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Implications of LHCb measurements and future prospects

Summary for input to the European Strategy Preparatory Group

The LHCb collaboration
and
various theorists [†]

Abstract

During 2011 the LHCb experiment at CERN collected $1.0\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 7\,\mathrm{TeV}$ pp collisions. Due to the large production cross-sections, these data provide unprecedented samples of heavy flavoured hadrons. The first results from LHCb have made a significant impact on the flavour physics landscape and have definitively proved the concept of a dedicated experiment in the forward region at a hadron collider. This document, which is a summary of a more detailed article [1], discusses the implications of these first measurements on classes of extensions to the Standard Model, bearing in mind the interplay with the results of searches for on-shell production of new particles at ATLAS and CMS. The physics potential of an upgrade to the LHCb detector, which would allow an order of magnitude more data to be collected, is emphasised.

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Background to the document

During 2011 both the LHC machine and the LHCb detector performed superbly, allowing LHCb to accumulate $1.0\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 7\,\mathrm{TeV}$ pp collisions that is available for physics analysis. Due to the large production cross-sections, these data provide unprecedented samples of heavy flavoured hadrons. The first results from LHCb have made a significant impact on the flavour physics landscape and have definitively proved the concept of a dedicated experiment in the forward region at a hadron collider.

The results to date cover several topics in the core flavour physics programme of LHCb in rare decays and *CP* violation. This programme is focussed on searching for physics beyond the Standard Model (SM) – referred to as "New Physics" (NP) – with an approach that is complementary to that used by the ATLAS and CMS experiments. While the high-p_{T} experiments search for on-shell production of new particles, LHCb can look for their effects in processes that are precisely predicted in the SM. In particular, the SM has a highly distinctive flavour structure, with no tree-level flavour-changing neutral currents, and quark-mixing described by the Cabibbo-Kobayashi-Maskawa quark mixing matrix [2] with a single source of *CP* violation, that is not necessarily replicated in extended models. Historically, new particles have first been seen through their virtual effects since this approach allows to probe beyond the energy frontier. For example, the observation of *CP* violation in the kaon system [3] was, in hindsight, the discovery of the third family of quarks, over 30 years before the observation of the top quark. Crucially, measurements of both high-p_{T} and flavour observables are necessary in order to understand the origin of NP.

In many channels, the LHCb results are already the world's most precise, and begin to reach the sensitivity where small deviations from Standard Model predictions may be observed. In several areas hints of large anomalies from previous measurements have not been confirmed: the branching fraction of $B^0_s \to \mu^+\mu^-$ [4], the forward-backward asymmetry of $B^0 \to K^{*0}\mu^+\mu^-$ [5] and the *CP*-violation phase in B^0_s oscillations [6] are all found to be consistent with the Standard Model, within current uncertainties. The situation regarding flavour-specific *CP* asymmetries in the B^0 and B^0_s system is still ambiguous [7]. Nevertheless, in all these cases more precise measurements are mandatory. Moreover, in other channels there are strengthened, or new, hints of unexpected effects: for example evidence of *CP* violation in the charm system [8] and anomalous isospin asymmetry in $B \to K\mu^+\mu^-$ decays [9]. These also demand to be followed up with more data, and with studies of complementary decay channels.

The physics output of LHCb also extends beyond this core programme. Examples of other topics include measurements of the production of electroweak gauge bosons in the forward kinematic region covered by the LHCb acceptance [10], studies of double parton scattering [11], and searches for exotic hadrons [12], for lepton number violation [13, 14], and for long-lived new particles [15].

In order to discuss the implications of its first measurements, and possibilities for future analysis directions, the LHCb collaboration arranged two workshops with theorists as satellite meetings of the series on implications of LHC results for TeV-scale physics.

The first was held on 10–11 November 2011, the second on 16–18 April 2012. These meetings focussed on the observables that are sensitive to physics beyond the Standard Model, such as models that predict new particles at the TeV scale – they were arranged in three main strands: rare charm and beauty decays, *CP* violation in the B system and mixing and *CP* violation in the charm sector. The interplay with the results of searches for on-shell production of new particles at ATLAS and CMS is therefore highly relevant and was discussed both in the LHCb meetings as well as in the main series of "Implications" workshops.

The full version of this document [1] gives a detailed summary of these workshops. It highlights the impact of the first results from LHCb, and emphasises the need to exploit fully the flavour physics potential of the LHC. This motivates a reassessment of the potential sensitivity of the upgraded LHCb experiment in the light of the latest results, as discussed below.

Highlights of LHCb measurements and their implications

Rare decays

Among rare decays, the LHCb limit on the rate of the decay $B_s^0 \to \mu^+\mu^-$ [4] places stringent limits on NP models that enhance the branching fraction. The measurement can be compared to the Standard Model prediction [16]:

$$\begin{aligned} \mathcal{B}(B_s^0 \to \mu^+\mu^-) &< 4.5 \times 10^{-9}\ (95\,\%\ \text{confidence level})\,, && (1) \\ \mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} &= (3.53 \pm 0.38) \times 10^{-9}\,. && (2) \end{aligned}$$

It should be noted that the measured value is the time-integrated branching fraction, and the SM prediction should be increased by around 10 % to allow a direct comparison [17]. This constraint effectively rules out large values of $\tan\beta$, *i.e.* of the ratio of vacuum expectation values of the Higgs doublets, in constrained supersymmetric models see, for example, Refs. [18, 19]). As a consequence, there is – within such models – a tension between the limit on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and the measurement of the anomalous magnetic moment of the muon [20]. Further measurements are needed to resolve the situation. In addition, models where the branching fraction is reduced below its SM value due to interference effects are starting to receive serious consideration.

The measurement of the forward-backward asymmetry in $B^0 \to K^{*0}\mu^+\mu^-$ [5] has to be viewed as the start of a programme towards a full angular analysis of these decays. The measurements that will be obtained from such an analysis, as well as similar studies of related channels, such as $B_s^0 \to \phi\mu^+\mu^-$ [21], allow model-independent constraints on NP, manifested as limits on the operators of the heavy quark effective theory (see, for example, Ref. [22]). Studies of radiative decays such as $B_s^0 \to \phi\gamma$ [23] provide additional constraints since they allow to measure the polarisation of the emitted photon. Similarly, studies of observables such as isospin asymmetries [9] are important since they allow to pin down in which operators the NP effects occur.

CP violation in the *B* sector

Measurements of the neutral B meson mixing parameters provide an excellent method to search for NP effects, due to the low theoretical uncertainties associated to several observables. The measurements of $\Delta\Gamma_s$ and ϕ_s [6, 24–26] by LHCb significantly reduce the phase space for NP. However, deviations from the SM are still possible and improved measurements are needed to reach the level of sensitivity demanded by theory. In particular, to understand the origin of the anomalous dimuon asymmetry seen by D0 [27], improved measurements of semileptonic asymmetries in both B^0_s [7] and B^0 systems are needed. Moreover, a constraint on, or a measurement of, the rate of the decay $B^0_s \to \tau^+\tau^-$ is important to provide knowledge of possible NP contributions to Γ_{12}.

Among the B^0 mixing parameters, improved measurements of both ϕ_d (*i.e.*, $\sin(2\beta)$) and $\Delta\Gamma_d$ are needed. Reducing the uncertainty on the former will help to improve the global fits to the CKM matrix [28, 29], and may clarify the current situation regarding the tension between measurements of $\sin(2\beta)$ and $\mathcal{B}(B^+ \to \tau^+\nu)$. Another crucial observable in this respect is the angle γ, which provides a benchmark measurement of *CP* violation. The first measurements from LHCb already help to improve the uncertainty on γ [30]: further improvements are both anticipated and needed.

Knowledge of γ from tree-dominated processes is also essential to test the consistency with measurements from loop dominated processes. In particular, the study of $B^0_s \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ decays [31], which are related by U-spin, allows a powerful test of the consistency of the observables with the SM. Similarly, the U-spin partners $B^0_s \to K^{*0}\overline{K}^{*0}$ [32] and $B^0 \to K^{*0}\overline{K}^{*0}$ are golden channels to search for NP contributions in $b \to sq\bar{q}$ penguin amplitudes. Another important channel in this respect is $B^0_s \to \phi\phi$ [33], for which the *CP* violating observables are predicted with low theoretical uncertainty in the SM.

Charm mixing and *CP* violation

In the charm sector, the evidence for *CP* violation in the observable ΔA_{CP} [8] has provoked a large amount of theoretical work. The emergent consensus is that while an asymmetry of the order of 1 % is rather unlikely in the Standard Model, it cannot be ruled out that QCD effects cause enhancements of that size. Further measurements are needed in order to establish if NP effects are affecting the charm sector. Among the anticipated results are updates of the ΔA_{CP} measurement as well as of the individual *CP* asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$. It is of great interest to look for direct *CP* violation in decays to other final states, and in decays of other charmed hadrons.

The Standard Model predictions are somewhat cleaner for indirect *CP* violation effects, and therefore it is also essential to search for *CP* violation in charm mixing. New results from time-dependent analyses of $D^0 \to K^+K^-$ [34] and $D^0 \to K^0_S\pi^+\pi^-$ will improve the current knowledge, and additional channels will also be important with high statistics.

Several authors have noted correlations between *CP* violation in charm and various other observables. These correlations appear in, and differ between, certain theoretical models, and can therefore be used to help identify the origin of the effects. Observables of interest in this context include those that can be measured at high-p_{T} experiments, such as $t\bar{t}$ asymmetries, as well as rare charm decays. Among the latter, it has been noted that CP asymmetries are possible in radiative decays such as $D^0 \to \phi\gamma$, and that searches for decays involving dimuons, such as $D^0 \to \mu^+\mu^-$ [35] and $D^+ \to \pi^+\mu^+\mu^-$ are well motivated.

Measurements exploiting the unique kinematic acceptance of LHCb

The workshops mentioned above focussed on the observables, mainly in the flavour sector, most sensitive to physics beyond the Standard Model, but the physics programme of LHCb includes additional topics. These will continue to be important in the upgrade era, since the unique kinematic region covered by the LHCb acceptance enables measurements that cannot be performed at other experiments. These include probes of QCD both in production, such as studies of multi-parton scattering [11,36], and in decay, such as studies of exotic hadrons like the $X(3872)$ [37] and the putative $Z(4430)$ state. Conventional hadrons can also be studied with high precision: one important goal will be to establish the existence of doubly heavy baryons. LHCb may also be able to make a unique contribution to the field of heavy ion physics, by studying soft QCD and heavy flavour production in pA collisions. The first pA run of the LHC will clarify the potential of LHCb in this field.

Measurements of production rates and asymmetries of electroweak gauge bosons in the LHCb acceptance are important to constrain parton density functions (PDFs) [10]. With high statistics LHCb will be well placed to make a precision measurement of the sine of the effective electroweak mixing angle for leptons, $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, from the forward-backward asymmetry of leptons produced in the $Z \to \mu^+\mu^-$ decay. Improved knowledge of PDFs, as can be obtained from studies of production of gauge bosons in association with jets [38], will help to reduce limiting uncertainties on the measurement of the W boson. These studies are also an important step towards a top physics programme at LHCb, which will become possible once the LHC energy approaches the nominal 14 TeV.

The forward geometry of LHCb is advantageous to observe new long-lived particles that are predicted in certain NP models. Although limits can be set with the current detector [15], this is an area that benefits significantly from the flexible software trigger of the upgraded experiment. Similarly, the efficiency to trigger on signatures of central exclusive production will be increased, allowing studies of various hadronic states, including the $X(3872)$.

Sensitivity of the upgraded LHCb experiment to key observables

Given the strong motivation to exploit fully the flavour physics potential of the LHC, it is timely to update the estimated sensitivities for various key observables based on the results to date. A detailed description of the upgraded LHCb experiment can be found in the Letter of Intent (LoI) [39], complemented by the recent framework technical design report (FTDR) [40], which sets out the timeline and costing for the project. The upgrade is necessary to progress beyond the limitations imposed by the current hardware ("level 0") trigger that, due to its maximum output rate of 1 MHz, leads to a maximum instantaneous luminosity at which data can most effectively be collected. To overcome this, the upgraded detector will be read out at the maximum LHC bunch-crossing frequency of 40 MHz so that the trigger can be fully implemented in software. With such a flexible trigger strategy, the upgraded LHCb experiment can be considered as a general purpose detector in the forward region. The upgraded detector will be installed during the long shutdown of the LHC planned for 2018.

Several important improvements compared to the current detector performance can be expected in the upgrade era, as detailed in the LoI and FTDR. However, the sensitivity studies that have been performed assume detector performance as achieved during 2011 data taking. The exception is in the trigger efficiency, where channels selected at level 0 by hadron, photon or electron triggers are expected to have their efficiencies double (channels selected by muon triggers are expected to have marginal gains, that have not been included in the extrapolations). Several other assumptions are made:

- LHC collisions will be at $\sqrt{s} = 14\,\text{TeV}$, with heavy flavour production cross-sections scaling linearly with $\sqrt{s}$;
- the instantaneous luminosity in LHCb will be $\mathcal{L}_{\text{inst}} = 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$: this will be achieved with 25 ns bunch crossings and an average number of visible interactions per crossing $\mu = 2$;
- the external crossing angle of the beams will be in the vertical plane (as already implemented for 2012 data taking);
- LHCb will change the polarity of its dipole magnet with similar frequency as in 2011/12 data taking, to approximately equalise the amount of data taken with each polarity for better control of certain potential systematic biases;
- the integrated luminosity will be $\mathcal{L}_{\text{int}} = 5\,\text{fb}^{-1}$ per year, and the experiment will run for 10 years to give a total sample of $50\,\text{fb}^{-1}$.

The sensitivity to various flavour observables is summarised in Table 1. This is an updated version of a similar summary that appears as Table 2.1 in the LoI [39], and also appears in the FTDR [40]. The measurements considered include *CP*-violating observables, rare decays and fundamental parameters of the CKM Unitarity Triangle, and are described below. The current precision, either from LHCb measurements or averaging groups [28,29,41] is given and compared to the estimated sensitivity with the upgrade. As an intermediate step, the estimated precision that can be achieved prior to the upgrade is also given for each observable. For this, a total integrated luminosity of 1.0 (1.5, 4.0) fb^{-1} at *pp* centre-of-mass collision energy $\sqrt{s} = 7\ (8, 13)\ \text{TeV}$ recorded in 2011 (2012, 2015–17) is assumed. Another assumption is that the current efficiency of the muon hardware trigger can be maintained at higher $\sqrt{s}$, but that higher thresholds will be necessary for other triggers, reducing the efficiency for the relevant channels by a factor of 2 at $\sqrt{s} = 13\,\text{TeV}$.

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [24]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [26]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [41]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [41]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [42]	0.025	0.008	0.02
	$s_0\,A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [42]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [43]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [28, 29]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [41]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [41]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\mathrm{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.

The extrapolations assume the central values of the current measurements, or the Standard Model where no measurement is available. While the sensitivities given include statistical uncertainties only, preliminary studies of systematic effects suggest that these will not affect the conclusions significantly, except in the most precise measurements, such as those of $A_{\rm fs}(B_s^0)$, A_Γ and ΔA_{CP}. Branching fraction measurements of B_s^0 mesons require knowledge of the ratio of fragmentation fractions f_s/f_d for normalisation [44]. The uncertainty on this quantity is limited by knowledge of the branching fraction of $D_s^+ \to K^+K^-\pi^+$, and improved measurements of this quantity will be necessary to avoid a limiting uncertainty on, for example, $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$. The determination of $2\beta_s$ from $B_s^0 \to J/\psi\,\phi$ provides an example of how systematic uncertainties can be controlled for measurements at the LHCb upgrade. In the most recent measurement [24], the largest source of systematic uncertainty arises due to the constraint of no direct *CP* violation that is imposed in the fit. With larger statistics, this constraint can be removed, eliminating this source of uncertainty. Other sources, such as the background description and angular acceptance, are already at the 0.01 rad level, and can be reduced with more detailed studies.

In the Standard Model (SM), the parameters of *CP* violation in B_s^0 mixing are highly constrained to be close to zero by global fits to the CKM matrix. LHCb has measured the mixing phase $2\beta_s = -\phi_s$ in both $J/\psi\,\phi$ and $J/\psi\ f_0(980)$ final states, with results that are consistent with the SM within the uncertainties [24, 26]. However, tensions in the global CKM fits (see, for example, Ref. [45]) suggest that deviations may be present at the level of a few degrees (~ 0.04 rad, in the units of Table 1), motivating much more precise measurements. A complementary measurement, $A_{\rm fs} = A_{\rm sl}$, can be made using semileptonic decays. This analysis requires excellent control of systematic uncertainties to be sensitive to small deviations from the SM prediction of $\mathcal{O}(10^{-4})$.

Decays dominated by $b \to s$ loop (penguin) transitions provide additional sensitivity to contributions beyond the SM. The B_s^0 decays to $\phi\phi$ and $K^{*0}\overline{K}^{*0}$ final states, both already observed at LHCb [32, 33], are particularly interesting since these effects could appear in both time-dependent and angular distributions. Another important measurement is that of the time-dependent decay distribution in $B_s^0 \to \phi\gamma$ decays. Determination of the effective *CP*-violation and lifetime parameters provides the most promising way to study the polarisation of the emitted photon, and is therefore uniquely sensitive to models that predict new right-handed currents.

Rare decays involving dimuon pairs constitute a significant part of the flavour physics programme of the LHCb experiment, and this will remain the case in the upgrade. As statistics increase, a larger set of angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ decays can be measured. The first measurement of the zero-crossing point (s_0) of the forward-backward asymmetry in this decay has recently been presented by LHCb [42], demonstrating the potential for the upgrade to fully explore the phase space for contributions beyond the SM. Another important observable with low theoretical uncertainty is the transverse polarisation asymmetry, which is probed by the parameter S_3.

LHCb has also recently published the world's most precise measurements of isospin asymmetries in $b \to s\mu^+\mu^-$ decays [9]. These have generated significant interest in the theory community, and this sector will be further explored as more data are accumulated. Similarly, the first observation of $B^+ \to \pi^+\mu^+\mu^-$ [43] shows the potential for a measurement of $|V_{td}/V_{ts}|$ in loop-mediated transitions. Note that some values quoted in Table 1 are integrated over the dimuon invariant mass range $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ to give a representative estimate of the sensitivity – however the full differential distribution will be studied.

The rare decay $B^0_s \to \mu^+\mu^-$ is a golden channel to search for effects beyond the SM. Although the latest measurement from LHCb [4] rules out new contributions of comparable size to that from the SM, much more precise measurements are well motivated since the theoretical prediction for the branching fraction has low uncertainty and the true value may be smaller than the SM expectation. With the $50\,\mathrm{fb}^{-1}$ data set it will also be possible to measure the rate of the B^0 decay to two muons down to the SM prediction: the ratio of B^0 to B^0_s branching fractions is given by $|V_{td}/V_{ts}|^2$ in the SM and any extension with minimal flavour violation, making this a crucial channel to diagnose the origin of any non-SM contributions.

The measurement of the angle γ of the Unitarity Triangle from $B \to DK$ decays is a SM benchmark. The first results from LHCb [30] already make a significant impact on the global averages – however, measurements at the degree-level of sensitivity are necessary to match the precision in lattice QCD. Similarly, improved measurements of the angle β will further constrain the global fits, and may reveal contributions beyond the SM if the "tensions" that are present in the current data persist.

In the charm sector, the evidence for *CP* violation from LHCb [8] has prompted a great deal of theoretical interest, which has highlighted several other observables that should be measured. Although hadronic uncertainties cloud the interpretation of the current measurement, when additional observables are measured it will be possible to constrain these effects, and hence to determine if the origin of the asymmetry is from physics beyond the SM. It is particularly important to be able to distinguish *CP*-violation effects from charm mixing and those from decay.

Although other experiments will study flavour-physics observables in a similar time-frame to the LHCb upgrade, the sample sizes in most exclusive B and D final states will be far larger than those that will be collected elsewhere, for example at the upgraded e^+e^- B factories. The LHCb upgrade will have no serious competition in its study of B^0_s decays and *CP* violation. Similarly the yields in charmed-particle decays to final states consisting of only charged tracks cannot be matched by any other experiment.

References

[1] LHCb collaboration, LHCb-PUB-2012-006.

[2] N. Cabibbo, Phys. Rev. Lett. **10** (1963) 531; M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.

[3] J. Christenson, J. Cronin, V. Fitch, and R. Turlay, Phys. Rev. Lett. **13** (1964) 138.

[4] LHCb collaboration, R. Aaij *et al.*, `arXiv:1203.4493`.

[5] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **108** (2012) 181806, `arXiv:1112.3515`.

[6] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **108** (2012) 101803, `arXiv:1112.3183`.

[7] LHCb collaboration, LHCb-CONF-2012-022.

[8] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **108** (2012) 111602, `arXiv:1112.0938`.

[9] LHCb collaboration, R. Aaij *et al.*, `arXiv:1205.3422`.

[10] LHCb collaboration, R. Aaij *et al.*, `arXiv:1204.1620`.

[11] LHCb collaboration, R. Aaij *et al.*, `arXiv:1205.0975`.

[12] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. **D85** (2012) 091103, `arXiv:1202.5087`.

[13] LHCb collaboration, R. Aaij *et al.*, `arXiv:1201.5600`.

[14] LHCb collaboration, LHCb-CONF-2012-015.

[15] LHCb collaboration, LHCb-CONF-2012-014.

[16] F. Mahmoudi, S. Neshatpour, and J. Orloff, `arXiv:1205.1845`.

[17] K. de Bruyn *et al.*, `arXiv:1204.1735`.

[18] F. Mahmoudi, `arXiv:1205.3099`, Proceedings of Moriond QCD 2012.

[19] O. Buchmueller *et al.*, Eur. Phys. J. **C72** (2012) 1878, `arXiv:1110.3568`.

[20] Muon g-2 collaboration, G. Bennett *et al.*, Phys. Rev. **D73** (2006) 072003, `arXiv:hep-ex/0602035`.

[21] LHCb collaboration, LHCb-CONF-2012-003.

[22] W. Altmannshofer and D. M. Straub, `arXiv:1206.0273`.

[23] LHCb collaboration, R. Aaij *et al.*, , in preparation.

[24] LHCb collaboration, LHCb-CONF-2012-002.

[25] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **108** (2012) 241801, `arXiv:1202.4717`.

[26] LHCb collaboration, R. Aaij *et al.*, `arXiv:1204.5675`.

[27] D0 collaboration, V. M. Abazov *et al.*, Phys. Rev. **D84** (2011) 052007, `arXiv:1106.6308`, Submitted to Phys. Rev. D.

[28] CKMfitter group, J. Charles *et al.*, Eur. Phys. J. **C41** (2005) 1, `arXiv:hep-ph/0406184`, updated results and plots available at: `http://ckmfitter.in2p3.fr`.

[29] UTfit collaboration, M. Bona *et al.*, JHEP **0507** (2005) 028, `arXiv:hep-ph/0501199`, updated results and plots available at: `http://www.utfit.org/UTfit/`.

[30] LHCb collaboration, R. Aaij *et al.*, Phys. Lett. **B712** (2012) 203, `arXiv:1203.3662`.

[31] LHCb collaboration, LHCb-CONF-2012-007.

[32] LHCb collaboration, R. Aaij *et al.*, Phys. Lett. **B709** (2012) 50, `arXiv:1111.4183`.

[33] LHCb collaboration, R. Aaij *et al.*, `arXiv:1204.2813`.

[34] LHCb collaboration, R. Aaij *et al.*, JHEP **04** (2012) 129, `arXiv:1112.4698`.

[35] LHCb collaboration, LHCb-CONF-2012-005.

[36] LHCb collaboration, R. Aaij *et al.*, Phys. Lett. **B707** (2012) 52, `arXiv:1109.0963`.

[37] LHCb collaboration, R. Aaij *et al.*, `arXiv:1112.5310`.

[38] LHCb collaboration, LHCb-CONF-2012-016.

[39] LHCb collaboration, CERN-LHCC-2011-001. LHCC-I-018.

[40] LHCb collaboration, CERN-LHCC-2012-007. LHCB-TDR-012.

[41] Heavy Flavor Averaging Group, D. Asner *et al.*, `arXiv:1010.1589`, updated results and plots available at: `http://www.slac.stanford.edu/xorg/hfag/`.

[42] LHCb collaboration, LHCb-CONF-2012-008.

[43] LHCb collaboration, LHCb-CONF-2012-006.

[44] LHCb collaboration, R. Aaij *et al.*, Phys. Rev. **D85** (2012) 032008, `arXiv:1111.2357`.

[45] E. Lunghi and A. Soni, Phys. Lett. **B697** (2011) 323, `arXiv:1010.6069`.