The LHCb experiment: status and expected physics performance

Sergey Barsuk^a on behalf of the LHCb Collaboration

^aEuropean Center for Nuclear Research (CERN), Geneva 23, CH-1211 Switzerland
and

Institute for Theoretical and Experimental Physics (ITEP), B.Chermushkinskaya 25, Moscow 117218, Russia

Physics motivation of the LHCb experiment, detector design, status of construction and installation of detector components, and expected performance of selected b physics measurements are discussed.

LHCb is a dedicated experiment at LHC to study CP violation and other rare phenomena in b hadron decays¹. The awaited contributions from the LHCb experiment are the precision measurements of the CKM parameters [1] and test the Standard Model (SM) predictions hoping to observe phenomena non-explainable within SM[2].

At the LHC energies, the production of b and $\bar{b}$ quarks are highly correlated with respect to the boost (Fig. 1), so that if one b quark goes into the detector acceptance, the corresponding $\bar{b}$ quark products are also captured with high probability. This proves high efficiency of a single arm spectrometer philosophy, where only a factor 2 is lost compared to a 4π geometry. Moreover owing to better acceptance in forward direction, a factor 2 better $b\bar{b}$ cross section is expected at the LHCb compared to the ATLAS or CMS experiments.

LHCb will run at a reduced LHC luminosity tuned in the range $2 \div 5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ in order to optimize the number of beam crossings with single pp interaction.

The prolific production of the b hadrons at the LHCb is expected with the annual yield of

a 10^{12} $b\bar{b}$ pairs. All the b species will be produced with the biggest samples of B_u , B_d , B_s and Λ_b , $B_u:B_d:B_s:\Lambda_b \approx 4:4:1:0.1:1$. While the lightest, B_u and B_d , mesons are being explored in great detail by B factories, the LHCb experiment can contribute to the studies of B_s (in particular time resolved studies), B_c and Λ_b . Also numerous excited states will be produced allowing the systematic study of the b hadron spectroscopy. There the LHCb will mainly be competing with Super B -factory and low luminosity runs of the ATLAS and CMS experiments.

At LHCb the cross section of $b\bar{b}$ production amounts to less than 1% of the total cross section. The first level trigger aims at reducing background ~ 40 times, so that for high level trigger dominant background originates from charm and beauty events. The goal is to exclusively reconstruct the B meson decay of interest, measure proper time even for fast oscillating B_s mesons and provide reliable tagging of the b flavour. Thus the crucial features of the experiment are robust and efficient trigger, particle identification and decay time resolution. Also important particularly for asymmetry measurements is to develop tools for control of the systematic uncer-

¹The LHCb reach in c , τ physics, jets, etc. is beyond the scope of this paper.

Figure 1. Polar angle distribution of the b and $\bar{b}$ hadrons produced at LHC

tainties [4].

Figure 2. Layout of the LHCb detector

The layout of LHCb detector [5,6] is shown on Fig. 2.

Charged particle tracks and vertices will be reconstructed using silicon stations of Vertex Locator (VELO), Trigger Tracker (TT) station upstream the magnet, and the three tracking stations T1-T3 downstream the magnet [7]. Photons

and π^0 mesons will be measured in the electromagnetic calorimeter.

The K/π separation is done using the two Cherenkov detectors, RICH1 upstream the magnet and RICH2 downstream the magnet [8]. For $\gamma/e/h$ separation used is the calorimeter consisting of scintillating pad detector (SPD), preshower detector (PS), electromagnetic (ECAL) and hadronic (HCAL) calorimeters. The five muon stations M1-M5 interlayed with the muon filters are used for muon identification.

VELO is a silicon microstrip detector of a 180k readout channels, installed inside the vacuum vessel (Fig. 3) around the interaction region [9]. The

Figure 3. Vacuum vessel for VELO arrived at NIKHEF in 04/2005

detector comprises 21 stations, each with r and ϕ measuring sensors, with the silicon $300\ \mu$ thick and the pitch varying from 40 to $100\ \mu$ depending on radius (Fig. 4, left). VELO is arranged in two retractable detector halves, where the sensors are as close as $8\ \text{mm}$ to the beam line in operation mode, and are $30\ \text{mm}$ away during injection. For primary vertex reconstruction the detector will provide resolution of $44\ \mu$ along the beam line and $8\ \mu$ in transverse direction. The impact parameter will be determined to a $30\ \mu$ precision. For each VELO half, pattern recognition and alignment will be pre-adjusted using the test beam in 2006 before installation in the LHCb.

Figure 4. Left: the VELO hybrid with silicon sensor and readout chips; right: sensor ladder for TT and IT with electronics hybrid, low mass Kapton cable and silicon sensors

The warm dipole magnet [10] provides an integrated field of 4 Tm . The magnetic field will be regularly reversed to reduce systematic error in CP studies. Construction of the magnet is com-

Figure 5. The LHCb magnet

pleted (Fig. 5), and the field mapping is ongoing.

TT is a silicon strip detector (Fig. 4, right) covering full acceptance upstream the magnet, with the total 8 m^2 of $500\text{ }\mu$ thick silicon, 144k readout channels [11]. T1-T3 stations also exploit silicon strips for inner part (IT) having 129k readout channels [11], and long straw tube chambers technology for the outer part (OT) having 54k readout channels [12]. The production of the silicon tracker is being started, while about 60% of OT chambers is already produced and tested. The tracker gives $\sim 0.4\%$ momentum resolution with efficiency of $\sim 94\%$ for fast ($p > 10\text{ GeV}/c$) tracks and ghost rate of $\sim 3\%$ for tracks with $p_T > 0.5\text{ GeV}/c$.

In order to provide good K/π separation for momentum range from 2 to $100\text{ GeV}/c$ the system of Cherenkov detectors [13] uses three radiators: silica aerogel, C_4F_{10} in RICH1 to identify low momentum tracks over full acceptance and CF_4 gas in RICH2 for high momentum tracks. The RICH1 vessel is under construction, and more than 50% of high quality aerogel is already produced. The shielding for photodetectors is installed in the LHCb (Fig. 6, left). The RICH2 vessel is com-

Figure 6. Left: shielding for RICH1 photodetectors installed in LHCb; right: hybrid photodiode

pleted, the mirrors installed and aligned. Both detectors use a dedicated photon detector, hy-

brid photodiode (HPD), 8 cm diameter tube, with over 1000 pixels sensitive to single photoelectrons (Fig. 6, right). The production of a 500 HPDs is ongoing.

The CALO system [14] consists of SPD/PS structure (two 15 mm scintillator layers with 14 mm lead inbetween), ECAL and HCAL, put in projective geometry, and having variable granularity. SPD/PS detector (Fig. 7) employs deep groove design of the cells, 2×6 k cells in total, with the light read out with the 64 channel multianode photomultipliers. The produc-

Figure 7. The SPD/PS modules with 144, 64 and 16 detector cells

tion of SPD/PS is ongoing. The ECAL modules employs Shashlyk technology with volume ratio $Pb : Sc = 2 : 4$ (mm), with 6k readout cells, having $25X_0$ depth and transverse granularity of 4, 6 and 12 cm cell size (Fig. 8, up). The detector production is completed, all the modules are installed in the LHCb. The HCAL is iron-scintillator tile calorimeter, 5.6λ deep, having 1.5k readout cells (Fig. 8, down). The detector production is completed, all the modules are installed in the LHCb.

Muon detector stations are composed of 1.4k microwire proportional chambers with projective pad readout [15]. A 30% of chambers are produced and tested. Muon system provides muon identification with a 95% efficiency with a fake rate of less than 1%.

LHCb trigger [16,17] fully exploits b decay topology, where substantial energy is released yielding high values of p_T , and b decay vertex is separated from its production vertex by ~ 1 cm yielding large impact parameter (IP) values. The

Figure 8. Up: ECAL modules with different cell size; down: optics assembly of HCAL module

level 0 hardware trigger relies on high- p_T e , γ , π^0 , μ or h candidates, while removing busy events², and decreases the event rate from 40 to 1 MHz. All higher level triggers are software and based on the same farm, they add first the IP discrimination, and then the information from the full detector.

Selected baseline physics measurements are discussed below. The related simulation [3] was based on the full detector simulation with pile-up and spill-over included, realistic digitization and reconstruction with full pattern recognition and realistic trigger simulation, with tuned toy Monte Carlo for sensitivity studies. The background was assumed to come from $b\bar{b}$ inclusive events, having similar topology.

To measure $B_s\bar{B}_s$ oscillations LHCb will fully

²In order to veto busy events, the information from pile-up system of VELO and the total transverse energy deposited in the HCAL will be used.

reconstruct the decay $B_s \rightarrow D_s \pi$. Having the proper time resolution of $\sim 40 fs$, a 80k events will be observed per 1 year of running³. A 5σ observation of mixing is possible up to Δm_s of $68 ps^{-1}$ which is well beyond the SM expectation. Once the effect is seen, the oscillation frequency is precisely determined with $\sigma_{stat}(\Delta m_s) \sim 0.01 ps^{-1}$.

The angle γ is feasible at LHCb in three different approaches. The most clean information should come from the measurement of $\gamma - 2\chi$ from the $B_s \rightarrow D_s K$ decay, where only tree diagrams contribute and no new physics effects are expected, potential contribution to the B_s mixing phase $\phi_s = -2\chi$ will be deducted from the independent measurement (see below). Here K/π separation allows to significantly suppress dangerous reflection from $B_s \rightarrow D_s \pi$. A 5.4k events annual sample is expected with⁴ $B/S < 1$. For $\Delta m_s = 20 ps^{-1}$ this measurement gives $\sigma(\gamma)$ of 14° . Another way of measuring γ comes from time-dependent asymmetries for $B_d \rightarrow \pi\pi$ and $B_s \rightarrow KK$, $A_{CP}(t) = A^{dir} \cos(\Delta m t) + A^{mix} \sin(\Delta m t)$. Four observables are parameterized with seven parameters, γ , ϕ_d and ϕ_s , and ratios of penguin over tree contribution, $P/T = de^{i\theta}$. Taking the ϕ_d and ϕ_s from other measurements and assuming U -spin symmetry [18], we arrive at 4 measurements with 3 unknowns, which we solve for γ . Here again K/π separation is crucial because of numerous reflections from $B_{d,s}$ and Λ_b decays. The annual yield of 25k events for $B_d \rightarrow \pi\pi$ and 37k for $B_s \rightarrow KK$ gives $\sigma(\gamma)$ of 5° . This measurement is sensitive to new physics in penguin loops. Having the system overconstrained, uncertainty from U -spin assumption can be evaluated. Another method to determine γ comes from analysis of $B_d \rightarrow DK^*$ decays [19], which is sensitive to new physics in $D\bar{D}$ mixing.

The $B_s \rightarrow J/\Psi \phi$, $B_s \rightarrow J/\Psi \eta$ and $B_s \rightarrow \eta_c \phi$ decays measure $\phi_s = -2\chi$ and $\Delta\Gamma_s/\Gamma_s$ simultaneously⁵. $B_s \rightarrow J/\Psi \phi$ provides more statistics, but requires partial wave analysis, being a non-CP

state (Table 1). The 1 year LHCb combined ϕ_s

Table 1
Sensitivity on $\Delta\Gamma_s$ and ϕ_s for 1 LHCb year

	annual yield	B/S	$\sigma(\Delta\Gamma_s/\Gamma_s)$	$\sigma(\phi_s)$ [rad]
$B_s \rightarrow J/\Psi \phi$	100k	< 0.3	0.018	0.06
$B_s \rightarrow J/\Psi \eta$	7k	< 5.1	0.025	0.1
$B_s \rightarrow \eta_c \phi$	3.2k	< 1.4	0.025	0.1
combined				0.05

sensitivity of ~ 0.05 is comparable to the predicted value, 5 years sensitivity is $\sigma(\phi_s) \sim 0.02$.

Rare loop-induced decays are sensitive to new physics in many SM extensions. At LHCb studies of radiative penguin decays $B_d \rightarrow K^* \gamma$, $B_s \rightarrow \phi \gamma$, $B_d \rightarrow \omega \gamma$, electroweak penguin decay $B_d \rightarrow K^* \mu\mu$, gluonic penguin decays $B_d \rightarrow \phi K_s$, $B_s \rightarrow \phi \phi$ and the decay $B_s \rightarrow \mu\mu$ will be performed [20]. The expected annual event yields and background over signal levels for rare decays are summarized in Table 2.

Table 2
Expected annual event yields and background over signal levels for rare decays

channel	annual yield	B/S
$B_d \rightarrow K^* \gamma$	35k	< 0.7
$B_s \rightarrow \phi \gamma$	9.3k	< 2.4
$B_d \rightarrow \omega \gamma$	0.04k	< 3.5
$B_d \rightarrow K^* \mu\mu$	4.4k	< 2.0
$B_d \rightarrow \phi K_s$	0.8k	< 0.2
$B_s \rightarrow \phi \phi$	1.2k	< 1.1
$B_s \rightarrow \mu\mu$	0.02k	< 440

The decay $B_c \rightarrow J/\Psi \pi$ illustrates the LHCb reach of heavier B mesons. The expected yield is 14k events per year of running with $B/S < 0.8$.

Selected performance results are summarized in Table 3.

³One year of LHCb running corresponds to $2fb^{-1}$ accumulated statistics.

⁴The 90% CL is assumed throughout the paper.

⁵The SM values are -0.04 and 0.1 correspondingly.

Table 3
Selected performance after 1 LHCb year

	channel	yield	precision
γ	$B_s \rightarrow D_s K$	5.4k	$\sigma(\gamma) \approx 14^\circ$
	$B_d \rightarrow \pi\pi$	26k	$\sigma(\gamma) \approx 6^\circ$
	$B_s \rightarrow KK$	37k	
	$B_d \rightarrow D^0 K^*$	0.5k	
	$B_d \rightarrow \bar{D}^0 K^*$	3.4k	$\sigma(\gamma) \approx 8^\circ$
	$B_d \rightarrow D_{CP} K^*$	0.6k	
χ	$B_s \rightarrow J/\Psi \phi$	120k	$\sigma(\chi) \approx 2^\circ$
$ V_{td}/V_{ts} $	$B_s \rightarrow D_s \pi$	80k	Δm_s up to $68ps^{-1}$
A_{CP}^{dir}	$B_d \rightarrow K^* \gamma$	35k	$\sigma(A_{CP}^{dir})$ ≈ 0.01

Statistical errors only are taken into account.

In summary, the LHCb detector is optimized to exploit huge sample of 10^{12} b hadrons per year, including all b species, serving e.g. as a first $B_{(s,c)}$ factory. The physics programme is complementary/competitive to (Super)- $B_{(d,u)}$ factories and Tevatron. The LHCb construction and installation are well ongoing, the experiment will be installed and commissioned by the LHC start-up in 2007. The LHCb physics potential can be fully exploited already with the initial LHC luminosity.

Acknowledgements. The author wishes to thank I. Belyaev, H. Dijkstra, D. Eckstein, A. Golutvin, R. Forty, R. Lindner, T. Ruf, O. Schneider, A. Schopper, F. Teubert and O. Ullaland for their help in preparing the talk.

REFERENCES

1. L. Silvestrini, *talk at this conference*.
2. T. Hurth, *talk at this conference*.
3. P. Koppenburg, *talk at this conference*.
4. G. Wilkinson, *talk at this conference*.
5. *LHCb Technical Proposal*, CERN/LHCC 98-4.
6. *LHCb Reoptimized Detector Design and Performance TDR*, CERN LHCC 2003-30.
7. M. Needham, *talk at this conference*.
8. T. Bellunato, *talk at this conference*.
9. *LHCb VELO Technical Design Report*, CERN LHCC 2001-011.
10. *LHCb Magnet Technical Design Report*, CERN LHCC 2000-007.
11. *LHCb Inner Tracker Technical Design Report*, CERN LHCC 2002-029.
12. *LHCb Outer Tracker Technical Design Report*, CERN LHCC 2001-024.
13. *LHCb RICH Technical Design Report*, CERN LHCC 2000-037.
14. *LHCb Calorimeter Technical Design Report*, CERN LHCC 2000-036.
15. *LHCb Muon System Technical Design Report*, CERN LHCC 2001-010.
16. *LHCb Trigger Technical Design Report*, CERN LHCC 2003-031.
17. F. Teubert, *talk at this conference*.
18. R. Fleischer, Phys.Lett. B **459** (1999) 306.
19. M. Gronau and D. Wyler, Phys.Lett. B **265** (1991) 172;
I. Dunietz, Phys.Lett. B **270** (1991) 75.
20. I. Belyaev, Chech.J.Phys.**55** Suppl.A (2005).