

## Probes of soft and hard QCD at LHCb

E. SANTOVETTI on behalf of the LHCb COLLABORATION

*Università di Roma "Tor Vergata" and INFN, Sezione di Roma 2 - Roma, Italy*

ricevuto il 7 Settembre 2012

**Summary.** — The LHCb experiment is instrumented in the forward region. Due to this, it can provide QCD and electroweak measurements complementary to the other LHC experiments. The  $W$  and  $Z$  production cross-sections have been measured in proton-proton collisions at  $\sqrt{s} = 7$  TeV. The measurements of the production cross-section of the  $\Psi(2S)$  meson and the  $\Upsilon$  mesons are reported. The observation of double-charm production is also discussed.

PACS 14.70.Fm –  $W$  bosons.

PACS 14.70.Hp –  $Z$  bosons.

PACS 14.40.Pq – Heavy quarkonia.

### 1. – Introduction

The LHCb experiment is designed to investigate the properties of the heavy-quark sector and aims to study  $CP$ -violation processes and rare decays involving  $b$  and  $c$  hadrons. It can also be used to study QCD and electroweak processes. The  $bb$  pair production are strongly correlated at small angle with respect to the beam line, therefore the LHCb detector [1] has been designed as a single-arm forward spectrometer covering a pseudorapidity range  $2 < \eta < 5$ . The detector consists of a silicon vertex detector, a dipole magnet, a tracking system, two ring-imaging Cherenkov (RICH) detectors, a calorimeter system and a muon system.

The LHCb experiments made several measurements in the soft QCD sector (baryon number transport, strange baryon suppression, charged track multiplicity, inclusive  $\phi$  cross-section, etc. . .) as well as in the quarkonium physics. In these proceedings we will present some of the latest results on electroweak physics (sect. 2) and quarkonia (sect. 3).

### 2. – Electroweak measurements

The  $W$  and  $Z$  production cross-sections at  $\sqrt{s} = 7$  TeV energy are measured using the decays  $W \rightarrow \mu\nu$ ,  $Z \rightarrow \mu\mu$  and  $Z \rightarrow \tau\tau$ . The  $W$  production charge asymmetry has been also measured as a function of the lepton pseudorapidity.

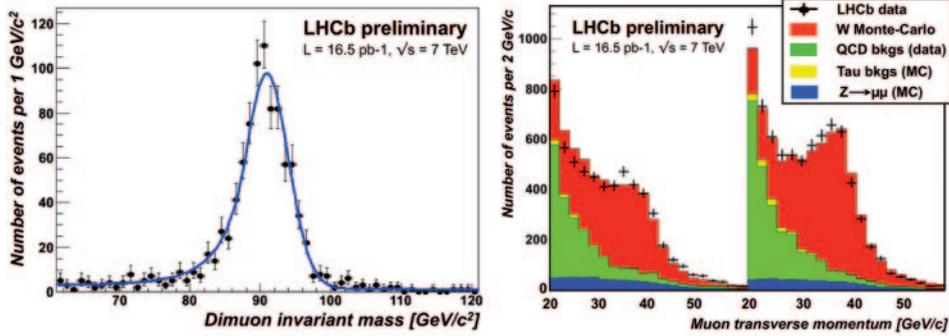


Fig. 1. – Left: Di-muon invariant mass of  $Z$  candidates: data points are fitted to a Crystal Ball function (signal) on an exponential (background). Right:  $p_T$  distribution for negative (left) and positive (right) charged muons.

This analysis uses  $\int \mathcal{L} = (16.5 \pm 1.7) \text{ pb}^{-1}$  of data, collected during 2010 [2]. This results are recently updated with a larger statistic sample [3].

*$Z \rightarrow \mu^+ \mu^-$  selection.* – Concerning the  $Z \rightarrow \mu\mu$ , the events are selected by requiring two well reconstructed muons with a transverse momentum,  $p_T$ , greater than  $20 \text{ GeV}/c$  and lying in the pseudorapidity ( $\eta$ ) range between 2.0 and 4.5. To further identify  $Z \rightarrow \mu^+ \mu^-$  events, the invariant mass is required to be consistent with  $Z$  production by imposing the mass constraint  $81 \text{ GeV}/c^2$ ,  $M_{\mu\mu} < 101 \text{ GeV}/c^2$ . 833 candidate events satisfy these criteria.

*$W \rightarrow \mu\nu$  selection.* – The signature for a  $W$  boson is a single isolated high-transverse-momentum lepton and minimal other activity in the event. As the background contamination is expected to be larger than in  $Z$  events, additional criteria to the  $p_T > 20 \text{ GeV}/c$  and  $2.0 < \eta < 4.5$  requirements are imposed; consistency with the primary vertex and muon isolation. Semi-leptonic  $B$  and  $D$  meson decays are suppressed by requiring the impact parameter significance of the muon with respect to the primary vertex to be less than 2. Isolation is imposed by demanding that the summed transverse energy in a cone of radius  $\sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$  around the muon is less than  $2 \text{ GeV}/c$ . 7624  $W^+ \rightarrow \mu^+ \nu$  and 5732  $W^- \rightarrow \mu^- \nu$  candidates pass these requirements.

A detailed background study is performed:  $Z \rightarrow \mu^+ \mu^-$  where one of the muons goes outside the LHCb geometrical acceptance;  $W \rightarrow \tau\nu$  and  $Z \rightarrow \tau\tau$  where one tau decays leptonically inside the detector to a muon;  $b$  and  $c$  events containing semi-leptonic decays with a muon in the final state; generic QCD events where pions or kaons are misidentified as muons (decay in flight or punch-through).

The signal yield is estimated by fitting the lepton  $p_T$  spectrum to the shapes expected for signal (simulation) and each background class (simulation and data-driven by anti-cuts) in 5 bins of the lepton pseudorapidity. The  $W$  selected candidates and the result of the fit are shown in fig. 1 (right). The fit estimates that  $(34 \pm 1)\%$  of the sample is composed by  $W^+ \rightarrow \mu^+ \nu$ ,  $(26 \pm 1)\%$  by  $W^- \rightarrow \mu^- \nu$  and  $(31 \pm 1)\%$  is due to the QCD background.

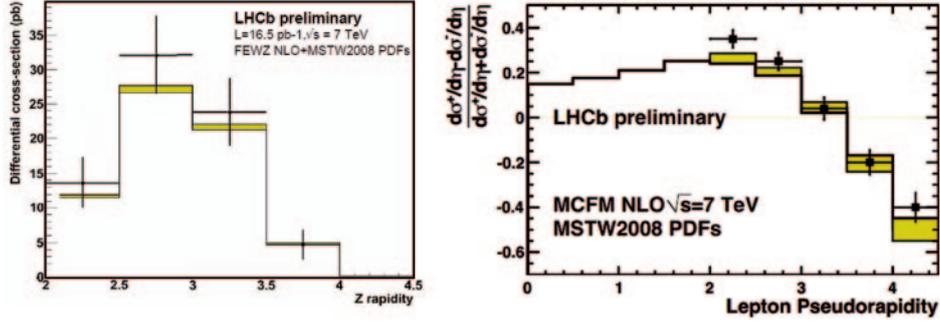


Fig. 2. – Left: Differential cross-section for  $Z$  production in bins of boson rapidity. Right:  $W$  charge asymmetry in bins of lepton pseudorapidity. The points are the measured data (statistical and systematic errors combined) compared to the NLO prediction with the MSTW084 PDF set; the yellow band is the theoretical uncertainty.

*Results.* – The  $Z$  and  $W$  production cross-sections are measured, with the kinematic requirements above specified, according to the formula:

$$(1a) \quad \sigma = \frac{N_{Candidates} - N_{Background}}{\epsilon_{Trigger} \cdot \epsilon_{Tracking} \cdot \epsilon_{\mu-ID} \cdot \epsilon_{Selection} \cdot \int \mathcal{L}},$$

where all involved efficiencies (trigger, tracking, muon identification and selection) are measured directly from data and cross-checked with simulation. Background estimates, efficiency measurements and luminosity determination are considered as sources of systematic error. Inclusive production cross-sections for  $Z$ ,  $W^+$  and  $W^-$  bosons are determined to be

$$(2a) \quad \sigma(W^+ \rightarrow \mu^+ \nu) = (1007 \pm 48 \pm 101) \text{ pb},$$

$$(2b) \quad \sigma(W^- \rightarrow \mu^- \nu) = (680 \pm 40 \pm 68) \text{ pb},$$

$$(2c) \quad \sigma(Z \rightarrow \mu\mu) = (73 \pm 4 \pm 7) \text{ pb}.$$

The differential  $Z$  cross-section in 5 bins of the boson rapidity and the  $W$  charge asymmetry in 5 bins of lepton pseudorapidity are shown in fig. 2. This measurements can be used to probe the PDF's and test the QCD predictions.

### 3. – Quarkonium results

*The measurement of  $\Psi(2S)$  meson production at  $\sqrt{s} = 7$  TeV.* – The differential cross-section for the inclusive production of  $\Psi(2S)$  mesons in  $pp$  collisions at  $\sqrt{s} = 7$  TeV has been measured [4] using an integrated luminosity of  $36 \text{ pb}^{-1}$ . The decay channels  $\Psi(2S) \rightarrow \mu^+ \mu^-$  and  $\Psi(2S) \rightarrow (J/\Psi \rightarrow \mu^+ \mu^-) \pi^+ \pi^-$  are reconstructed using prompt  $\Psi(2S)$  and  $\Psi(2S)$  decaying from a  $b$ -hadron (delayed). The separation between the two samples is done using a pseudo-decay-time distribution defined as  $t = d_z(M/p_z)$ , where  $d_z$  is the separation along the beam axis between the  $\Psi(2S)$  decay vertex and the primary vertex,  $M$  is the nominal  $\Psi(2S)$  mass and  $p_z$  is the component of its momentum along the beam axis. The polarization of promptly reconstructed  $\Psi(2S)$ 's is not measured

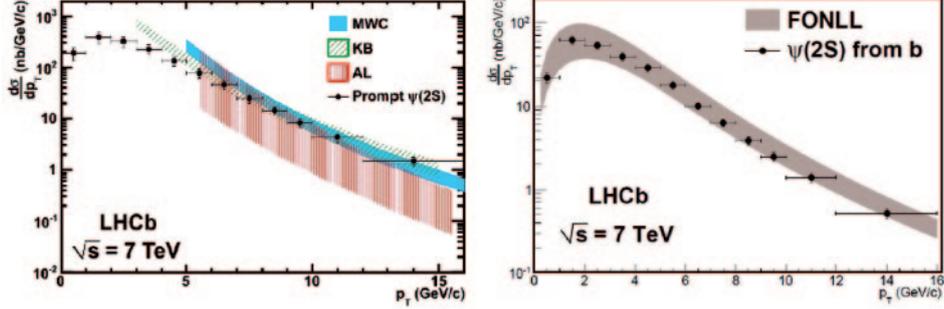


Fig. 3. – Left: Differential production cross-section *vs.*  $p_T$  for prompt  $\Psi(2S)$ . The predictions of three non-relativistic QCD models are also shown for comparison. MWC [6] and KB [7] are NLO calculations including colour-singlet and colour-octet contributions. AL [8] is a colour-singlet model including the dominant NNLO terms. Right: Differential production cross-section *vs.*  $p_T$  for delayed  $\Psi(2S)$ . The shaded band is the prediction of a FONLL calculation [9].

here, therefore a systematic uncertainty is computed separately for the unknown state of the polarization. This does not effect the delayed  $\Psi(2S)$ . The differential cross-sections for prompt  $\Psi(2S)$  and delayed  $\Psi(2S)$  mesons are measured in the kinematic range  $p_T(\Psi(2S)) < 16 \text{ GeV}/c$  and  $2 < y(\Psi(2S)) < 4.5$ :

$$(3a) \quad \sigma_{prompt}(\Psi(2S)) = 1.44 \pm 0.01(\text{stat}) \pm 0.12(\text{syst})^{+0.20}_{-0.40}(\text{pol}) \mu\text{b},$$

$$(3b) \quad \sigma_b(\Psi(2S)) = 0.25 \pm 0.01(\text{stat}) \pm 0.02(\text{sys}) \mu\text{b}.$$

Recent QCD calculation on the differential cross-sections are found to be in a good agreement with these results as shown in fig. 3. Combining this result with the LHCb measurement of the  $J/\Psi$  cross-section (from  $b$  decay) in the same fiducial range [5], the inclusive branching ratio has been determined to be

$$(4a) \quad \mathcal{B}(b \rightarrow \Psi(2S) X) = (2.73 \pm 0.06(\text{stat}) \pm 0.16(\text{syst}) \pm 0.24(\text{BR})) \times 10^{-3},$$

where the last uncertainty is due to the  $\mathcal{B}(b \rightarrow J/\Psi X)$ ,  $\mathcal{B}(J/\Psi \rightarrow \mu^+ \mu^-)$  and  $\mathcal{B}(\Psi(2S) \rightarrow e^+ e^-)$  branching fraction uncertainties. The later branching fraction is used and justified by the leptons universalities.

$\Upsilon(1S)$  production cross-section. – The  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(3S)$  states have been observed via their decays into two muons with sufficient resolution to separate fully the  $\Upsilon(2S)$  and  $\Upsilon(3S)$  invariant mass peaks (see fig. 4 (left)). The  $\Upsilon(1S)$  differential production cross-section as a function of  $\Upsilon(1S)$   $y$  and  $p_T$  has been measured [10] in the fiducial region  $p_T < 15 \text{ GeV}/c$  and  $2.0 < y < 4.5$ . The fiducial region has been divided into bins of width  $1 \text{ GeV}/c$  in  $p_T$  and one unit of rapidity ( $y$ ) and a dataset corresponding to an integrated luminosity of  $32.4 \text{ pb}^{-1}$  has been used. The  $\Upsilon(1S)$  yield has been extracted from a fit to the di-muon invariant mass distribution using a Crystal Ball to model the signal shape and an exponential to model the background shape (see fig. 4 (left)). The results have been reported under the assumption of unpolarized  $\Upsilon(1S)$  and the largest systematic uncertainty comes from this assumption. The measured  $\Upsilon(1S)$  production cross-section, integrated over the fiducial region, assuming unpolarized  $\Upsilon(1S)$

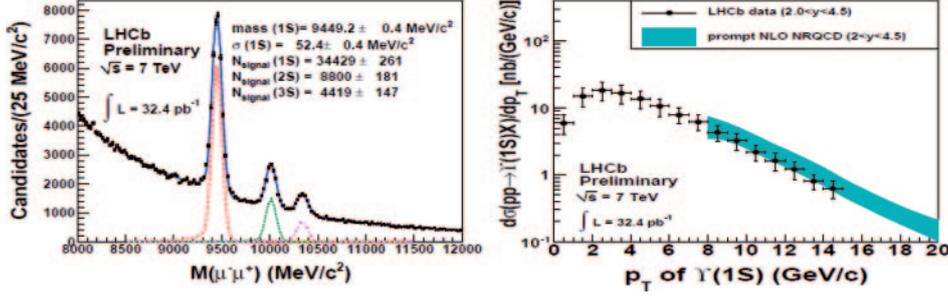


Fig. 4. – Left: The invariant-mass distribution of the selected  $\Upsilon \rightarrow \mu^+\mu^-$  candidates. The three peaks correspond to the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ , and  $\Upsilon(3S)$  signals (from left to right). The superimposed curves and the signal yields are the result of the fit. Right: The measured differential  $\Upsilon(1S)$  production cross-section as a function of  $p_T$  integrated over  $y$  (black dots) compared to the prediction calculated from NRQCD at NLO, including contributions from  $\chi_b$  and  $\Upsilon(2S)$  decays, summing the colour-singlet and colour-octet contributions [11] (coloured band).

is  $\sigma_{\Upsilon(1S)} = 108.3 \pm 0.7^{+30.9}_{-25.8}$  nb where the first uncertainty is statistical and the second is systematic. The measured  $\Upsilon(1S)$  differential production cross-section as a function of  $\Upsilon(1S)p_T$  ( $d\sigma/dp_T$ ) has been compared with LO and NLO NRQCD, and with NLO and NNLO CS theoretical predictions. The predictions take into account the  $\Upsilon(1S)$  feed down from  $\chi_b$  and  $\Upsilon(2S)$  and are in good agreement with data (see, for example, fig. 4 (right)). The results are allowing for the different rapidity range in good agreement with those obtained by the CMS Collaboration [12].

*Observation of double-charm production involving open charm.* – The production of a  $J/\Psi$  accompanied by open charm and pairs of open-charm ( $C$ ) hadrons are observed [13] in  $pp$  collisions at  $\sqrt{s} = 7$  TeV using an integrated luminosity of  $355 \text{ pb}^{-1}$ . Leading-order calculation in perturbative QCD and a model including Double-Parton Scattering (DPS) [14, 15] give significantly different prediction,  $\sigma(J/\Psi C) + J/\Psi \bar{C} \sim 18$  nb and  $\sim 280$  nb, respectively. The DPS predictions can also be tested through the ratios of cross-sections of the charm hadrons involved: in a DPS scenario  $\sigma(C_1) \times \sigma(C_2) / \sigma(C_1 C_2)$  should be equal (twice bigger if  $C_1 \neq C_2$ ) to the effective DPS cross-section measured at the Tevatron [16]. The open charm hadrons considered here are:  $D^0$ ,  $D^+$ ,  $D_s^+$  and  $\Lambda_c^+$ , while the  $C\bar{C}$  are used as control channels. Selected charged tracks are combined to form  $J/\Psi \rightarrow \mu^+\mu^-$ ,  $D^0 \rightarrow K^-\pi^+$ ,  $D^+ \rightarrow K^-\pi^+\pi^+$ ,  $D_s^+ \rightarrow K^-K^+\pi^+$  and  $\Lambda_c^+ \rightarrow pK^+\pi^+$ . Subsequently these candidates are combined into  $J/\Psi C$ ,  $CC$  and  $C\bar{C}$ . The combinations are requested to come from the same primary vertex and lie in the rapidity range  $2 < y(J/\Psi, C) < 4$  and the  $p_T$  range  $p_T(J/\Psi) < 12$  GeV/c and  $3 \text{ GeV/c} < p_T(C) < 12$  GeV/c. In addition a flight distance  $c\tau > 100 \mu\text{m}$  is required for the  $C$ .

Signals with a statistical significance over five standard deviations have been observed for the four  $J/\Psi C$ , for six  $CC$  modes:  $D^0 D^0$ ,  $D^0 D^+$ ,  $D^0 D_s^+$ ,  $D^0 \Lambda_c^+$ ,  $D^+ D^+$  and  $D^+ D_s^+$ , and for seven  $C\bar{C}$  channels:  $D^0 \bar{D}^0$ ,  $D^0 D^-$ ,  $D^0 D_s^-$ ,  $D^0 \bar{\Lambda}_c^-$ ,  $D^+ D^-$ ,  $D^+ D_s^-$  and  $D^+ \bar{\Lambda}_c^-$ . In fig. 5 the cross-sections are shown on the left and the DPS fraction on the right. Results favour the DPS model using the effective cross-section measured at Tevatron, which is also favoured with the absence of azimuthal and rapidity correlations. The transverse momentum of these events has also been studied. In the  $J/\Psi C$  case we can see a harder  $p_T^{J/\Psi}$  spectra compared to the prompt  $J/\Psi$  production.

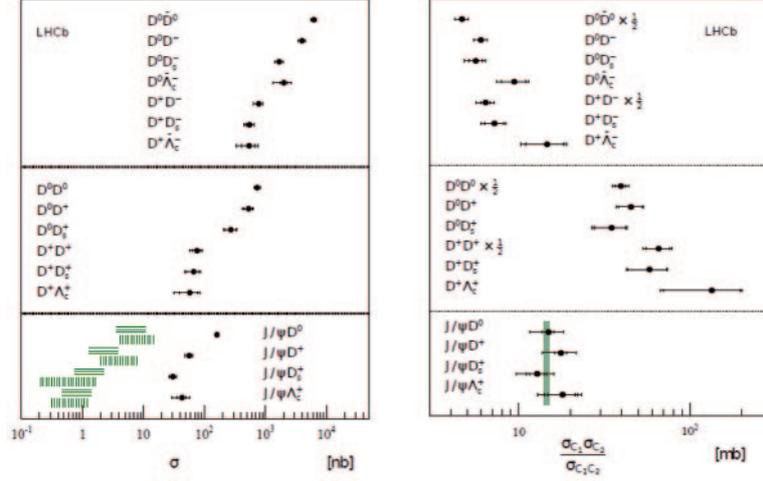


Fig. 5. – Left: Measured cross-sections  $\sigma_{J/\Psi C}$ ,  $\sigma_{CC}$  and  $\sigma_{C\bar{C}}$  (points with error bars) compared, in  $J/\Psi C$  channels, to the calculations in refs. [17] (vertical hatched areas) and ref. [18] (horizontal hatched areas). The inner error bars show the statistical uncertainty whilst the outer error bars show the sum of the statistical and systematic uncertainties in quadrature. Right: Measured ratios  $\sigma(C_1) \times \sigma(C_2)/\sigma(C_1 C_2)$  (points with error bars) in comparison with the expectations from DPS using the cross-section measured at Tevatron for multi-jet events (light green shaded area). For the  $D^0\bar{D}^0$ ,  $D^0\bar{D}^0$ ,  $D^+D^+$  and  $D^+D^-$  cases the ratios are rescaled by the symmetry factor of one half. The inner error bars show the statistical uncertainty whilst the outer error bars show the sum of the statistical and systematic uncertainties in quadrature. For the  $J/\Psi C$  case the outermost error bars correspond to the total uncertainties including the uncertainties due to the unknown polarization of the prompt  $J/\Psi$  mesons.

## REFERENCES

- [1] ALVES A. A. *et al.* (THE LHCb COLLABORATION), *JINST* **3**, **13** (2008) s08005.
- [2] LHCb COLLABORATION, *JHEP*, **06** (2012) 058.
- [3] LHCb COLLABORATION, LHCb-CONF-2011-039.
- [4] LHCb COLLABORATION, *Eur. Phys. J. C*, **72** (2012) 2100.
- [5] LHCb COLLABORATION, *Eur. Phys. J. C*, **71** (2011) 1645; *Eur. Phys. J. C*, **71** (2011) 1645.
- [6] MA Y. Q., WANG K. and CHAO K. T., arXiv:hep-ph/1012.1030.
- [7] KNEIHL B. and BUTENSCHÖN M., *Phys. Rev. Lett.*, **106** (2011) .
- [8] ARTOISENET P. *et al.*, *Phys. Rev. Lett.*, **101** (2008) 152001; *Eur. Phys. J. C*, **61** (2009) 693.
- [9] CACCIARI M., GRECO M. and NASOU P., *JHEP*, **9805** (1998) 007; *JHEP*, **07** (2004) 033.
- [10] LHCb COLLABORATION, *Eur. Phys. J. C*, **72** (2012) 2025.
- [11] WANG K., MA Y. Q. and CHAO K. T., private communication.
- [12] CMS COLLABORATION, arXiv:1012.5545v1.
- [13] LHCb COLLABORATION, *JHEP*, **06** (2012) 141.
- [14] BEREZHNOY A. V. *et al.*, *Phys. Rev. D*, **57** (1998) 4385.
- [15] KOM C. H., KULESZA A. and STIRLING W. J., *Phys. Rev. Lett.*, **107** (2011) 082002; *Phys. Rev. B*, **705** (2011) 116 and arXiv:1106.2184.
- [16] CDF COLLABORATION, *Phys. Rev. D*, **56** (1997) 3811.
- [17] BARANOV S. P., *Phys. Rev. D*, **73** (2006) 074021.
- [18] LANSBERG J. P., *Eur. Phys. J. C*, **61** (2009) 693.