Production measurements at LHCb with the first data

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We report on the perspective measurements of inclusive particle production in high-energy p-p collisions with data to be collected by the LHCb experiment at CERN’s LHC. These include V0 and D meson production studies, which can be based on a minimum bias sample, as well as charmonia production studies, which need a muon-triggered sample. Using reconstructed $J/\psi \rightarrow \mu^+\mu^-$ decays, both the prompt $J/\psi$ and $b \rightarrow J/\psi$ production cross-sections will be determined, in the forward pseudo-rapidity range of 2-5 covered by LHCb. Due to the large production rate, such analyses will be possible with very small integrated luminosities of the order of a few pb$^{-1}$. Other charmonia related measurements will also be discussed, such as that of the $J/\psi$ polarization at production or of the production of some of the new X, Y and Z states.

I. INTRODUCTION

Dedicated to the study of the $b$-flavour quark sector, the LHCb experiment will take data in proton-proton collisions at the CERN’s LHC. At an energy in the center of mass of 14 TeV, the cross section for $b\bar{b}$ pair production is 500 pb$^{-1}$, so that, with a nominal luminosity of $2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$, $10^{12}$ $b\bar{b}$ pairs will be produced in one year ($10^7$ s) of data taking. Within this frame the CP violation and rare decays will be studied and CKM matrix tests will be performed on the full $b$-hadron spectrum as well as in the charm sector in search for hints of new physics. The detector of the LHCb experiment is presented in this article.

It is expected that the 2009 - 2010 LHC data taking will start at the center of mass energy $\sqrt{s} = 7$ TeV (may go up to 10 TeV) and an integrated luminosity of 100 to 200 pb$^{-1}$ is anticipated. With these conditions around $10^8$ minimum bias events will be collected during the first days of data taking. These data will allow to perform various production studies on V0 particles, $D$ mesons and $J/\psi$’s, which will be presented in detail in this article.

II. LHCB DETECTOR

The LHCb detector is a single-arm spectrometer placed in the forward region of the p-p interaction point. With an angular coverage, with respect to the beam-axis, from 10 (15) to 300 (250) mrad in the bending (non-bending) plane, it has an acceptance from 1.9 to 4.9 in rapidity, suited to collect the $b\bar{b}$ quarks production which, at the LHC energies, is well measured by the dipole magnet (integrated field of 4 Tm) and the tracking system. The latter is subdivided in a Trigger Tracker (TT), a silicon micro-strips detector, and three tracking stations (T1-T3) made up of silicon micro-strips for the inner part and straw tubes for the outer part. Particle identification, and in particular $\pi - K$ separation, is ensured by two Ring Imaging Cherenkov detectors, RICH1 and RICH2. Identification of muons is given by the MUON system, composed by one detector station (M1) placed upstream of the calorimeter system and 4 downstream (M2-M5); the stations are build up from MWPC’s with the exception of the very inner part of M1 where triple-GEM detectors are exploited. Finally, energy measurement is made by the calorimeter system: a Scintillator Pad Detector (SPD) and Pre-Shower (PS), the shashlik Electromagnetic Calorimeter (ECAL) and a hadronic calorimeter (HCAL) with Fe and scintillator tiles. A summary of the expected performances of LHCb is shown in Table I.

A fundamental feature of LHCb is its trigger system. The rate reduction from 40 MHz, LHC bunch crossing frequency, to 2 kHz, at which events are written on tape for later analysis, is done by two trigger levels. The Level 0 trigger is hardware based, build up of custom made electronics, and reduces the rate from 40 to 1 MHz mainly requiring particles with high transverse momentum ($p_T$) respect to the beam direction in the calorimeters and muon system. The High
TABLE I: Résumé of the LHCb detector performances.

| Description                                      | Performance                        |
|--------------------------------------------------|------------------------------------|
| Momentum resolution                              | $\sigma(p)/p \sim 0.4\%$           |
| Energy resolution (ECAL)                         | $\sigma_E/E \simeq 9\%/\sqrt{E} \oplus 0.8\%$ |
| Energy resolution (HCAL)                         | $\sigma_E/E \simeq 69\%/\sqrt{E} \oplus 9\%$ |
| $b$-hadrons mass resolution                      | $\sigma(M) \sim 14$ MeV/$c^2$     |
| Primary [secondary] vertex position               | $\sigma(\bar{x}) \sim 50[150]$ $\mu$m |
| Impact parameter                                 | $\sigma(IP) \simeq 14 + 35/p_T(GeV/c)$ $\mu$m |
| Time resolution on $b$-hadrons proper lifetime   | $\sigma(t) \sim 40$ fs            |
| Kaon identification                              | $\varepsilon(K) \sim 95\%$ at 5% of $\pi/K$ mis-id. |
| Muon identification                              | $\varepsilon(\mu) \sim 94\%$ at 3% of $\pi,K/\mu$ mis-id. |

Level Trigger will exploit the full event data from the detector to select events at 2 kHz. It is software based and its algorithms will evolve with the knowledge of the apparatus performance and physics programme leading to high flexibility.

III. PHYSICS WITH MINIMUM BIAS

As already said the LHC 2009-2010 run conditions will not be the nominal ones, nevertheless, as soon as the collisions start, lot of interesting physics will be available to be studied. Already within the minimum bias events, many measurements can be done: in particular in Fig. 2 is shown the physics reach as a function of the number of minimum bias collected. The physics reach is defined as the relative cross-section of a process (with respect to the minimum bias one) times the global efficiency for LHCb to detect it. As it can be seen $K_0^S$ and $\Lambda$ production can start to be studied with about $10^6$ minimum bias events (i.e. seconds of data taking); this study is described in [IV]. With $10^7$ minimum bias $D$ production can be studied, as described in [V] as well as $J/\psi$ production ([VI]), while for $b \to J/\psi$ something more than $10^8$ minimum bias events will be needed. This last sample, $10^8$ events, is taken as a reference for the performances of the analysis studies presented in the following. It is to be bare in mind that such a sample corresponds to days of data taking at nominal conditions, so these studies will be performed as soon as the proton collisions will take place; in particular the mentioned physics channels, apart from being interesting by themselves, are propaedeutic for the main analyses of LHCb, helping either to understand the detector performances and as building blocks of $b$-hadrons decays (e.g. $B \to J/\psi K^0_S$).

IV. V0 PRODUCTION

The hadronization process is still not well understood within the theoretical frame. At hadron col-
so that from these samples RICH calibration will be available as well. Finally these particles are building blocks of subsequent and more complex analysis.

A. V0 analysis

The study of V0 particles in LHCb will start from the following channels: \( K_S^0 \rightarrow \pi^+\pi^- \), \( \Lambda \rightarrow p\pi^- \), \( \bar{\Lambda} \rightarrow \bar{p}\pi^+ \). The results that will be presented in the following come from a study based on simulated minimum bias events with full detector simulation.

In order to deal with clean events, the ones with just one primary vertex have been selected. The analysis starts from combining two opposite charged tracks, in particular just long tracks are used: i.e. tracks with hits along the whole Tracker and in the VELO. As already said, no particle identification information is required, the analysis being based only on geometry and kinematics.

The \( K_S^0 \) analysis requires just the following two simple cuts: one on the distance of closest approach (DOCA) between the two tracks (required to be less than 0.2 mm) and one on the \( K_S^0 \) proper time \( c\tau > 4 \) mm. The \( \Lambda \) selection imposes the same cuts, plus a cut on the impact parameter of the \( \Lambda \) with respect to the Primary Vertex (PV), which is required to be less than 0.1 mm. In order to distinguish between \( K_S^0 \), \( \Lambda \) and \( \bar{\Lambda} \) decays, without particle identification, the Armenteros-Podolanski plot will be used: the transverse momentum \( p_T \) of decay products with respect to the mother particle is plotted versus the longitudinal momentum asymmetry, which is defined as

\[
\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}
\]

where \( p_L^\pm \) is the longitudinal momentum (with respect to the mother’s direction) of the daughters particles. The Armenteros-Podolanski plot, for the studied samples, is shown in Fig. 3 where the three signal regions can be easily distinguished one from each other and from the combinatorial background in the lower part of the plot. Giving the possibility to separate the three mentioned decays, this technique leads to kinematic particle identification so that unbiased pions and protons samples are available for PID (and hence RICH) calibration.

Apart from production studies, also the baryonic asymmetry will be measurable in the \( \Lambda \) sector. The \( \Lambda/\bar{\Lambda} \) ratio, in fact, provides discrimination between different hadronization processes. In Figure 5 (a) the theoretical expectation for \( \Lambda/\bar{\Lambda} \) as a function of \( \eta \) is shown as calculated with different tunings of the Monte Carlo generators. As it can be seen from the plot, the LHCb experiment will have a larger sensitivity with respect to other LHC experiments due to its coverage in the forward region of \( p-p \) interactions. A first analysis within the LHCb experiment, based just on 480k Monte Carlo minimum bias events leads to the plot shown in Figure 5 (b): the relative error on the determination of \( \Lambda/\bar{\Lambda} \) ratio is shown as a function of the pseudorapidity. As it can be seen the error is already at the level of 20-30% which, extrapolated to the reference sample of \( 10^8 \) minimum bias events, leads to expected statistical errors at the level of 1.5% which will provide discrimination between different models.

V. D MESON PRODUCTION STUDIES

During the first days of data taking, as well as strange production, charm production will also be studied. In particular early studies on D mesons production will be made, by means of the following decays: \( D^0 \rightarrow K^-\pi^+ \) and \( D^+ \rightarrow K^-\pi^+\pi^+ \) plus charge conjugate modes. The analysis strategy for the selection of these decays is very similar to the one for V0 searches. Again only VELO and Tracker information are required, no particle identification being needed from RICH, and using only kinematic and geometric variables. No use of significance variables (i.e. variables divided by their errors) will be made in order to avoid biases coming from errors not properly understood during the early stage of the experiment.

\[
\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}
\]
Moreover particle ratios will only be studied in order to cancel out largely systematics. Finally a use of Multivariate analysis techniques is made in order to reduce background. The particular algorithm used in this case is called RIPPER, which is a rule based classifier. Analysis studies have been based on 9.5 M Monte Carlo minimum bias events. Taking the $D^0 \rightarrow K^+\pi^-$ decay as an example, the following variables have been considered both for a traditional cut based analysis and for a Multivariate analysis: $p_T$ of the daughter particles, $p_T$ of the $D^0$, impact parameters of daughters with respect to PV and angle between the two IP vectors, $D^0$ flight length, DOCA, impact parameters of $D^0$. The results of the analysis can be seen in Fig. 6, where the invariant mass distributions obtained by selecting events with the two techniques are shown: by setting the Multivariate method to have the same efficiency on the signal as the cut based method, the background is reduced by the former of a factor $\sim 3$.

From the analyzed sample an average of about 200 events for each species has been, for the expected analysis sample of $10^8$ minimum bias events around 2000 events for each species are foreseen. This results lead to an expected error on the particle ratios in the sensitivity region of $\sigma(D^0/D\pi) = 5\%$ and $\sigma(D^0/D\pi) = 6\%$.

VI. $J/\psi$ PRODUCTION

The production of prompt $J/\psi$ is not completely understood. Using the Non-Relativistic QCD (NRQCD) with Colour Octet Model is possible to reproduce the transverse momentum spectrum measured at Tevatron; unfortunately this model foresees also an increasing of the transverse polarization with
The easiest $J/\psi$ decay to look for in order to measure its production is the one into two muons. Even if, as already said, many $J/\psi$ will be already present in the minimum bias sample, the use of the Muon trigger, which is one of the main blocks of the LHCb trigger, will allow to have many more events. The selection of $J/\psi$ candidates starts from two opposite long tracks with hits also in the Muon stations. A cut is made on the $\chi^2$ of the track and of the vertex of the two tracks. One of the two muons is required to have a transverse momentum greater than 1.5 GeV. Moreover a cut on the identification likelihood ($L$) is applied, with an efficiency on the muons $\varepsilon_\mu \sim 90\%$ at a level of pion mis-identification of $\varepsilon_\pi \sim 1.4\%$.

About 8% of the $J/\psi$ produced at LHC are expected to come from $b$-hadron decays; in order to distinguish between these and the prompt $J/\psi$’s the following variable will be used:

$$t = \frac{z_{J/\psi} - z_{PV}}{p_{J/\psi}^z} \cdot m_{J/\psi}$$

where $z_{PV}$ and $z_{J/\psi}$ are the two vertices coordinates and $p_{J/\psi}^z$ the momentum both along z and $m_{J/\psi}$ the mass of the $J/\psi$. From studies at the generator level $t$ is known to be a good approximation of the $b$-quark lifetime. In particular in Fig. 7 the distribution of $t$ is shown together with the $b$-decay time and the two distributions are close one to each other. In Fig. 8 instead, the distribution of the $t$ variable for different $J/\psi$ contributions is shown. In particular, apart from a flat combinatorial background (the shape of which will be estimated from $J/\psi$ invariant mass sidebands), the prompt $J/\psi$ peak at $t = 0$ and the $J/\psi$ from $b$ exponential tail can be distinguished. Within the long tail of the distribution there is also a component due to true prompt $J/\psi$ associated to the wrong primary vertex giving so a wrong $t$ value. The amount of this component will be estimated by using true reconstructed $J/\psi$ and associating them with primary vertices coming from other events chosen randomly.

B. $J/\psi$ measurement

Using the first 5 pb$^{-1}$ of integrated luminosity 3 million reconstructed $J/\psi$ are expected. The event counting will be made in pseudorapidity and transverse momentum bins. In order to compute the number of $J/\psi$ in each bin a fit of the invariant mass distribution will be made. In particular the plot shown in Fig. 9 shows this distribution obtained by just using 19 millions minimum bias events (corresponding to seconds of data taking at nominal luminosity), the mass resolution obtained is about 11 MeV. Monte Carlo data will be used to correct for detector acceptance.
FIG. 7: $b$ quark lifetime distribution studied at the event generator level in blue and $t$ variable distribution in red; it can be seen that the two distribution are very similar. Prompt $J\psi$ events in this plot would lie on the very far left.

FIG. 8: Distribution of the $t$ variable for different components: the blue curve is the prompt $J\psi$ distribution, the red curve are $J\psi$ from $b$, and the magenta the sum of the two. Within the blue curve, the long tail is due to the combination of true $J\psi$ with wrong Primary Vertices.

and efficiencies for trigger and offline selection. Finally in order to measure the absolute cross-section, integrated luminosity measurements will be needed.

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FIG. 9: $J/\psi$ invariant mass distribution (in MeV) as obtained by applying the selection sketched in §VI A to a sample of 19 millions minimum bias events.

FIG. 10: $J/\psi$ polarimetry distribution in the helicity frame as parametrized as $dN/d\cos(\theta) \propto 1 + \alpha \cos^2(\theta)$

where $\alpha = 1$ means transverse polarization, $\alpha = -1$ longitudinal polarization and $\alpha = 0$ no polarization.

VII. $\chi_c$ PRODUCTION

From Tevatron measurements it’s known that about 30% of $J/\psi$ come from $\chi_{c(1,2)} \to J/\psi \gamma$ and hence have different polarization. The production of $\chi_{c(1,2)}$ is also interesting by itself being the ratio $R_{\chi_c} = \sigma(\chi_1)/\sigma(\chi_2)$ important to distinguish different production models. While the NRQCD predicts $R_{\chi_c}$ to be close to 1, Colour Evaporation Model predicts it to be 5/3 from the expectation from spin-counting.

In order to select $\chi_c$ candidates a photon with $p_T > 500$ MeV is combined with a $J/\psi$ selected as before (restricted to a $\pm 40$ MeV mass window). The distribution of $\Delta M = M_{\mu\mu\gamma} - M_{\mu\mu}$ is then used to extract the $\chi_{c1}$ and $\chi_{c2}$ signals. This distribution, shown in Fig. 10, will be fitted with two gaussians which represent the signal and a background component parametrized as $P(\Delta M) = \Delta M^c \cdot \exp(-c_1 \cdot \Delta M - c_2 \cdot \Delta M^2)$. The obtained resolution is $\sigma(\Delta M) \sim 27$ MeV which has to be compared with the mass difference of the two resonances, $m(\chi_{c2}) - m(\chi_{c1}) = 46$ MeV; the achievable separation is limited but still some sensitivity is present leading to a discrimination between $\chi_{c1}$ and $\chi_{c2}$ and to the measurement of $R_{\chi_c}$.

VIII. OTHER QUARKONIA MEASUREMENTS

Beyond the already mentioned studies, measurements will be performed also on other charmonia and bottomonia channels. The $\psi(2S)$ production and in particular the $\sigma(\psi(2S))/\sigma(J/\psi)$ ratio will be studied. Moreover, similar measurements to the charmonia case will be performed also for bottomonium
FIG. 10: Distribution of the $\Delta M$, as defined in § VII, for inclusive $J/\psi$ events. The $\Delta M$ for $\chi_{c(1,2)} \rightarrow J/\psi \gamma$ events peak can be seen. The red and green curves are the gaussian distribution used to represent the signal; the blue curve represents the background ($J/\psi$ not from $\chi_{c}$) distribution.

production and spectroscopy (e.g. $\Upsilon(1S, 2S, 3P)$ resonances, $\chi_b \rightarrow \Upsilon \gamma$).

The exotic $X$, $Y$ and $Z$ charmonia states, recently observed, will also be studied at LHCb. In particular is under investigation the possibility to measure the $X(3872)$ quantum numbers by means of an angular analysis of the decay $X(3872) \rightarrow J/\psi \pi^+ \pi^-$; this analysis will be even more sensitive if studied in the frame of the $B^+ \rightarrow X K^+$ decay where the $X$ is expected to be produced polarized: in this context will be possible to distinguish if the $X$ has $J^{PC}$ equal to $1^{++}$ or $2^{−+}$.

IX. CONCLUSIONS

To summarize, the LHCb experiment, ready to take data at the LHC proton collisions, will be able to exploit the very first data, apart for detector calibrations and tunings, also for very interesting physics analyses. Within a sample of $10^8$ minimum bias events it will be possible to probe hadronization models with $V_0$ production studies and D-mesons ratios will be measurable with about $\sim 5\%$ error. Quarkonia spectroscopy will be also investigated and $J/\psi$ production and polarization will be measured.

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