $i a_M(x \rightarrow x)$ and $i a_M(x \rightarrow x)$ and subsequent decay. Introducing also the non-mixing amplitudes $a_N(x \rightarrow x)$ and $\bar{a}_N(x \rightarrow x)$, one has

$$a(x \rightarrow y \epsilon) = a_N \cdot a_D + i a_M \cdot \bar{a}_D \hfill \text{and} \hfill a(x \rightarrow y \epsilon) = \bar{a}_N \cdot \bar{a}_D + i a_M \cdot a_D.$$  \hspace{1cm} (2)

The generic forms for the contributing amplitudes are $a_N = \cos(\Delta m t / 2)$, $a_M = \sin(\Delta m t / 2) \epsilon^0$ and $a_D = \Delta \epsilon^0$. Complex conjugation yields $\bar{a}_N, M, D$. The term $\Delta m t$ in the mixing amplitudes is the mass difference of the mass eigenstates, $\phi$ and $\omega$ are the mixing and decay phases, respectively. Substituting these expressions one obtains

$$A_{CP} = -\sin(\Delta m t) \sin(\phi - 2\omega).$$  \hspace{1cm} (3)

Note that the possibility of a CP-asymmetry in mixing induced modes arises only because the factor $i$ in front of the mixing amplitudes makes $a(x \rightarrow y \epsilon) \neq \bar{a}(x \rightarrow y \epsilon)$. This is an example of the general case that in order for a CP-asymmetry to arise, there has to be a phase which is not affected by charge conjugation. Such a phase can also come, for example, from strong interactions, which then allows to observe CP-violation also in charged B-decays.

Finally it should be mentioned that a time dependence proportional to $\sin(\Delta m t)$ in mixing-induced CP-violation is not the only possibility. In addition, there can also be contributions from direct CP-violation, which would add a term proportional to the time dependence of particle
propagation without mixing, \( \cos(\Delta m t) \). Usually the phenomenology will therefore be much richer than the simple example discussed above, providing many observables which are sensitive to phases from the Standard Model and beyond.

3 CKM-Matrix and Unitarity Triangle

Within the Standard Model the phases \( \phi \) and \( \omega \) in eq.(2) arise only from the CKM-matrix [2] elements describing the weak charged current coupling to the different quark flavours

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}.
\]

(3)

The matrix \( V \) is unitary, with in general complex valued matrix elements. Since absolute phases do not affect the physics, as is illustrated by the fact that \( A_{\phi} \) in eq.(2) is only a function of phase differences, there is the possibility to select a phase convention for \( V \) for which the underlying physics becomes most transparent. This is exploited by the Wolfenstein parameterization of the CKM matrix [3]

\[
V = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A \lambda^2 (\rho - i \eta) \\
-\lambda & 1 - \lambda^2/2 & A \lambda^2 \\
A \lambda^2 (1 - \rho - i \eta) & -A \lambda^2 & 1
\end{pmatrix} + O(\lambda^4).
\]

(4)

The expansion parameter \( \lambda \) is the sine of the Cabibbo angle \( \sin \theta_C \approx 0.22 \), the parameters \( A, \rho \) and \( \eta \) are of order unity. The weak couplings within one generation are of \( O(1) \), between different generations they are of \( O(\lambda^2) \) and \( O(\lambda^3) \), for transitions 1 \( \leftrightarrow \) 2, 2 \( \leftrightarrow \) 3 and 1 \( \leftrightarrow \) 3, respectively. This hierarchy is directly related to the mass-hierarchy of the different quarks, since for a degenerate mass spectrum the CKM-matrix would reduce to the unit matrix. In other words, precision measurements in the CKM sector are complementary to the Higgs-search in addressing the problem of the origin of particle masses.

The formal criterion for \( V \) being a unitary matrix is that the scalar product of two rows or two columns satisfies \( R_i \cdot R_j^* = C_i \cdot C_j^* = \delta_{ij} \). Each scalar product being a sum of three complex numbers, the case \( i \neq j \) can be visualized as triangle in the complex plane. To the accuracy of eq.(4) only \( C_1 \cdot C_2^* \) yields a non-degenerate triangle, the so-called Unitarity Triangle (UT). In the Wolfenstein parameterization eq.(4), the UT-angles are directly related to the phases of certain CKM-matrix elements: \( \arg(V_{ud}) = -\beta \), \( \arg(V_{ub}) = -\gamma \). These matrix elements play a role for example in \( B_d \)-mixing (\( V_{td} \)) and in \( B_d \to \tau^+ \tau^- , \rho^+ \rho^- \)-decays (\( V_{ub} \)). Including the next higher order term into eq.(4) one also picks up a phase in the matrix element \( V_{ts} \) which is relevant for \( B_s \)-mixing. It is given by \( \arg(V_{ts}) = \chi + \pi \approx \eta \lambda^2 + \pi \).

4 Probing New Physics

There are several strategies for finding New Physics in \( B \)-meson decays. One approach is to measure Standard Model parameters, such as for example the angles of the Unitarity Triangle, both in processes which are insensitive to New Physics and in decay channels that can have NP contributions. Any discrepancy between the results would point to New Physics. Another ansatz is the study of observables which have a very small expectation value in the Standard Model. Any enhancement due to New Physics thus would be clearly noticeable. Examples for these two scenarios will be discussed below. Finally, a third possibility is the comparison of UT-angles extracted from CP-asymmetries with those from a measurement of the sides of the triangle. Incompatible results would again be indicative of physics beyond the Standard Model.

4.1 The Decay \( B_d \to \phi K_s \)

Figure (1) illustrates how in the Standard Model \( B_d \)-mixing is induced through second order weak transitions. From the Wolfenstein parameterization one sees that in this case the mixing phase comes from \( V_{td} \), which appears twice and thus generates an overall phase of \( \phi_d = 2 \beta \). The dominant tree level decay into \( J/\Psi K_s \) depicted in fig.(2) picks up no additional phase factor. It follows that the CP-asymmetry of the so called “golden decay” \( B_d \to J/\Psi K_s \) measures \( \sin(2\beta) \).

![Fig. 1. Feynman-diagram describing \( B_d \)-mixing through a second order weak process](image)

![Fig. 2. Feynman diagram for the “golden decay” \( B_d \to J/\Psi K_s \)](image)
order is mediated by a QCD penguin. Like the “golden decay”, this process does not pick up additional weak phases in the decay and its CP-asymmetry should also measure \( \sin(2\beta) \).

4.2 The Decay \( B_d \to J/\Psi \phi \)

Another interesting decay channel is the analog of the “golden decay” in the \( B_d \) system. The \( J/\Psi \phi \) final state is obtained from (4.2) by substituting the \( d \)-quark with an \( s \)-quark. In the same way as the “golden decay” measures the \( B_d \)-mixing phase, therefore \( B_d \to J/\Psi \phi \) measures the \( B_s \)-mixing phase \( \phi_s \). It is close to zero in the Standard Model, but can adopt large values in alternative theories. For example, with supersymmetric particles in the box diagrams describing \( B_s \)-mixing, one can have values \( \sin \phi_s \sim 1 \) [4]. Given the existence of a new up-type quark singlet, one would naturally expect \( \sin \phi_s \sim \lambda \) [5].

4.3 FCNC Processes and Rare Decays

In the Standard Model, Flavour Changing Neutral Current (FCNC) processes can arise only through higher order weak transitions and in addition often are GIM suppressed. As a consequence the study of FCNC processes
is a promising field to look for enhancements due to New Physics. A process that has already been observed is the decay $B \rightarrow K^\ast \gamma$, which to leading order proceeds through the diagram shown on the left-hand side of fig. (6) when the emitted photon is on-shell and does not convert into a lepton pair. The generic Standard Model prediction for CP-asymmetries in this type of decays is around 1 percent or below. On the other hand, New Physics with an enhanced chromodynamic dipole operator in the effective $bs\gamma$-vertex could cause large CP-asymmetries [6].

Even more interesting are the decays $B \rightarrow \mu^+\mu^-X$ depicted in fig. (8), with, for example, $X = K^\ast, \rho, \phi$. In addition to the electromagnetic penguin which mediates $B \rightarrow K^\ast \gamma$, one has contributions from a weak penguin and from box diagrams, which lead to a much richer phenomenology. For example, the Z-boson in the weak penguin could be replaced by an extra heavy $Z'$, or, like in the case of mixing diagrams, supersymmetric particles could contribute to the box graphs.

Also from the experimental point of view the study of FCNC processes of the type $B \rightarrow \mu^+\mu^-X$ is very attractive, since the generic signature of a detached vertex with two muons is very clean. Selecting specific final states $X$, such as $X = K^\ast, K^0$, allows further background suppression. Even though the theory point of view inclusive measurements which integrate over all final states $X$ are preferred, but also for exclusive final states the Standard Model prediction is rather reliable. This is particularly true for ratios, such as the forward-backward asymmetry $A_{FB}$ of the final state muons with respect to their combined momentum, which is shown in fig. (7) as a function of the square of the di-muon invariant mass, $s$. One clearly sees the contributions from the $J/\psi$ and the $\Upsilon$ on top of a non resonant background. For the latter, the Standard Model predicts a zero crossing in $A_{FB}$ at a value $s \approx 3$ GeV$^2$, whereas supersymmetry naturally expects no change of sign.

Via crossing symmetry and allowing to substitute the $s$-quark by a $d$-quark, the $b \rightarrow s$ transition in the diagrams of fig.(8) also describes the rare decays $B_{d,s} \rightarrow \mu^+\mu^-$. These decays are experimentally very clean, and in the presence of New Physics could be significantly enhanced. For example, given the ratio $\tan\beta$ of the vacuum expectation values of the two Higgs doublets in the MSSM, an enhancement proportional to $\tan^6\beta$ is expected.

5 Experimental Constraints on New Physics

Apart from providing a highly successful description of the fundamental interactions between all elementary particles, the Standard Model also defines the starting point in any search for New Physics. Therefore, in a phenomenological approach the generic form of a Lagrangian containing New Physics can be written as

$$\mathcal{L} = \mathcal{L}_{SM}^{\gamma\gamma} + \mathcal{L}_{SM}^{\rho\rho} + \mathcal{L}_{SM}^{\phi\phi} + \frac{1}{\Lambda} \mathcal{L}^{(5)} + \frac{1}{\Lambda^2} \mathcal{L}^{(6)} + \ldots$$

The NP terms proportional to $\mathcal{L}^{(5)}$ would contribute for example to $(g - 2)$ or to $b \rightarrow s\gamma$ penguin decays, terms from $\mathcal{L}^{(6)}$ could show up in FCNC processes. An analysis to extract New Physics contributions from deviations to the Standard Model could either start from a specific NP model and determine masses and coupling constants for this particular model, or be performed in a model independent way. Here the observed deviations are interpreted in terms of generic NP operators and allow to extract the scale $\Lambda$ where NP starts to contribute. From precision measurements in the $B$-system one expects sensitivities for $\Lambda$ in the range from a few-100 GeV up to a few TeV, i.e. very similar to the sensitivity of direct searches at LHC.

A first flavour of the quality of results that can be expected at LHC can already be obtained from current measurements at the $B$-factories. Figure (8) shows one example from the combination of two measurements, the ratio $W_{bs}/V_{cd}$ measured in semi-leptonic $B$-decays, and a first measurement of the UT-angle $\gamma$ from tree-level dominated $B^\pm \rightarrow D^{\pm\ast}K^\pm$ decays. These two results do already significantly constrain the position of the apex of the Unitarity Triangle, giving one solution [8] for $\sin^2 2\theta = 0.724 \pm 0.074$, which is perfectly consistent with the world average [9]...
Fig. 8. Determination of the apex of the Unitarity Triangle from tree-level dominated measurements.

from the “golden decay” sin 2\(\beta\) = 0.69 ± 0.03. Assuming that the tree level processes contributing to the measurements in fig.8 are unaffected by New Physics, then NP contributions in \(B_d\)-mixing can only be large if they have the same phase as the SM terms. Otherwise the limit is \(\sim 10\%\) [16]. It follows, that New Physics is either of the type “Minimal Flavour Violation”, i.e. it does not contribute new phases w.r.t. the CKM-sector, or that new CP-violating effects are limited to the \(B_s\)-sector.

Another interesting compilation [9] is shown in fig.(9). Here results from different CP-asymmetries sensitive to sin 2\(\beta\) (sin 2\(\phi_1\) in the Belle-nomenclature) are collected and compared to the world average from \(B_d \rightarrow J/\psi K_s\). Although generally compatible with each other and the global average, the results all tend to lie below the average. Since the different channels are affected differently by New Physics or higher order SM corrections, straight averaging may not be appropriate to combine these numbers into one more precise figure. On the other hand, independently of any details in the underlying physics and assuming that the true value is the same in all cases, the probability that from a total of 14 measurements at most two results fluctuate above the world average is only \(p \approx 0.0055\).

Fig. 9. CP-asymmetries sin 2\(\beta\)\(^{\text{eff}}\) from different decay channels sensitive to sin 2\(\beta\) in comparison to the world average from the “golden decay”.

6 B-Physics at LHC

At the Large Hadron Collider, LHC, B-physics will be studied with two general purpose detectors ATLAS [11] and CMS [12], and a dedicated B-physics experiment, LHCb [13]. The former two are designed for high luminosity running and provide hermetic coverage, which is essential for Higgs and SUSY discovery. The LHCb detector is a single arm forward spectrometer, optimized for the requirements of B-physics. At LHC energies these are characterized by the fact that \(b\bar{b}\)-pairs created in pp-collisions are preferentially emitted under small angles relative to the beam direction. Since in most cases both quarks go into the same hemisphere, a single arm spectrometer offers a cost-effective way to cover the relevant phase space. At LHC the b-cross section is expected to be \(\sigma_b = 0.5\) mb. This is around 0.5% of the total cross section, i.e. LHC is a genuine B-factory. Already at a luminosity of \(\mathcal{L} = 2 \times 10^{33}\) cm\(^{-2}\) s\(^{-1}\), the nominal operating point of LHCb, which can be adjusted independently of the other experiments, b-events are produced at a rate of 100 kHz. This results in a total of 2 - 10\(^8\) B-hadrons per nominal year of running. ATLAS and CMS are expected to operate initially at \(\mathcal{L} = 10^{33}\) cm\(^{-2}\) s\(^{-1}\) before going up to the design luminosity of \(\mathcal{L} = 10^{34}\) cm\(^{-2}\) s\(^{-1}\).

The phase space coverage of these experiments is shown in fig.(10). LHCb can measure down to \(p_T = 2\) GeV and thereby, despite its small angular coverage 1.9 < \(\eta\) < 4.9, has access to a visible b-cross section \(\sigma_b = 230\) nb. In contrast, ATLAS and CMS cover the central range \(|\eta| < 2.5\) but will operate at higher luminosities and thus have to raise the \(p_T\)-threshold to values around 10 GeV in order to achieve sufficient background reduction.

The trigger of LHCb is sensitive to both lepton and hadronic B-decays, with a logging rate of 200 Hz for exclusive B-candidates, 500 Hz for high mass di-muon pairs, 300 Hz for D* candidates and 900 Hz for an inclusive b-trigger using single high-\(p_T\) leptons. The other LHC experiments will do B-physics mainly by exploiting a high-\(p_T\)-muon trigger, with an expected logging rate around 10 Hz. The large \(p_T\)-threshold and the focus on final states with muon pairs is necessary to get rid of QCD background. Typical examples for the B-physics program of
ATLAS and CMS therefore are measurements of $\sin 2\beta$ in the “golden decay” $B_d \rightarrow J/\psi K^*_s$, or studies of the FCNC processes $B_d \rightarrow \mu^+ \mu^-$, with $X = K^* \mu, \nu$, and rare decays such as $B_{d,s} \rightarrow \mu^+ \mu^-$. In this kind of reactions the large detectors can be expected to be competitive with LHCb.

Table (1) illustrates how many signal events are expected by the various experiments for one nominal year of running, corresponding to an integrated luminosity of 2 fb$^{-1}$ for LHCb and 100 fb$^{-1}$ for ATLAS and CMS. The numbers show how the potential advantage of being able to run at high luminosities is lost to a large extent by the requirement to fight the background.

Studies by the LHCb collaboration indicate that with two years of nominal running the zero crossing in the forward-backward asymmetry shown in fig.7 for $B_d \rightarrow K^* \mu^+ \mu^-$ can be determined with an error $\Delta s(\mu^+ \mu^-) \sim 1 \text{ GeV}^2$. This would be highly significant to distinguish between the Standard Model and alternative, supersymmetric, theories.

Using the particle identification capabilities provided by the two RICH detectors, the calorimeters and the muon system, LHCb will be able to measure precisely also purely hadronic $B$-decays. It will thus provide precision measurements for many interesting decay channels both in the $B_d$ and the $B_s$-system, and by over-constraining the Standard Model can be expected to narrow down and hopefully find New Physics.

A measurement which illustrates the importance of precise vertexing for a $B$-experiment is $B_s$-mixing. While ATLAS and CMS have sensitivity up to $\Delta m_s \sim 30 \text{ ps}^{-1}$, LHCb will be able to explore oscillation rates up to $\Delta m_s \sim 60 \text{ ps}^{-1}$ [11]. If the Standard Model is correct, then a measurement of $\Delta m_s$ should be within reach for all LHC experiments. If, however, New Physics induces much faster oscillations in the $B_s$-system, then only LHCb may be able to find them.

### Table 1. Expected SM event yields for some FCNC processes and rare decays at LHC after one nominal year of running.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>BR(SM)</th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \rightarrow K^* \mu^+ \mu^-$</td>
<td>$1.5 \times 10^{-6}$</td>
<td>6650</td>
<td></td>
<td>4400</td>
</tr>
<tr>
<td>$B_d \rightarrow \rho \mu^+ \mu^-$</td>
<td>$10^{-5}$</td>
<td>740</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_d \rightarrow d \rightarrow \pi \mu^+ \mu^-$</td>
<td>$10^{-7}$</td>
<td>1370</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_d \rightarrow \mu^+ \mu^-$</td>
<td>$1.5 \times 10^{-6}$</td>
<td>14</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>$B_s \rightarrow \mu^+ \mu^-$</td>
<td>$3.5 \times 10^{-9}$</td>
<td>92</td>
<td>26</td>
<td>17</td>
</tr>
</tbody>
</table>

### 7 Summary

$B$-Physics is an excellent field to look for New Physics in a way which is complementary to direct searches for supersymmetric particles or other kinds of new particles at high energies. The rich phenomenology of $B$-decays allows to overconstrain the CKM-matrix and, by comparing tree level dominated measurements which are expected to be well described within the Standard Model to penguin- or box-dominated processes, to establish the existence of New Physics. Exploiting the fact that different processes are related at the fundamental level will then also permit to pin down the nature of these NP contributions.

The general purpose detectors ATLAS and CMS, designed to operate at high luminosities, are expected to contribute to the $B$-physics program at LHC by studies of rare decay processes and measurements of muonic final states. LHCb on the other hand, which is optimized for $B$-physics, will in addition be able to measure with high precision also purely hadronic decays. The comparatively low nominal running luminosity will enable LHCb to exploit its full physics potential essentially from day-one of LHC operations.

### References
14. R. Forty, these proceedings.