Physics with first LHCb data

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The LHCb experiment is designed for hadronic flavour physics and will look for New Physics manifestations in the decay of charm and bottom hadrons abundantly produced at the LHC. All parts of the LHCb physics programme can be embarked on with the expected statistics to be collected during the first 2010–2011 physics run at $\sqrt{s} = 7$ TeV. We present first preliminary results on strangeness production, and demonstrate, using the few nb^{-1} of already collected data, the potential for initial measurements in heavy-flavour physics.

1 Physics goals and strategy

The Standard Model (SM) of particle physics cannot be the ultimate theory. It is incomplete and contains too many free parameters, such as masses and quark mixing angles. The pattern of these parameters should be governed by a hidden mechanism yet to be discovered, and so the SM is believed to be a low-energy effective theory of a more fundamental theory at a higher energy scale, anticipated to be in the TeV region and accessible at the Large Hadron Collider (LHC). This would imply new symmetries, particles, dynamics, and flavour structure.

The most exciting task of the LHC experiments will be to find this New Physics, whatever it may be. This can be done either directly or indirectly. The direct approach, pursued mostly by the ATLAS and CMS experiments, aims at the observation of new particles produced in LHC's proton-proton collisions at 14 TeV. The indirect approach, on the other hand, consists in measuring quantum corrections in the decay of already known particles especially in flavour-changing neutral-current (FCNC) transitions, and looking for deviations from the SM predictions. At LHC, this will be best done by the LHCb experiment, which has been designed specifically for precise measurements of CP violation and rare decays of hadrons containing a b quark. Both approaches are complementary: while the indirect approach is sensitive to higher energy scales and may therefore sense a new effect earlier, the direct observation of any new particle is necessary to establish its unambiguous discovery as well as for measuring its main properties. New Physics (NP) at the TeV scale needs to have a non-trivial flavour structure in order to provide the suppression mechanism for the already observed FCNC processes. Only indirect measurements can access the phases of the new couplings and therefore shed light on the NP flavour structure.

One of the strategies for indirect searches in hadronic decays consists of measuring as many observables as possible that can be related to the magnitudes and phases of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix describing the SM flavour structure in the quark sector. Any inconsistency between the interpretation of these measurements within the CKM picture will be a sign of New Physics. The most awaited progress in this area is a precise

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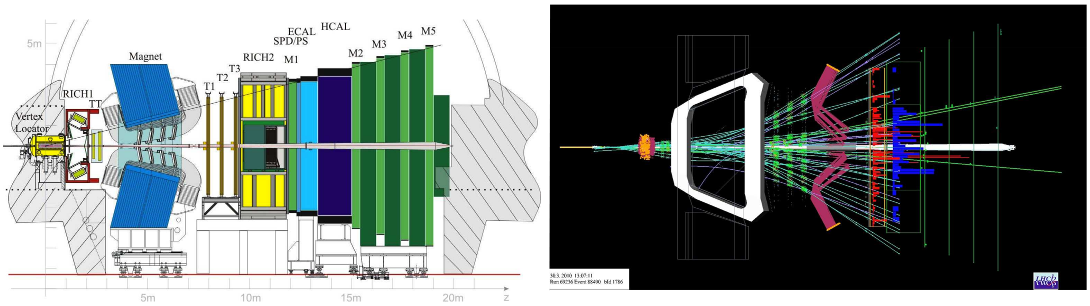

Figure 1: Left: Side view of the LHCb spectrometer, showing the Vertex Locator around the interaction region on the left, the tracking stations before (TT) and after (T1–T3) the dipole magnet, the ring-imaging Cherenkov detectors (RICH1 and RICH2), the calorimeter system (SPD/PS, ECAL, HCAL), and the muon stations (M1–M5). Right: Event display (top view, in bending plane) of one of the first recorded pp collisions at $\sqrt{s} = 7$ TeV on March 30, 2010. Reconstructed tracks, originating from the pp collision point on the left, have been reconstructed from hits in the VELO and hits (green) in the tracking stations. Cherenkov photons (mauve) are reflected on mirrors towards photo-detectors (orange). Energy depositions in ECAL (red) and HCAL (blue) as well as hits in the muon chambers (green, far right) are also visible.

NP-free determination of the CKM angle γ from tree-level processes.

Another strategy is to identify and measure single FCNC processes with good NP discovery potential, *i.e.* where NP is likely to emerge and for which a clear SM prediction can be made. Decays involving the $b \to s$ transition, which is less constrained by the current data, are good candidates. They are theoretically calculated using the Operator Product Expansion in terms of short-distance Wilson coefficients and long-distance operators describing effective vertexes such as tree diagrams, or gluon-, photon-, electroweak-, scalar- and pseudoscalar-penguin loops. New physics may both enhance some of the Wilson coefficients or introduce new operators, in particular in the right-handed sector which is suppressed in the SM.

Following these strategies, LHCb is preparing to perform rate measurements (such as the $B_s^0 \to \mu^+\mu^-$ branching fraction), determine CP-violating phases (most notably mixing-induced effects in $B_s^0 \to J/\psi\phi$ and $B_s^0 \to \phi\phi$ decays, interference between $b \to u$ and $b \to c$ transitions in tree-level $B \to DK$ decays, CP asymmetries in charmless two-body B decays), and probe the helicity structure of weak interactions (photon polarization in $B_s^0 \to \phi\gamma$ and other radiative decays, asymmetries in $B^0 \to K^{*0}\mu^+\mu^-$ decays). Such promising measurements are central to the core physics programme of LHCb; they have been studied in detail and are described in a recent roadmap document [1]. However, the wider programme will include many more measurements, mostly in (but not limited to) the heavy-flavor sector.

2 LHCb and first physics run

The LHCb detector [2] is a single-arm spectrometer (see Fig. 1 left) covering the forward region ($1.9 < \eta < 4.9$) where the $b\bar{b}$ production is peaked. It will rely on relatively soft p_{T} triggers, efficient for both leptonic B decays ($\sim 90\%$) and purely hadronic B decays ($\sim 40\%$). By design the luminosity will be limited to an average of $\sim 2 \times 10^{32}$ cm^{-2}s^{-1} in order to avoid a significant fraction of events with more than one pp inelastic interaction. A nominal year (10^7 s) of running in design conditions will give an integrated luminosity of 2 fb^{-1} at $\sqrt{s} = 14$ TeV. However, in the first LHC physics run started on March 30, 2010 (see Fig. 1 right) the centre-of-mass energy is $\sqrt{s} = 7$ TeV, reducing the expected $b\bar{b}$ and $c\bar{c}$ production rates by factors ~ 2.3 and ~ 1.8, respectively, although without dramatic impact on the physics reach. The nominal instantaneous luminosity is expected to be reached in 2011, while the current lower luminosity period in 2010 allows for lower trigger thresholds, and hence better efficiencies for hadronic B decays ($\sim 75\%$). This represents also a good opportunity to collect rapidly very large samples of charm events, with a corresponding trigger efficiency boosted up from $\sim 10\%$ to $\sim 40\%$. Approximately 14 nb^{-1} of data have been collected during April and May 2010, mostly with a fully inclusive trigger requesting at least one reconstructed track in the detector. Since the last week of May, a loose High-Level Trigger is run in rejection mode to limit the output rate to a few kHz. The overall status of the experiment [3], the data-taking experience [4], and the event reconstruction performance [5, 6] obtained from the first data are described elsewhere.

The first physics measurements within reach are those of the production of known and most abundantly produced particles. LHCb is focusing initially on unstable particles which can be reconstructed through their decay into charged tracks, and therefore cleanly identified as narrow signals above some combinatorial background. So far close to 30 different mass peaks have been seen in the LHCb data, including decays involving neutrals such as $\eta \to \pi^+\pi^-\pi^0$, $\eta' \to \pi^+\pi^-\gamma$, and $D^0 \to K^-\pi^+\pi^0$. Because of the nature of the LHCb core measurements, which will most often rely on fully reconstructed decays, the understanding and modelling of the structure of minimum bias events is not of utmost importance, hence more difficult production measurements of stable particles such as charged pions, kaons, protons or tracks in general are not at the centre of the present effort. Of more direct interest are the production measurements of strange (and neutral), charm, and bottom hadrons, as well as of electroweak bosons (see Fig. 2).

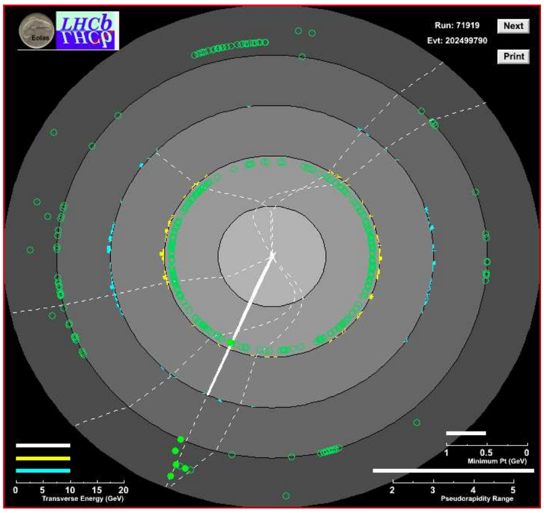

Figure 2: LHCb's first $W^+ \to \mu^+\nu$ candidate, shown in a '$z - \phi$ view' of the detector, with the Vertex Locator at the centre and muon stations at the periphery of the display. The white thick straight line represents a high p_T track ($p_\mathrm{T} = 35.4$ GeV) with hits in the muon chambers, while the curved dotted lines are accompanying soft tracks.

Production measurements at LHCb are necessarily new since LHC is operating at an unexplored energy. In order to turn them into cross section measurements, an estimate of the luminosity is needed. The principle of a direct determination of the luminosity based on a new 'beam imaging' technique [7] has been demonstrated using the data collected during the LHC pilot run in December 2009 [8], and used for the first absolute production cross section measurement described below.

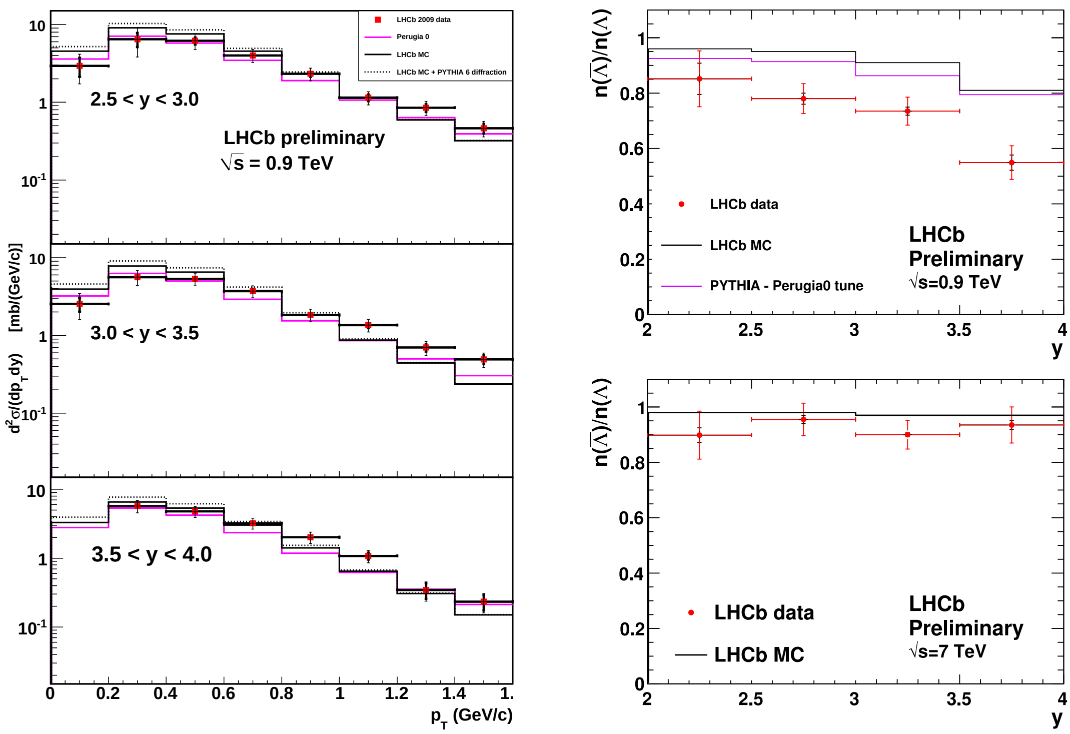

Figure 3: Left: Double-differential prompt K^0_S production cross section in pp collisions at $\sqrt{s} = 0.9$ TeV, shown as a function of K^0_S transverse momentum p_T in three different bins in K^0_S rapidity y. Right: $\bar{\Lambda}/\Lambda$ production ratio as a function of rapidity y in pp collisions at $\sqrt{s} = 0.9$ TeV (top) and 7 TeV (bottom). In all cases the red points represent LHCb data, with statistical and total uncertainties shown as vertical error bars, while the histograms are expectations from the PYTHIA 6.4 generator with different parameter settings, including the LHCb Monte Carlo (black) and the 'Perugia 0' tune [11] (purple).

3 Results on strangeness production

Strange quarks appear in the hadronization process of soft hadronic interactions, and their production is an excellent probe of the fragmentation field. In particular the measurement of strangeness production in hadronic interactions provides input for the understanding of QCD in the non-perturbative regime and for the tuning of Monte Carlo generators.

The data collected during the LHC pilot run in December 2009 at $\sqrt{s} = 0.9$ TeV were used to measure the prompt K^0_S production as a function of the K^0_S transverse momentum p_T and rapidity y in the region $0 < p_\mathrm{T} < 1.6$ GeV/c and $2.5 < y < 4.0$ (see Fig. 3 left). At this low beam energy the beam sizes and crossing angle (induced by the LHCb dipole magnet) do not allow the complete closure of the Vertex Locator (VELO) around the interaction region. As a result the data were collected with the VELO silicon detectors retracted by 15 mm from their nominal position, reducing significantly the azimuthal coverage provided by the VELO. However $K^0_S \to \pi^+\pi^-$ decays could still efficiently be reconstructed using tracks reconstructed in the tracking stations (TT and T1–T3). On the other hand the VELO was essential to measure *pp* and beam-gas interaction vertices, and determine the positions, sizes and angles of the colliding proton bunches. Together with bunch current measurements obtained from the LHC machine instrumentation, this allowed a direct determination of the integrated luminosity ($6.8 \pm 1.0\ \mu\text{b}^{-1}$) of the sample used for the K^0_S analysis. As can be seen from Fig. 3 (left), the preliminary measurements of the absolute prompt K^0_S production cross section are in fair agreement with the expectations from the PYTHIA generator, before any tuning to LHC data. These results have been finalized and published [9] since the conference.

The data collected in 2010, both at $\sqrt{s} = 0.9$ TeV and 7 TeV, were also used to study $\Lambda \to p\pi^-$ production. We show for the first time at this conference [10] preliminary measurements of the $\bar{\Lambda}/\Lambda$ production ratio as a function of rapidity y for the two centre-of-mass energies (Fig. 3 right). Contrary to the results at high energy, the measurements of the $\bar{\Lambda}/\Lambda$ ratio at $\sqrt{s} = 0.9$ TeV are significantly below the expectation and show a strong dependence in rapidity. Such studies are useful to investigate and understand the baryon-number transport from the beams in the more central region of the detector.

4 Charm: first look and prospects

Clean charm signals reconstructed in the first $2.7\ \text{nb}^{-1}$ of data at $\sqrt{s} = 7$ TeV (Fig. 4) already allow to firm up exciting prospects for measurements of $D^0 - \bar{D}^0$ mixing and CP violation in the charm sector [12]. Indeed, with $0.1\ \text{fb}^{-1}$ the statistics of (flavour-tagged) D^0 decays are expected to exceed that of the BABAR experiment by an order of magnitude. Significant contributions from LHCb are expected soon on several mixing-related observables, in particular:

- $y_{\text{CP}} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$ from the proper-time measurements of untagged $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$ decays (Fig. 4 top);

- $A_\Gamma = \frac{\tau(\bar{D}^0 \to K^+K^-) - \tau(D^0 \to K^-K^+)}{\tau(\bar{D}^0 \to K^+K^-) + \tau(D^0 \to K^-K^+)}$ from the proper-time measurements of flavour-tagged $D^0 \to K^-K^+$ decays, where the flavour of the D^0 meson at production (D^0 or $\bar{D}^0$) is determined from the sign of the charged pion in the reconstructed $D^{*-} \to D^0\pi^+$ decay (Fig. 4 middle left);

- mixing parameters related to the mass and decay-width differences in the $D^0 - \bar{D}^0$ system, from the time-dependent analysis of wrong-sign flavour-tagged $D^0 \to K^+\pi^-$ decays (interference between doubly-Cabibbo suppressed decays without mixing and Cabibbo-favoured decays with mixing).

Similarly, huge statistics of charged D mesons will allow an unprecedented search for direct CP violation in charm. The most interesting modes are the singly-Cabibbo suppressed decays, governed by gluonic penguin diagrams where New Physics may enter. The three-body mode $D^+ \to K^-K^+\pi^+$, together with the two Cabibbo-favoured decays $D^+_s \to K^-K^+\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ to be used as control channels, offers the interesting possibility of a Dalitz plot analysis where local CP asymmetries can be probed (Fig. 4 middle right and bottom).

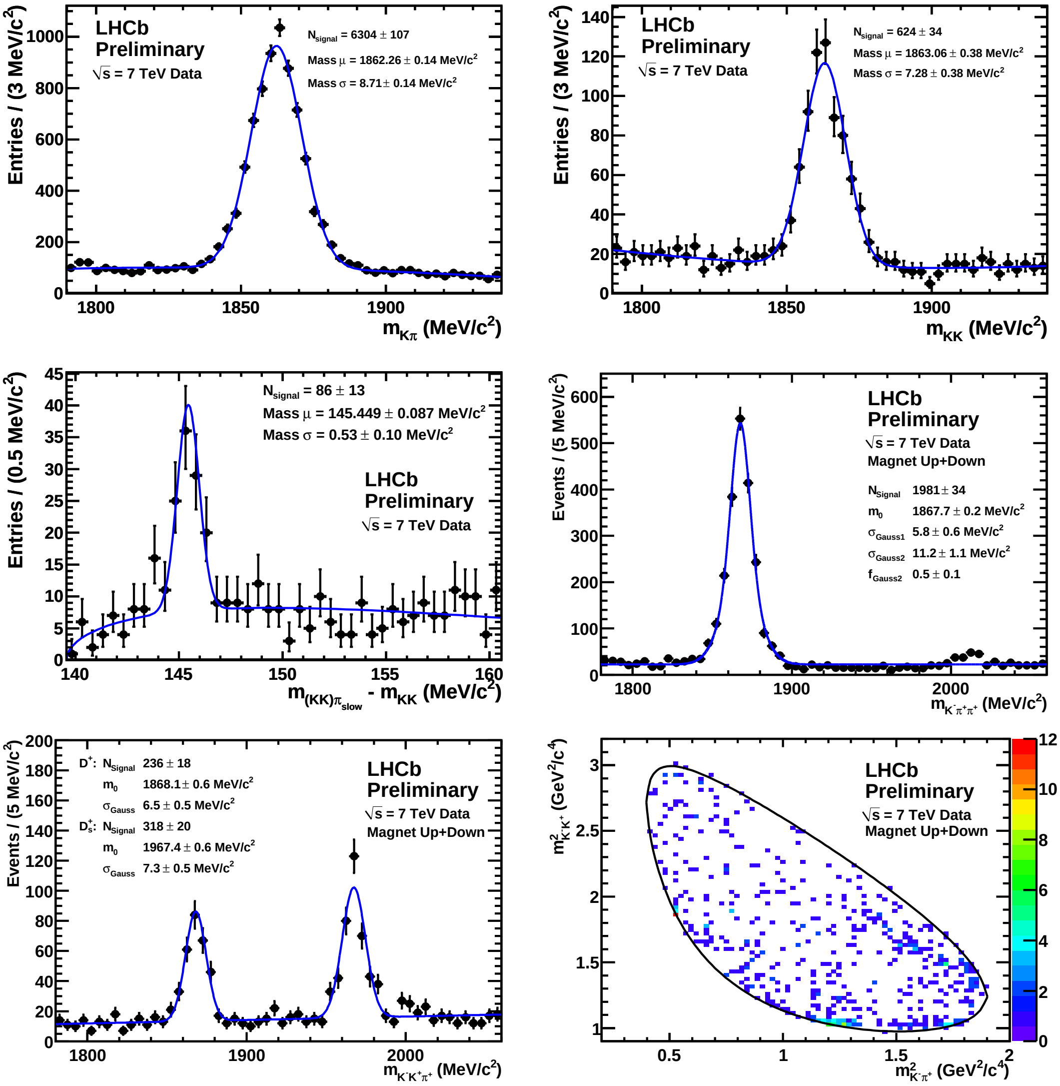

Figure 4: Some charm signals reconstructed in ~ 2.7 nb^{-1} of data at $\sqrt{s} = 7$ TeV. Top: $D^0 \to K^-\pi^+$ mass (left) and $D^0 \to K^-K^+$ (right) mass. Middle: difference between the $K^-K^+\pi^+$ and K^-K^+ masses for $D^{*+} \to D^0\pi^+ \to K^-K^+\pi^+$ candidates (left), and $D^+ \to K^-\pi^+\pi^+$ mass (right). Bottom: $K^-K^+\pi^+$ mass showing the $D^+ \to K^-K^+\pi^+$ and $D_s^+ \to K^-K^+\pi^+$ signals (left), and Dalitz plot of $D^+ \to K^-K^+\pi^+$ candidates (right).

5 First $b \to J/\psi X$ and $b \to D^0\mu X$ signals

Bottom production can easily be observed with a few nb^{-1} of data, if inclusive selections are used. Two approaches are described here, which will soon yield the first measurements of the

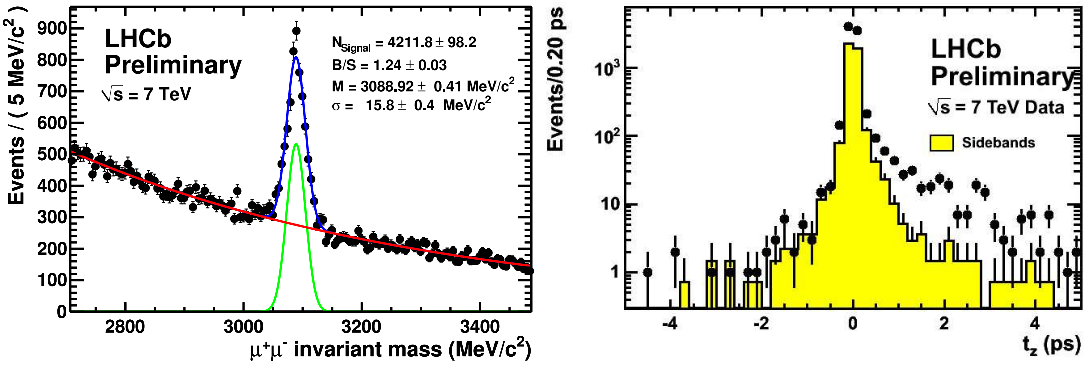

Figure 5: Left: Dimuon invariant mass distribution showing the $J/\psi \to \mu^+\mu^-$ signal in $\sim$ 14 nb^{-1} of data at $\sqrt{s} = 7$ TeV. Right: Pseudo-proper time distribution of the J/ψ candidates in the signal window (black points) and in the sidebands (yellow histogram). The difference between the two distributions corresponds to signal J/ψ and displays a tail at large proper time indicative of $b \to J/\psi X$ production.

$b\bar{b}$ production cross section at $\sqrt{s} = 7$ TeV.

An important part of LHCb's physics programme is based on the selection of $J/\psi \to \mu^+\mu^-$ decays, which leave a clear signature in the detector and which can efficiently be recognized both at the trigger level and in the offline analysis. At the present level of understanding of the detector alignment and calibration, and using a very loose trigger, a signal of ~ 300 events per nb^{-1} is obtained, with a mass resolution of 16 MeV/c^2 and a signal-to-background ratio of 0.8 in a ± 45 MeV/c^2 window around the central value of the mass peak (Fig. 5 left). This abundant signal will be an important tool to further understand and improve the reconstruction performance. The two main sources of J/ψ mesons, prompt production at the pp interaction vertex and secondary production in b-hadron decays, can be separated by measuring the pseudo-proper time $t_z = (z_{J/\psi} - z_{\mathrm{PV}}) \times m_{J/\psi}/p_z$, where $z_{J/\psi}$ and z_{PV} are the reconstructed positions of the J/ψ decay and of the pp interaction point along the beam direction (z axis), $m_{J/\psi}$ is the nominal J/ψ mass, and p_z the z component of the reconstructed J/ψ momentum. The distribution of t_z is shown in Fig. 5 (right) for J/ψ candidates with reconstructed masses in the signal and sideband regions. The $b \to J/\psi X$ component of the signal is clearly visible as an exponential tail in the positive t_z region.

A similar analysis is performed by selecting $D^0 \to K^-\pi^+$ decays and using the distribution of the D^0 impact parameter (IP) with respect to the primary vertex to extract the b component. A yield of $1330 \pm 350\,(\mathrm{stat})$ events is obtained in ~ 3 nb^{-1}, which the largest b-hadron signal observed so far in LHCb. In order to increase the purity an identified muon track is required in association with the D^0. If the $D^0\mu$ combination comes from a semileptonic $b \to D^0\mu^-\bar{\nu}X$ decay, the muon and the kaon from the D^0 must have equal charges ('right-sign' combination). Figure 6 shows the distributions of the D^0 mass and of the IP logarithm for both the right-sign and wrong-sign samples. Prompt D^0 production (associated with a random muon) contributes equally to both samples with small IP values, while semileptonic b-hadron decays contribute with larger IP values only to the right-sign sample. In the latter a clean and significant $(8\,\sigma)$ signal of $85.3 \pm 10.6\,(\mathrm{stat})$ b events is extracted from a fit of the ln(IP) distribution, where the

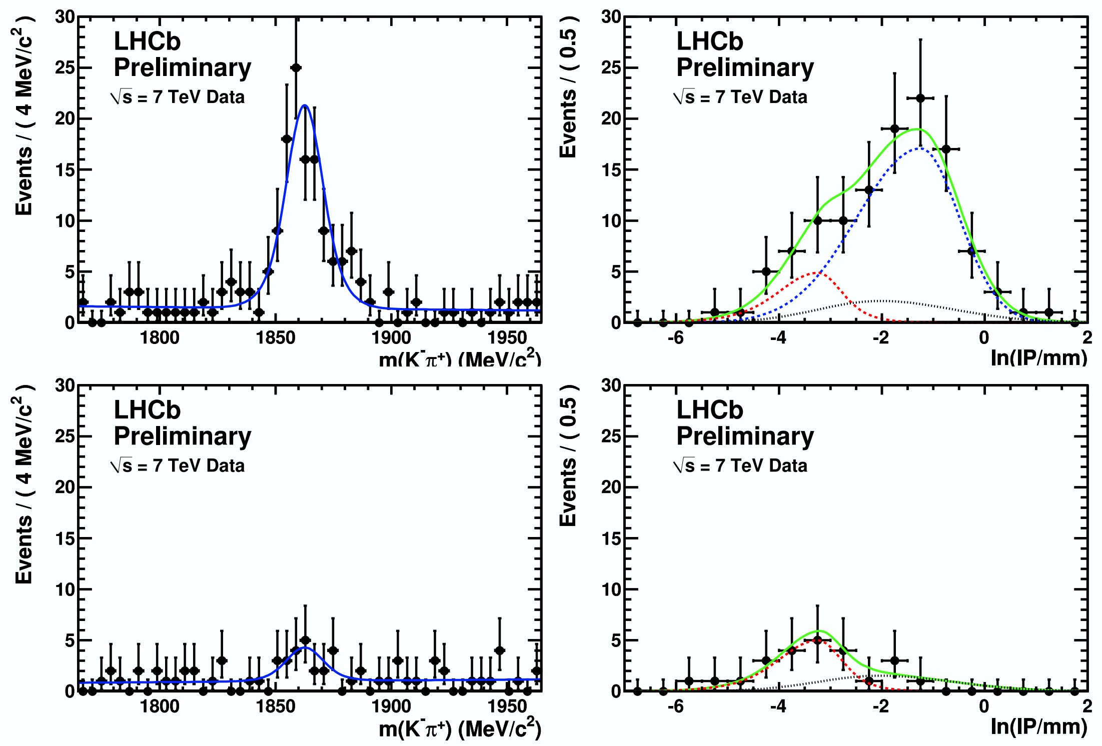

Figure 6: $D^0 \to K^-\pi^+$ invariant mass (left) and logarithm of the D^0 impact parameter in millimeters with respect to the primary vertex (right) for $D^0\mu$ candidates with 'right sign' (top) and 'wrong sign' (bottom) correlation, in $\sim 3\text{nb}^{-1}$ of data at $\sqrt{s} = 7$ TeV. Fit results are superimposed as curves. In the right-hand side plots, the black dotted curve represents the non-D^0 background estimated from the mass sidebands, and the blue (red) dotted curve represents the D^0 signal from b-hadron decays (prompt production).

shape of the b (prompt) component is fixed from MC (data without the muon requirement). These results have been finalized [13] since the conference.

In the future the abundant signals of semileptonic $B^0 \to D^0\mu^+\nu$ and $B^0_s \to D^-_s\mu^+\nu$ decays are expected to play a major role in the study of CP violation in B^0 and B^0_s mixing: Monte Carlo studies indicate that a measurement competitive with the Tevatron results can be obtained with less than 1 fb^{-1} of data, which is the statistics expected by the end of 2011.

6 Some prospects with fully reconstructed *B* decays

While several fully reconstructed B candidates have already been selected, the first significant mass peak has been seen by combining the $B^0 \to D^+\pi^-$ and $B^+ \to D^0\pi^+$ modes (Fig. 7). A $B^0_s \to D^-_s\pi^+$ signal as well as $B \to DK$ Cabibbo-suppressed signals are expected soon. The main physics goal with such hadronic B decays is the determination of the CKM angle γ using the interference between $b \to c$ and $b \to u$ tree-level diagrams in $B_{(s)} \to D_{(s)}K$ decays, where

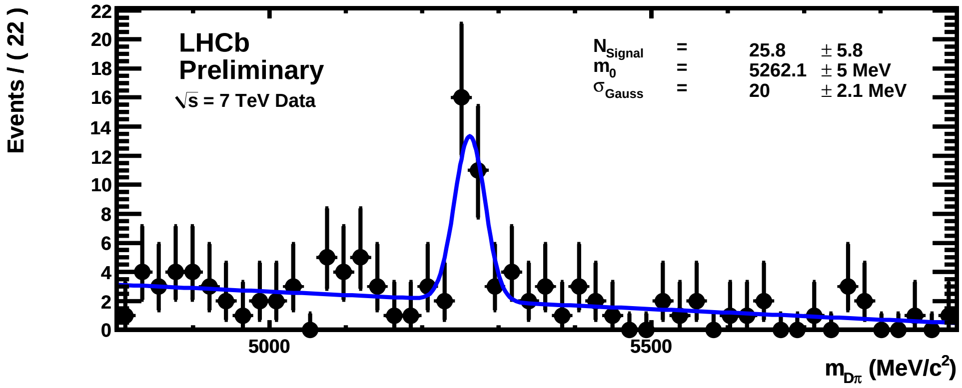

Figure 7: Sum of the $D^+\pi^-$ and $D^0\pi^+$ invariant mass distributions for ~ 13 nb^{-1} of data at $\sqrt{s} = 7$ TeV, showing the first signal of exclusively reconstructed $B \to D\pi$ decays.

a statistical precision of ~ 7 degrees (three times better than the current knowledge from the B factories) is expected with 1 fb^{-1} of data [1].

The current data already allow LHCb to prepare for a few key B_s^0 analyses. Amongst those, the measurement of mixing-induced CP violation in $B_s^0 \to J/\psi\phi$ decays and the search for the very rare $B_s^0 \to \mu^+\mu^-$ decay based on the first 0.1 fb^{-1} of data are expected to compete with Tevatron results, and may reveal hints of New Physics with 1 fb^{-1} [1].

7 Summary

LHCb is taking data with success. First strangeness production measurements have been performed, and clean charm and bottom signals have been reconstructed. LHCb will embark on its core physics programme during the 2010–2011 run, where the expected integrated luminosity should already give access to heavy-flavour observables sensitive to possible New Physics.

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