IL NUOVO CIMENTO **40 C** (2017) 35
DOI 10.1393/ncc/i2017-17035-4

COLLOQUIA: IFAE 2016

First LHCb measurement with data from the LHC Run 2

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received 17 October 2016

Summary. — LHCb has recently introduced a novel real-time detector alignment and calibration strategy for the Run 2. Data collected at the start of each LHC fill are processed in few minutes and used to update the alignment. On the other hand, the calibration constants will be evaluated for each run of data taking. An increase in the CPU and disk capacity of the event filter farm, combined with improvements to the reconstruction software, allow for efficient, exclusive selections already in the first stage of the High Level Trigger (HLT1), while the second stage, HLT2, performs complete, offline-quality, event reconstruction. In Run 2, LHCb will collect the largest data sample of charm mesons ever recorded. Novel data processing and analysis techniques are required to maximise the physics potential of this data sample with the available computing resources, taking into account data preservation constraints. In this write-up, we describe the full analysis chain used to obtain important results analysing the data collected in proton-proton collisions in 2015, such as the J/ψ and open charm production cross-sections, and consider the further steps required to obtain real-time results after the LHCb upgrade.

The LHCb experiment, designed as a flavour experiment at the LHC, is today a *General Purpose Experiment* in the forward region, covering a unique *pseudorapidity* range, $2 < \eta < 5$, with a fully equipped detector [1].

The excellent performance of the LHCb detector in Run 1, discussed in ref. [2] opened the door to a new era of precision measurements. To fully exploit the high luminosity deliverable by the LHC reducing the statistical uncertainties, it is necessary to rely on such performance already at trigger level, defining an *online* selection strategy.

In the first two sections of this write-up, we discuss the techniques used to calibrate the detector *just-in-time* before the application of the second layer of the High Level Trigger and a novel light-weight data processing procedure, named *Turbo Stream*. Sections **3** and **4** are devoted to the first physics measurements at the center-of-mass energy of 13 TeV performed by LHCb, using this new procedure. A short summary and possible outlooks conclude this document in sect. **5**.

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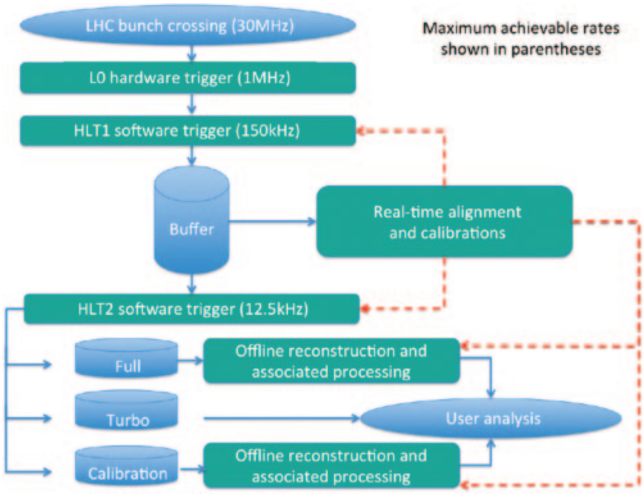

Fig. 1. – Upgraded data-processing strategy. The figure was published in ref. [4].

1. – Real-time alignment and calibration

The upgraded data-processing strategy of the LHCb experiment is depicted in fig. 1. Since July 2015, the LHC operates with a bunch-crossing spacing of 25 ns, corresponding to about 30 MHz rate considering the empty bunches. The hardware trigger stage L0 discards events based on rough information from the calorimeters and the muon system, to provide the first stage of the High Level Trigger (HLT) with an input frequency of 1 MHz. At this frequency, the entire detector can be read out and a first tracking algorithm can be used to perform a preliminary reconstruction of the event and identify secondary vertices. Selected events are temporarily buffered in the local storage of the HLT computing farm at a frequency of about 12.5 kHz.

The first few events of each fill are used to define the alignment constants in an iterative procedure of minimization of the average track χ^2 performed fully reconstructing the selected set of events at each iteration. Calibration constants, not requiring such an iterative procedure, are obtained more frequently, at the beginning of each run, with fits to some reconstructed quantities. A complete description of the online alignment and calibration procedure is presented in ref. [3].

After the calibration is performed, the events buffered on disk are fully reconstructed with the updated alignment and calibration constants using reconstruction algorithms identical to those used in the offline reconstruction procedure. The full reconstruction includes Particle Identification (PID) information obtained from the RICH detectors and neutral objects inferred from calorimeter clusters not matching any track.

Each fully reconstructed event is then processed at the HLT2 level by a large number of trigger algorithms trying to reconstruct and select decay modes in an exclusive or inclusive manner. In some cases, candidates for complex decay chains such as $D_s^+ \to \phi K^+$ with $\phi \to K^+K^-$ are available at trigger level, implementing non-trivial selection strategies as *tag-and-probe* to measure single-track trigger-level performance as detailed in ref. [5].

2. – Full, turbo and calibration streams

While, on the one hand, events are reconstructed online, with off-line quality algorithms, on the other, it would be almost impossible to reprocess offline the whole amount of events selected by HLT2, due to the limited disk resources and slowness of the procedure staging data from tape to disk. Therefore, for a large fraction of the events reconstructed by the HLT, only the candidates defined and selected at trigger-level are stored to disk, discarding the rest of the event, including *raw* detector data. Such a procedure, named *Turbo Stream* allows to save disk and CPU resources and is a preferable option for measurements requiring a large statistics (*e.g.*, charm physics).

For measurements of rare processes or searches of rare states, the option of saving the whole event to tape, to exploit every single bit to reject background, is still viable and takes the name of *Full Stream.* Events addressed to Full Stream are selected online exploiting the full upfront reconstruction, and since the full event is stored offline, it is the favorite option for inclusive trigger selection, as those based on the search of secondary vertices [6].

A *Calibration Stream* matching candidates reconstructed and selected at trigger level with the candidates for the same decay as reconstructed offline complete the picture. Calibration Stream provides the efficiency of the selection algorithm running online and offers the opportunity of measuring the performance of newly developed algorithm storing to disk the raw event of special decay modes whose single-particle properties can be inferred from kinematics without relying on the detector.

The streaming strategy of the LHCb trigger is discussed in deeper detail in ref. [7].

3. – Production cross-section of prompt and detached J/ψ mesons

The novel data processing technique was tested by measuring the production cross-section of J/ψ mesons studying the decay channel $J/\psi \to \mu^+\mu^-$ [8]. The measurement was the first result of the LHC at $\sqrt{s} = 13\,\mathrm{TeV}$ and validated the data-processing technique for the signal mode and the calibration samples used to measure the tracking and muon identification efficiencies.

As already done for the analyses of the data sample collected in pp collisions at $\sqrt{s} = 2.76, 7$ and $8\,\mathrm{TeV}$ [9], the production measurement was performed separately for prompt J/ψ, produced directly in the pp collision, and detached J/ψ whose production is mediated by the production and weak decay of a b-hadron.

In order to disentangle the contributions to the selected samples of combinatorial background, signal from prompt J/ψ and signal from b decays, a two-dimensional maximum-likelihood unbinned fit is performed, combining the information on the invariant mass of the dimuon system and the pseudo-proper decay time t_z defined as $t_z = \frac{1}{p_z} d_z M_{J/\psi}$, where d_z is the projection on the beam axis (named z) of the distance between the dimuon vertex and the primary vertex, p_z is the z-component of the dimuon momentum, and $M_{J/\psi}$ is the nominal mass of the J/ψ meson [10].

The fit is repeated for each kinematic bin, spanning a fiducial volume defined by $0 < p_T < 14\,\mathrm{GeV}/c$ and $2 < y < 4.5$, where p_T represents the component of the dimuon momentum transverse to the beam axis, and y its rapidity.

The projections of the resulting comparison of the dataset and the statistical model are presented in fig. 2 for one of the bins with higher statistics. The double-differential cross-section obtained correcting the yields from the fit for the reconstruction and trigger

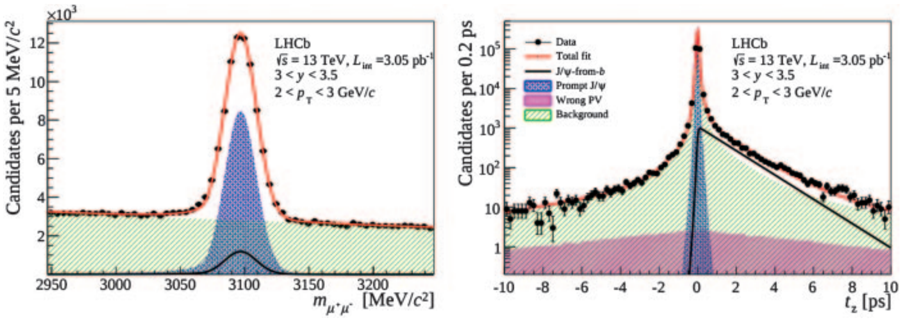

Fig. 2. – Invariant mass (left) and pseudo-proper decay time (right) distributions for the kinematic bin $2 < p_T < 3\,\mathrm{GeV}/c^2$, $2 < y < 4.5$. The figure was published in ref. [8].

efficiencies and dividing by the integrated luminosity of $3.05 \pm 0.12\,\mathrm{pb}^{-1}$ corresponding to the analysed dataset are represented in fig. 3.

Theoretical predictions are confirmed, including those on detached J/ψ which represents an important confirmation that the $b\bar{b}$ production cross-section in pp collisions scales roughly linearly with the center-of-mass energy.

4. – Production cross-section of open-charm mesons

A similar analysis was performed to measure the production cross-section of open charm hadrons, studied in a dataset corresponding to an integrated luminosity of $4.98\,\mathrm{pb}^{-1}$ through the $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^-K^+\pi^+$, and $D^{*0} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$ decay channels. The contribution from b-hadron decays is measured studying the compatibility of the charm hadron trajectory with the primary vertex, in a similar way to how the J/ψ cross-section measurement exploits t_z.

The double-differential production cross-sections in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, shown in fig. 4, was obtained correcting the yields from a maximum-likelihood unbinned fit for the reconstruction and selection efficiencies.

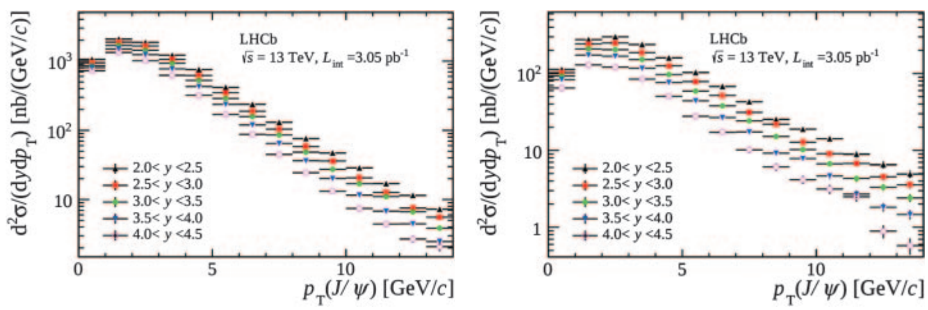

Fig. 3. – Double-differential production cross-section of prompt (left) and detached (right) J/ψ mesons as measured by LHCb in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$. The figure was published in ref. [8].

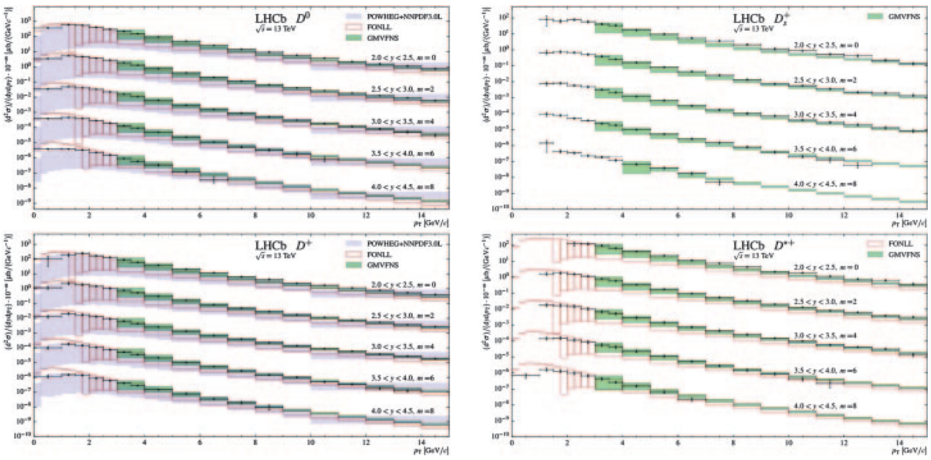

Fig. 4. – Double-differential cross-section measurement of prompt D^0 (top-left), D_s^+ (top-right), D^+ (bottom-left), and D^{*+} (bottom-right) in pp collisions at $\sqrt{s} = 13\,\text{TeV}$. The figure was published in ref. [11]).

5. – Summary and conclusion

Looking towards an upgrade at much higher luminosity, the LHCb experiment has started an evolution of the data-processing strategy moving at an earlier stage the calibration and alignment of the detector, and the full event reconstruction. Already since the start of Run 2, the High Level Trigger of the LHCb experiment is able to select decay candidates relying on the same information as available offline. When only the decay candidate is needed by the analysis, the rest of the event, including raw detector data, can be discarded saving precious disk resources. Such a data processing strategy, referred to as *Turbo Stream*, has allowed fast and precise measurements of the production cross-section of charm and J/ψ mesons at the new energy of the LHC pp collisions of $\sqrt{s} = 13\,\text{TeV}$.

Future evolutions of the data processing will rely on the online reconstruction for the whole event allowing a Turbo-like data processing also for inclusive selection strategies. Faster and more efficient algorithms, implemented also on new platforms, are changing the way we process data. The offline selection and offline analysis stages are getting closer actually merging into real-time analysis.

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