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Physics opportunities with LHCb and its planned upgrade

The LHCb Collaboration[1]

Abstract

We describe the physics opportunities opened using LHCb data, and the potential impact in discovering and understanding physics beyond the Standard Model, using the current data and that from the planned upgrade. A short summary of the upgrade plans and schedule is also given.

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1 Introduction

There are several problems in high-energy physics that the Standard Model (SM) cannot explain. Baryogenesis, the current dominance of matter over anti-matter requires, according to current models, much more CP violation than can be obtained from SM quark mixing [1]. The SM also cannot explain dark matter affecting stars orbiting in galaxies, and the "hierarchy problem," which can be summarized as our lack of understanding how to get from the Planck scale of Energy $\sim 10^{19}$ GeV to the Electroweak scale $\sim$100 GeV without fine-tuning quantum corrections.

While the LHC provides enough energy that new particles could appear in direct production, or that extra dimensions could be revealed, in any scenario of new physics the direct manifestations do not serve to specify sufficiently its properties. For example, in Supersymmetry (SUSY) there are many possible models. Even in the minimal version (MSSM) there are 120 free parameters, and what is found may not be minimal. Besides, other models, e.g. Little-Higgs, Technicolor, etc., could be hard to distinguish from SUSY. The main purpose of LHCb is to discover, and define the properties of, physics beyond the SM. This is a powerful approach because decays of b and c quarks can probe large mass scales via virtual quantum loops. Historically, the effects of new particles have been observed first in loop processes before their production at energy frontier machines.

Searches via quantum loops already have reached quite large mass scales given certain assumptions. Consider an effective Lagrangian given as $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{c_i}{\Lambda_i}\mathcal{O}_i$, where $\mathcal{O}_i$ corresponds to new physics operators, and Λ_i the mass scale. Taking the coupling constants c_i to be unity, the new physics reach in terms of mass scale (Λ_i) for various processes in flavor physics can be in the range of 10–10^5 TeV (for a detailed discussion see Ref. [2]).

However, these limits can be avoided if the new particles are degenerate in mass, or the mixing angles in the new physics sector may be the same as in the SM: this is known as Minimal Flavor Violation [3]. Collectively these considerations already provide strong constraints on new physics. To set limits on new physics one needs to adopt a specific scenario. One approach is to assume that tree-level diagrams (i.e. those without loops) are dominated by the SM while loop diagrams contain both SM and possibly new physics.

The CKM quark mixing matrix has four independent parameters, that in the Wolfenstein formalism are labeled A, λ, ρ and η [4]. The values of A and λ are well-known and are about 0.8 and 0.225, respectively [5]. Many flavor physics observables depend on an algebraic combination of ρ and η so the results are typically shown as bands on a ρ–η plot. Analysis of data involving only tree diagrams (Fig. 1(a)) and loop diagrams (Fig. 1(b)) is provided by the CKM fitter group [6]. A comparison of these measurements shows that the agreement is only at the 5% confidence level, leaving a lot of room for new physics. LHCb and its upgrade offer unique possibilities to enhance our knowledge of CKM structure to unprecedented levels.

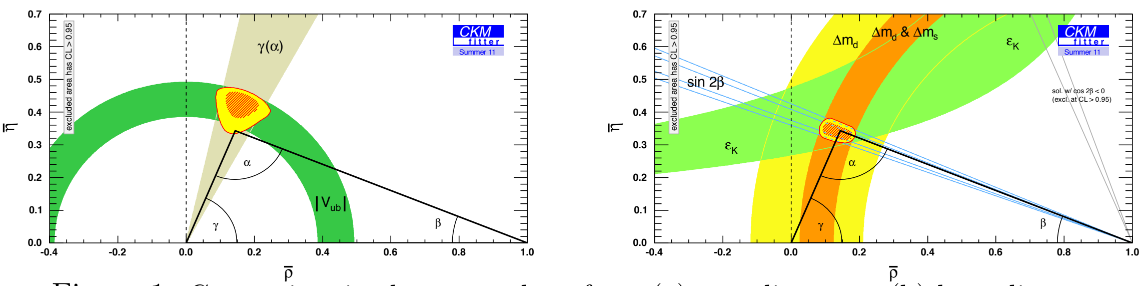

Figure 1: Constraints in the $\rho - \eta$ plane from (a) tree diagrams, (b) loop diagrams.

2 The LHCb detector

LHCb is a forward spectrometer, with its detector elements placed along the beam line of the LHC as shown in Fig. 2 [7]. The Vertex Locator (VELO), a silicon strip device, surrounds the proton-proton interaction region and is positioned with its sensitive area 8 mm from the beam during collisions. It provides precise locations for primary pp interaction vertices, the locations of decays of long-lived particles, and contributes to the measurement of track momenta. Other devices used to measure track momenta comprise a large area silicon strip detector (TT) located in front of a 4 Tm dipole magnet, and a combination of silicon strip detectors (Inner Tracker, IT) and straw drift chambers (Outer Tracker, OT) placed behind. Two ring-imaging Cherenkov (RICH) detectors are used to identify charged hadrons. Further downstream an Electromagnetic Calorimeter (ECAL) is used for photon detection and electron identification, followed by a Hadron Calorimeter (HCAL), and a Muon system consisting of alternating layers of iron and chambers (MWPC and triple-GEM) that distinguishes muons from hadrons. The ECAL, HCAL and Muon system provide the capability of first-level hardware triggering.

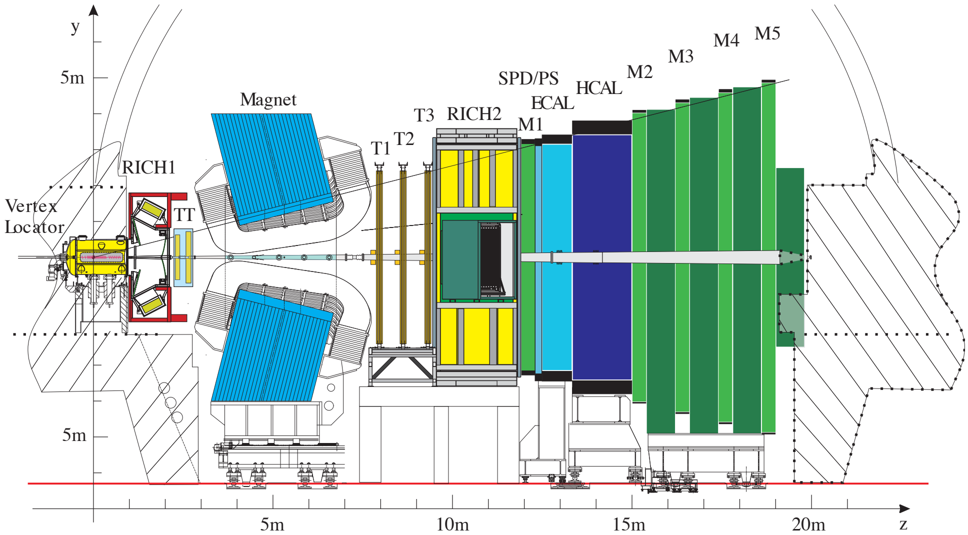

Figure 2: Layout of the LHCb detector.

The experiment currently runs at an instantaneous luminosity of $3.5 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a value that is maintained constant due to the ability to make small displacements in the radial bunch separation between the two beams ("luminosity leveling"), and an average number of interactions per crossing of $\mu \sim 1.6$. This rate is about twice the original planned instantaneous luminosity and four times the expected μ. In 2011 LHCb has accumulated in excess of 1 fb^{-1} of data, and expects to collect the same amount, or more, in 2012. The LHC will undergo a conversion to 14 TeV center-of-mass energy in 2013–14, so as to run the experiments at this energy in years 2015–17. It is expected that LHCb will accumulate at least another 3 fb^{-1} before the long shutdown in 2018. Note that the $b\bar{b}$ cross-section will increase by about a factor of two due to the increase in energy, bringing the total yield of collected data in interesting channels to at least a factor 8 with respect to the 2011 statistics. LHCb is planning to be ready with an upgraded detector in 2018, which will allow the experiment to run up to luminosities of 1–2 $\times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with a substantial increase of trigger efficiency for hadronic final states. In 2011 the LHCb collaboration submitted a Letter of Intent [8] to the LHC Committee which has approved the physics case and has endorsed the preparation of a Technical Design Report [9] by 2013. More details about the upgrade are given in Sec. 5.

3 Recent LHCb physics results

Already in 2011, using up to 0.4 fb^{-1}, LHCb has started to produce world-best results in flavor physics, particularly for B_s^0 decays. Among the most important are the determination of the CP violating phase ϕ_s, the search for the rare decay $B_s^0 \to \mu^+\mu^-$, and the study of the forward-backward asymmetry in $B^0 \to K^{*0}\mu^+\mu^-$ decays.

Measurement of the phase ϕ_s in $B_s^0 \to J/\psi\,\phi$ decays by the CDF and D0 experiments showed a possible large phase, in disagreement with the small SM expectation. The LHCb result [10] does not support a large phase, and has much smaller errors than the previous experiments (the clean, high-statistics signal is shown in Fig. 3, and the results in Fig. 4). This measurement has been confirmed by an independent measurement of ϕ_s using the $B_s^0 \to J/\psi\, f_0(980)$ decay [11], for which angular decomposition is not required. This mode was discovered by LHCb using 35 pb^{-1} [12] and appears promising as it shows a very small level of systematic uncertainty. LHCb combined these data to produce an overall result of $\phi_s = -0.03 \pm 0.16 \pm 0.07\,\text{rad}$, and the first significant direct observation of the width difference in the B_s^0 system, $\Delta\Gamma_s = 0.123 \pm 0.029 \pm 0.008\,\text{ps}^{-1}$.

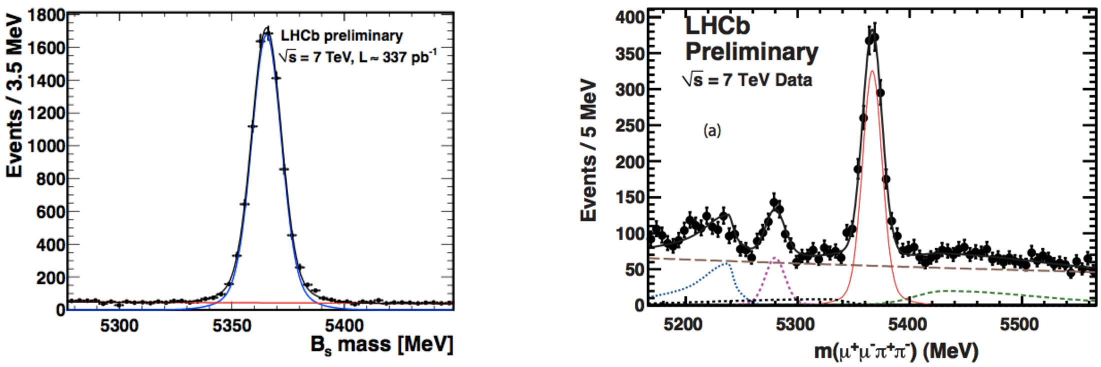

Figure 3: Invariant mass distributions for the $B_s^0 \to J/\psi\,\phi$ decay (left) and for the $B_s^0 \to J/\psi\, f_0(980)$ decay (right).

LHCb has also set the most constraining upper limit on the branching fraction $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8}$ at 95% C.L. This significantly improves on previous limits from D0 and CDF. When combined with a result from CMS, the LHC experiments' limit is at three times the expected SM level, so there is still plenty of room for new physics [13]. The possible branching ratio enhancement due to new physics makes this channel particularly appealing to constrain Supersymmetric models in the $(\tan\beta, M_A)$ plane, in a complementary approach with respect to direct searches at ATLAS and CMS [14].

LHCb measured the forward-backward asymmetry in the $B^0 \to K^{*0}\mu^+\mu^-$ decays with unprecedented precision. Previous data from Belle, BaBar and CDF showed a possible indication of new physics originating from the deviation of experimental points with respect to the SM in $A_{\text{FB}}(q^2)$, the forward-backward asymmetry in bins of the dimuon invariant-mass squared. As shown in Fig. 4(right), the result of the angular analysis in LHCb [15] shows no such inconsistency, being in good agreement with the SM expectations, although still leaving room for new physics effects.

As the statistics is increasing, LHCb will be able to produce world class results also in other flavor physics domains. Of particular interest is measurement of the CKM angle γ, which is presently known to $\sim$10%, in a variety of methods, based on both tree- and loop-diagram decays, opening the possibility to see signs of new physics. LHCb is already surpassing the sensitivity of previous experiments to γ, and has seen suppressed decay rates in $B \to DK$ decays with unprecedented accuracy [16]. In addition, in the analysis of charmless B decays (for which loop diagrams are involved), LHCb shows already the world-best precision in time-integrated asymmetries [17].

LHCb has also started to show its potential in the reconstruction of events with photons in the final states, such as in the radiative B decays, $B^0 \to K^{*0}\gamma$ and $B_s^0 \to \phi\gamma$ [18]. The ratio of these two branching ratios is currently the best available measurement and the analysis is proceeding towards the evaluation of CP asymmetries.

With only around 30 pb^{-1} of data accumulated in 2010, LHCb selected samples of low-multiplicity charm decays, such as $D^{*+} \to D^0(K^+K^-)\pi^+$, that are comparable in size to those of the previous experiments, BaBar and Belle. These have been exploited in measurements of the mixing and CP-violation parameters y_{CP} and A_Γ [19, 20]. In these studies it has been demonstrated that excellent systematic control can be achieved, despite the challenges of the hadronic environment. Analysis of the much larger 2011 data-set is underway, and a corresponding increase in sensitivity is anticipated.

LHCb has performed many studies beyond flavor physics, many of which have exploited the experiment's unique forward coverage and very low transverse-momentum acceptance. An example of the former is the measurement of heavy boson production [21], including the asymmetry between W^+ and W^- production as a function of the muon pseudorapidity in leptonic W decays, which provides unique insight into the structure of the proton.

These results demonstrate the excellent quality of the detector, the performance of which (for tracking, vertexing, mass resolution, and particle identification) match well the expectations, also considering the operation at much higher luminosity and at a larger number of interactions per crossing.

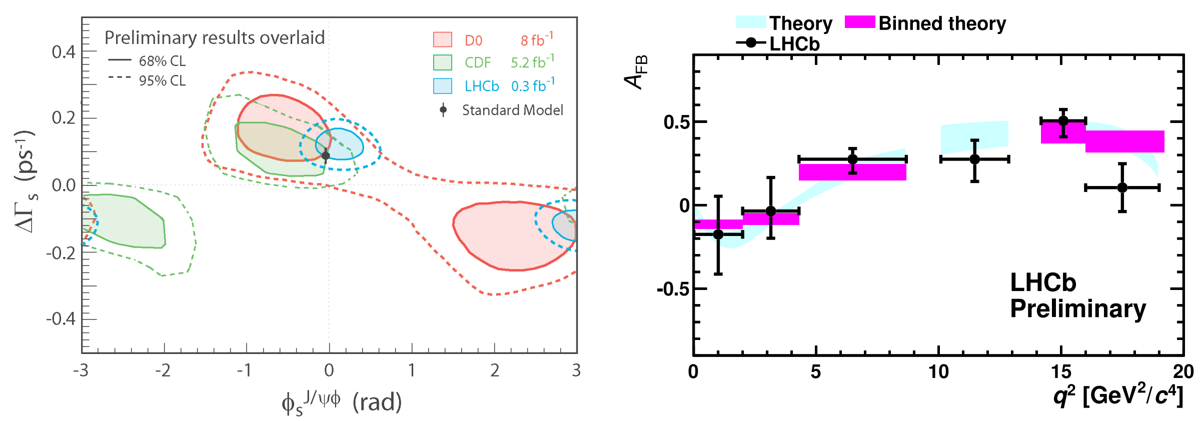

Figure 4: Measurements of the CP violating phase ϕ_s from CDF, D0 and LHCb, shown as likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane (left), and the forward-backward asymmetry in $B^0 \to K^{*0}\mu^+\mu^-$ (right).

4 Physics goals of the LHCb upgrade

In the first phase of the experiment, i.e. with data collected up to 2017, LHCb will attain results that will severely test the SM. Whatever the outcome of this initial exploration, however, precision measurements of these important quantities will be required. There are several key measurements (for a review see Ref. [22]) where the proposed "Super B-factory" experiments cannot compete, and that can be done *only* with the LHCb upgrade. LHCb has unique potential in the B_s^0 and b baryon sectors, since these particles are not produced in e^+e^- collisions at the $\Upsilon(4S)$ resonance. It will be the only experiment that can perform time-dependent CP violation

Table 1: Sensitivities of the LHCb upgrade to key observables. The current sensitivity is compared to that expected after 5 fb^{-1} and that which will be achieved with 50 fb^{-1} by the upgraded experiment, all assuming $\sqrt{s} = 14$ TeV. Note that at the upgraded LHCb, the yield/fb^{-1} in hadronic B and D decays will be higher on account of the software trigger.

Type	Observable	Pre-LHCb precision	LHCb (5 fb^{-1})	Upgrade (50 fb^{-1})	Theory uncertainty
Gluonic penguin	$S(B_s \to \phi\phi)$	-	0.08	0.02	0.02
	$S(B_s \to K^{*0}\bar{K}^{*0})$	-	0.07	0.02	< 0.02
	$S(B^0 \to \phi K^0_S)$	0.17	0.15	0.03	0.02
B_s mixing	ϕ_s $(B_s \to J/\psi\phi)$	0.35	0.019	0.006	~ 0.003
Right-handed currents	$S(B_s \to \phi\gamma)$	-	0.07	0.02	< 0.01
	$\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	-	0.14	0.03	0.02
E/W penguin	$A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$	-	0.14	0.04	0.05
	$s_0\, A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	-	4%	1%	7%
Higgs penguin	$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	30%	8%	$< 10\%$
	$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s\to\mu^+\mu^-)}$	-	-	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	γ $(B \to D^{(*)}K^{(*)})$	$\sim 20°$	$\sim 4°$	0.9°	negligible
	γ $(B_s \to D_s K)$	-	$\sim 7°$	1.5°	negligible
	β $(B^0 \to J/\psi\, K^0)$	1°	0.5°	0.2°	negligible
Charm CPV	A_Γ	2.5×10^{-3}	2×10^{-4}	4×10^{-5}	-
	$A^{\text{dir}}_{CP}(KK) - A^{\text{dir}}_{CP}(\pi\pi)$	4.3×10^{-3}	4×10^{-4}	8×10^{-5}	-

measurements in the B^0_s system. Moreover, in exclusive final states composed solely of charged particles, LHCb will accumulate enormous numbers of events, far in excess of what will be available at any other facility.

These data will allow for super-precise measurements of fundamental quantities such as the mixing-induced CP violation in $B^0_s \to J/\psi\,\phi$, the analysis of theoretically clean vector-vector final states in charmless two-body B decays, and the tree-level determination of the CKM angle γ at a precision to match anticipated progress in lattice QCD. They will also allow a precise evaluation to be made of the rate of the $B^0_s \to \mu^+\mu^-$ decay and the extension of the program to $B^0 \to \mu^+\mu^-$, to exploit the new physics sensitivity of the full kinematic distributions in $B^0 \to K^{*0}\mu^+\mu^-$ decay, the measurement of photon polarization in $b \to s\gamma$ decays, and an unchallenged sensitivity to CP violation in charm. A summary of the achievable sensitivities for some key channels is given in Table 1. More details are available in Ref. [8].

The scientific goals of LHCb extend well beyond quark-flavor physics. Important studies are also possible in the lepton sector, including searches for lepton-flavor violating tau decays and for low-mass Majorana neutrinos. The upgraded experiment can be regarded as a general-purpose detector in the forward direction. The unique acceptance, coupled with the flexible trigger, will enable LHCb to make measurements that are either complementary or of higher sensitivity, to those possible at the LHC general-purpose detectors (ATLAS/CMS) and other facilities. Examples include the search for long-lived exotic particles, and measurements in the electroweak sector such as the determination of the weak mixing angle. In Ref. [8], a brief survey is presented of opportunities which exist for LHCb in the lepton sector and in non-flavor topics.

In most of these areas work is only now beginning, and further study is needed to quantify more precisely the sensitivities that can be achieved. Nevertheless, a clear message emerges as to the richness of the physics possibilities that are open to LHCb beyond the studies of b and c decays.

5 Technical challenges of the LHCb upgrade

In 2010, due to the reduced number of bunches in the LHC, LHCb accumulated data with a mean number of interactions per crossing up to $\mu = 2.5$. This experience has shown that LHCb is capable of performing high quality measurements even in these harsh conditions. However, the experiment as it is now cannot profit from a luminosity much larger than the present value, due to the readout limitation on the lowest level hardware trigger of 1 MHz. This is because an increase in luminosity requires the raising of trigger thresholds that decrease the efficiencies, especially that for hadronic final states, and results in an almost constant B yield independent of luminosity.

The change that will make much larger luminosities useful is to read the data out of the detector at the 40 MHz beam crossing frequency, assuming 25 ns bunch spacing, and forming the trigger purely in software, rather than relying on fixed hardware thresholds. This necessitates a rebuild of electronic front ends of all detector systems except for the calorimeters and muon, including replacement of the RICH photon detectors. In addition, the entire vertex detector (VELO), and other silicon tracking systems need to be replaced. Muon and Calorimeter systems will stay with the present detectors. The aerogel system in RICH1 will be replaced by another particle ID device based on time of flight that uses Cherenkov light in quartz, called the TORCH [23], complementing the RICH detectors in the low-momentum particle ID. The TORCH is a challenging project, and its installation could come later, without compromising the operation of the upgraded detector.

One challenge of the LHCb upgrade lies in the redesign of the tracking system which should be able to sustain luminosities up to $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The VELO detector is particularly demanding as it is very near to the beam pipe and its material budget should be as light as possible to increase vertexing and tracking performance. The new tracking systems which will replace the TT, the IT and partially the OT, are based on two possible options: one on fibers readout by silicon photo-multipliers, and the other on silicon strips. As for the VELO, the tracking detectors must ensure radiation resistance, good granularity, low material budget and fast response to minimize spillover events in the 25 ns LHC bunch scheme. A bigger CPU farm, more disk storage and more computing power will be needed to swallow a factor 10 more events at the output of HLT trigger. The upgraded detector will be able to collect at least 5 fb^{-1} per year, running at a minimal luminosity of $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The increase in trigger efficiency for the hadronic channels will result in a yield at least ten times greater than the present experiment.

Given the current LHC schedule, which foresees a long shutdown in 2018, the upgrade should be organized so as not to miss this slot for detector installation. Therefore the plan is to continue with intense detector R&D and choose technologies in 2011 and 2012. In 2013 finish the TDR and validate prototype systems. In 2014–16 orders will be sent and production started. In 2016–17 the production ends and all systems will be tested and ready for installation in 2018.

6 Conclusions

LHCb has started to constrain physics beyond the SM by searching for rare and CP-violating processes, taking advantage of quantum loops. Results have been obtained from samples of up to 0.4 fb^{-1}. At least one order of magnitude more data will be obtained by the end of 2017. Making precision measurements of new physics found at the LHC, or providing even more constraining limits on such physics, can be assured with an upgrade that will allow a further order of magnitude of data to be collected. This upgrade does not depend on LHC luminosity improvements beyond $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In addition, other physics in the forward direction at the LHC can be pursued.

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