Status and Physics Reach of LHCb

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LHCb is the experiment at the Large Hadron Collider devoted to studies of new phenomena in CP violation and in rare decays. This review summarizes the status of the experiment in the imminence of the data taking, the prospects for the first measurements and highlights of its full physics program.

I. INTRODUCTION

LHCb is a second generation b-physics experiment, devoted to studies of new phenomena in CP violation and in rare decays. Previous experiments have provided extensive studies on $b \to d$ transitions [1], but a limited knowledge on $b \to s$ transitions is available up to now and in this sector large space is still available for New Physics (NP) effects, beyond Standard Model (SM). Precision measurements of the parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix have provided stringent constraints to the SM [2], but these are much relaxed if we consider only tree level measurements. B physics at LHC has the great advantage of high $b\bar{b}$ cross section ($_{bb}$ 500 b), with production of all species of b-hadrons. The challenge in the analysis is related to the presence of the underlying event, to the high particle multiplicity and to the high rate of background events ($_{inelastic}$ 80 mb). LHCb intends to perform extensive studies in a wide set of channels with the following goals:

- to improve the precision in the measurement of the angle and the other CKM parameters, searching for evidence of NP from comparisons between tree level and box and penguin contributions. Some examples which I will discuss in the following are the measurements of from $B \to DK$ decays, and the measurement of the B_s^0 mixing phase from $B_s^0 \to J/$ and $B_s^0 \to$ decays.

- to search for NP in rare decays from high precision measurements of branching ratios and time dependent CP asymmetries. Examples are $B_s^0 \to {}^+$, $B^0 \to {}^+ K^0$ and $B_s^0 \to$ decays.

II. THE LHCb EXPERIMENT

The start-up of the Large Hadron Collider is now approaching and the LHCb experiment is completely installed in IP8 and ready for taking data. During 2008 LHC is expected to run at $\sqrt{s}$ = 10 TeV with a reduced luminosity, about 10^{31} $cm^{-2}s^{-1}$, for about one month. These data will be of great utility for detector and trigger commissioning and calibration, they will also allow first studies on physics parameters like particle multiplicities and cross sections. In 2009 [3], in $\sqrt{s}$ = 14 TeV collisions, LHCb should collect around 0.5 fb^{-1} of data, which will allow first results on CP physics and rare decays. LHCb has chosen to run at a nominal luminosity lower than the design LHC luminosity, around $2-5 \times 10^{32}$ $cm^{-2}s^{-1}$. This is to limit pile up of proton-proton interactions in order to help trigger and event reconstructions and to limit detectors irradiation. LHCb expects to collect 2 fb^{-1} per year (10^7 s) integrating a total luminosity of about 10 fb^{-1} around year 2013.

A schematic of the detector is shown in Figure 1.

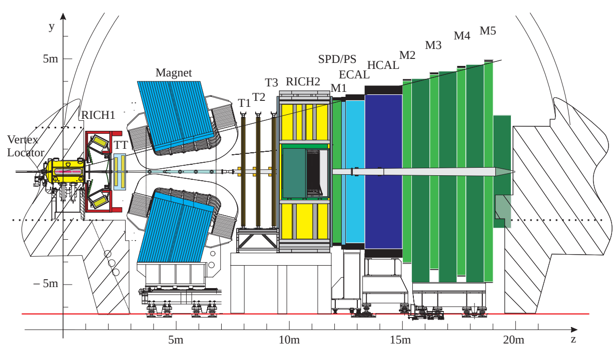

FIG. 1: Schematic of the LHCb detector

A full description of the LHCb detector can be found in [4]. I will just mention the crucial aspects of the expected performance which are a good spatial resolution (30 m resolution on the impact parameter with respect to the primary vertex, 140 m resolution on the secondary vertex) and a momentum resolution $(p)/p$ = 0.3–0.5% giving a precision on the reconstructed B mass of 15–20 MeV/c^2 and a B proper time resolution of about 40 fs. The Cherenkov detectors system provides a good $/K$ separation in the momentum range between 2 to 100 GeV/c while the calorimeter system (PS, ECAL, HCAL) and the muon chambers provide good electron and muon identification. Particle identification is of extreme importance for signal selection and background rejection in many exclusive B channels as well as for flavour tagging. For this purpose several algorithms are used, the combined performance is a tagging power D^2 = 4–5% for B^0 and 7–9% for B_s^0, depending on the channel.

LHCb has a two stage trigger, the Level-0 is hardware and reduces the rate from the initial 40 MHz to 1 MHz, it is based on moderate p_T requirements on muons, electrons, photons and hadrons. The following stage, called High Level Trigger, is entirely software, therefore completely tunable on different situations and using data from the whole detector. It reduces the rate to 2 kHz, the output includes about 200 Hz of exclusive B candidates and 1.8 kHz of inclusive channels, to be used also for calibration purposes and systematic studies. The trigger efficiencies, normalized to offline reconstructed events, range from about 80% in channels with muons to about 40% in fully hadronic channels.

III. B_s^0 MIXING PHASE FROM $b \to c\bar{c}s$ DECAYS

The phase arising from interference between B_s^0 decays with and without mixing is expected to be very small in the SM: $\phi^{SM} = -2\beta_s = (-0.037 \pm 0.002)$ rad from Unitarity Triangle fits [2]. New particles contributing to the box diagram can alter this value which becomes a sensitive probe to New Physics. ϕ_s can be precisely measured from the time dependent asymmetry in the decay rate of $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$ using flavour tagged events. In the decay of a pseudoscalar meson to a vector-vector pair an angular analysis is needed to disentangle the contributions of the CP-even and the CP-odd components. LHCb expects to select 130000 untagged events in 2 fb^{-1} obtaining a sensitivity $\sigma(2\beta_s) = 0.023$ rad. Other parameters are determined from the fit with sensitivities: $\sigma(\Delta\Gamma_s/\Gamma_s) = 0.009$ and $\sigma(R_T) = 0.004$, where R_T is the fraction of CP-odd component at $t = 0$.

Several B_s^0 decay channels with CP-even final states have been also considered: $J/\psi\eta$, $J/\psi\eta'$, $\eta_c\phi$ and $D_s^+D_s^-$. In one nominal year a total statistics of about 25000 events is expected in all these channels, corresponding to a sensitivity on ϕ_s of $\sigma(2\beta_s) = 0.048$. The $J/\psi\phi$ result alone indicate that LHCb can provide already with 0.5 fb^{-1} of data a measurement of ϕ_s with a 0.05 sensitivity.

Within the SM the CP violation effects in $B_s^0 \to \phi\phi$ are expected to be smaller than 1%, due to a cancellation between the mixing and the penguin phases. The observation of a significant CP violating phase in this decay mode would indeed be due to the presence of NP giving different contributions to the box and penguin diagrams. In LHCb it is expected that about 3100 signal events will be selected in this channel in 2 fb^{-1}, with a background to signal ratio below 0.8 at 90% CL. A time dependent angular analysis of flavour tagged events will be performed to extract the CP asymmetry resulting in a statistical sensitivity $\sigma(\phi^{NP}) = 0.11$.

IV. MEASUREMENTS OF γ

Precision measurements of the γ angle can be performed using several channels and different methods, a summary of the estimated sensitivities is presented in Table I [5]. In addition to B^+ and B^0 channels, already studied at the B-Factories, LHCb will also use B_s^0 ones.

$B_s^0 \to D_s K$ decay, where two tree diagrams interfere via mixing, allows a very clean determination of γ. The main background to this mode is represented by the $B_s^0 \to D_s\pi$ channel, having a 10 times higher branching fraction. However the two channels are well separated thanks to the good PID capabilities of LHCb. Monte Carlo studies have shown that 6200 D_sK events will be collected in 2 fb^{-1}, together with 140000 $D_s\pi$ [6]. A combined fit to the time dependent rates of the two channels allows to constraint Δm_s and the tagging dilution to extract $\gamma + 2\beta_s$ with a sensitivity of $9^\circ - 12^\circ$, depending on the value of the strong phase difference [7]. In Figure 2 the proper time distribution of $B_s^0 \to D_s^- K^+$ events is shown.

A combination of all measurements of γ reported in the first 4 lines of Table I, which involve tree diagrams only, has been performed and a combined sensitivity $\sigma(\gamma) \sim 4^\circ$ in one nominal year of data taking has been obtained [5].

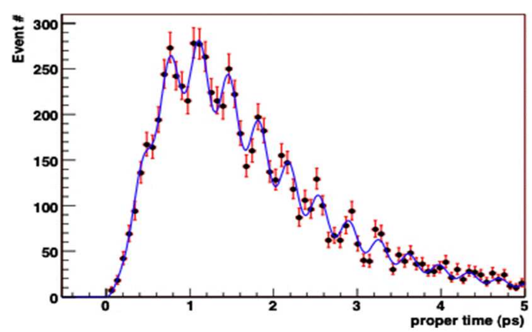

FIG. 2: Proper time distribution of $B_s^0 \to D_s^- K^+$ events in 10 fb^{-1} of data. The curve is the result of a likelihood fit.

V. RARE DECAYS

$B_s^0 \to \mu^+\mu^-$ is a rare decay involving flavour changing neutral currents highly suppressed in the SM ($BR(B_s^0 \to \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}$) which could be strongly enhanced in some SUSY scenarios, in particular at high $\tan\beta$. Current limits from searches performed at the Tevatron Collider are above the SM prediction by a factor 10. At LHCb the signal will

TABLE I: A summary of LHCb sensitivity studies

B mode	D mode	Method	Parameter	( ) in 2 fb ^{1}
$B_s^0 \to D_s K$	KK	tagged, $A^{CP}(t)$	$2 _s$	9° 12°
$B^0 \to DK^{0}$	K , KK ,	ADS+GLW		9°
$B^+ \to DK^+$	K , KK /	ADS+GLW		11° 14°
$B^+ \to DK^+$	K_S	3 body Dalitz		7° 12°
$B^+ \to DK^+$	KK /	4 body Dalitz		18°
$B^0 \to$, $B_s^0 \to KK$	–	tagged, $A^{CP}(t)$	; $_d$; $_s$	10°

be easily triggered with high efficiency, and an efficient background rejection will be obtained by using a combination of a geometrical likelihood (from secondary vertexes and impact parameters variables) a particle identification likelihood and B mass cuts. In the SM context, in the sensitive region, about 30 signal events and 80 from background are expected in 2 fb ^{1}. If only background will be observed, a 90% CL limit at the SM value is reached with 0.5 fb ^{1} of data. The expected sensitivity to the signal, as a function of the integrated luminosity is shown in Figure 3 [8] showing that a 3 evidence can be achieved in 2 fb ^{1}.

the $B^0 \to$ $^+$ K^{0} channel, with a B/S of about 0.5. An example of a forward-backward asymmetry distribution in 2 fb ^{1} of data is shown in Figure 4 [10]. The value s_0 can be extracted with a linear fit with a precision $(s_0) = 0.5\ (GeV/c^2)^2$. Additional sensitivity to NP comes from measurements of the longitudinal polarization fraction of the K^0, F_L, and the second polarization amplitude asymmetry $A_T^{(2)}$. As an example, in the region $1 < q^2 < 6\ (GeV/c^2)^2$, preferred for theoretical calculation, the statistical precision on the measurement of $A_T^{(2)}$ is 0.42, in 2 fb ^{1} [11]. A full angular analysis is also under study.

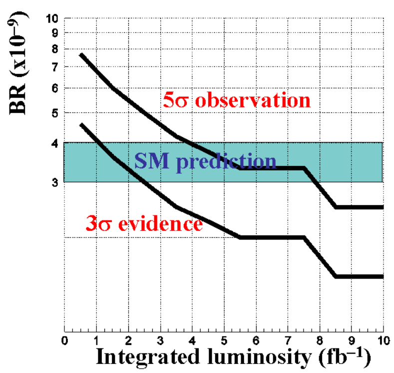

FIG. 3: Luminosity needed for the observation of a given branching ratio of $B_s^0 \to$ $^+$ at 3 (lower line) and 5 (upper line) level.

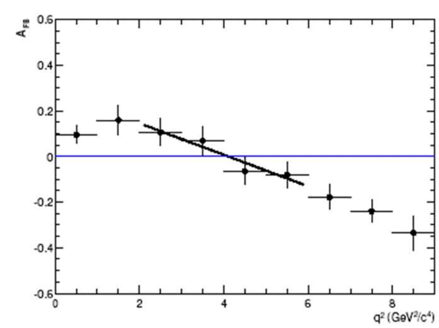

FIG. 4: Example of the expected forward-backward asymmetry in $B^0 \to$ $^+$ K^{0} decays as a function of the di-muon invariant mass, with 2fb ^{1} of data.

The decay $B^0 \to$ $^+$ K^{0} is another $b \to s$ transition which happens in the SM only via loops. New particles contributions in the loops could modify the predictions and a sensitive quantity is the angular distribution of the $^+$ pair. The forward-backward asymmetry of the $^+$ relative to the K^0 direction in the di-muon rest frame, as a function of $^+$ invariant mass is precisely calculated in the SM and several SUSY models, below the charmonium resonances. The value s_0 at which the asymmetry is equal to zero is predicted in the SM $s_0^{SM} = 4.39^{+0.38}_{0.35}$ $(GeV/c^2)^2$ [9]. LHCb expects to select 7200 events in

The first radiative channel to be observed at LHCb will be probably $B^0 \to K^{0}$, for which a yield of 68000 events per year is expected, with a B/S of about 0.6. Particular interest is given to the $B_s^0 \to$ decay because it allows to test the helicity structure of the emitted photon. In the SM the emitted photons are predominantly left-handed. The time dependent CP asymmetry is given by:

$$A_{CP}(t) = \frac{A^{dir}\cos(m\,t) \quad A^{mix}\sin(m\,t)}{A \quad \sinh(\quad t/2) \quad \cosh(\quad t/2)}$$

In the B_s^0 system, where is different from zero, this

TABLE II: Number of D^* tagged events from b hadrons, expected in 2 fb^{-1}

Decay mode	Yield in 2 fb^{-1}
$D^0 \to K^-\pi^+$	12.4×10^6
$D^0 \to K^+\pi^-$	46.5×10^3
$D^0 \to K^-K^+$	1.6×10^6

measurement is also sensitive to the A^{Δ} term, as well as to A^{dir} and A^{mix}. Within the SM $A^{dir} \approx 0$, $A^{mix} = \sin 2\psi \sin\phi$ and $A^{\Delta} \approx \sin 2\psi \cos\phi$ where $\tan\psi$ is the ratio between the right-handed and the left-handed components and ϕ is the sum of B_s^0 mixing and CP-odd weak phases. In the SM it is expected $\cos\phi \approx 1$ so that a measurement of $A^{\Delta} \approx \sin 2\psi$ determines the fraction of wrongly polarized photon. With 2 fb^{-1} LHCb expects to select 11500 events in this channel, with a B/S smaller than 0.5, and statistical errors on the parameters of: $\sigma(A^{\Delta}) = 0.22$, $\sigma(A^{dir}) = 0.11$, $\sigma(A^{mix}) = 0.11$.

VI. CHARM PHYSICS

LHCb will collect also a large sample of charm events. Prompt charm events are disfavored by the LHCb trigger tuned on long lived beauty particles, however a high statistics on charm produced in beauty hadrons decays will be available. Present studies are focused on this component. The D^0 flavour will be tagged by the pion charge in $D^{*+} \to D^0\pi^+$, $D^{*-} \to \overline{D}^0\pi^-$ decays. Part of the inclusive trigger bandwidth will be dedicated to inclusive D^* events, which will also be used for PID calibration. The number of D^* tagged events from b hadrons, expected in 2 fb^{-1} is reported in Table II.

This huge sample of charm decays will allow to perform several studies on mixing and CP violation [13]. Only few examples will be mentioned here. In 2 fb^{-1} of data, using "wrong-sign" $D^0 \to K^+\pi^-$ decays it is expected to obtain a statistical precision on the mixing parameters $\sigma(x'^2) \approx 0.14 \times 10^{-3}$ and $\sigma(y') \approx 2 \times 10^{-3}$. Through the ratio of mean lifetime of $D^0 \to K^-\pi^+$ to the mean lifetime of the CP-even decay $D^0 \to K^+K^-$ the mixing parameter y_{CP} can be measured with a sensitivity $\sigma(y_{CP}) \approx 1.1 \times 10^{-3}$. With tagged and untagged $D^0 \to K^+K^-$ decays, the direct CP violation in the lifetime asymmetry can be measured with a sensitivity $\sigma(A_{\Gamma}) \approx 1 \times 10^{-3}$.

VII. FUTURE PROSPECTS

Results obtained by LHCb in the first years of the experiment, with about 10 fb^{-1}, will allow to probe the presence of New Physics in CP violation and rare decays. However the evidence of small effects and the discrimination among different models will require improved precision, and several measurements will still be limited by statistical precision. Higher luminosity is needed for a real step forward and the LHCb collaboration is investigating the upgrade of the detector to handle a luminosity around 2×10^{33} $cm^{-2}s^{-1}$ and to integrate up to about 100 fb^{-1}. This upgrade does not require a machine upgrade, since this luminosity will be already available in the standard LHC program, however it may overlap in time with it and with ATLAS and CMS upgrades. The main issues are related to the increase of the number of interactions per bunch crossing, therefore to the higher detector occupancy, the higher radiation dose, the need of fast vertex detection in order to increase the trigger efficiency for hadronic modes. Technical solutions are under study and an expression of interest for an LHCb upgrade has been submitted to LHCC [14]. Concerning some of the key measurements discussed in the previous sections, the goal is to reach a sensitivity in CP violation measurements in the B_s^0 mixing at few per-mille level in $B_s^0 \to J/\psi\phi$ and at the per-cent level in $B_s^0 \to \phi\phi$, a precision of about 1 degree on the measurement of γ and to test the chiral structure of the photon emitted in $b \to s\gamma$ decays at the percent level.

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