Quarkonia and Exotics at LHCb

Philippe Ghez, on behalf of the LHCb Collaboration

LAPP, 9 Chemin de Bellevue - BP 110, 74941 Annecy-le-Vieux Cedex - France

E-mail: `ghez@lapp.in2p3.fr`

Abstract. We present here the latest results from the LHCb collaboration on quarkonia and exotics. This summary includes three analyses in the charmonium sector, two of which concerning exotics, and one analysis in the bottomonium sector on χ_b production.

1. Introduction

Since charmonium and bottomonium production cross-sections lie in the [µb, pb] range [1], with a delivered integrated luminosity of several fb^{-1} for Run1, the LHC is a quarkonium factory. Its first years of running mark "The return of the Quarkonia" [2]. In this report, we address four of the many questions raised in the 2011 summary report of the Quarkonium Working Group [3]: $\psi(2S)$ polarisation, nature of the X(3872) state, existence and nature of the Z(4430) state and χ_b production. These four studies are all based on the detection of muon pairs.

2. Prompt $\psi(2S)$ polarisation

The measurement of the quarkonium polarisation is an important input to the many QCD-based models which have not yet been able to describe both quarkonium production and polarisation. At the LHC, the $\psi(2S)$ meson is produced in three ways: directly from the hard scattering, from feed-down of higher mass quarkonia or via the decay of b hadrons. The first two modes are prompt. The feed-down mode is negligible. The $\psi(2S)$ is observed through its decay into a muon pair. The prompt $\psi(2S)$ polarisation is obtained from the angular distribution of the muons which is related to the polarisation parameters $(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$ once a spin-quantization frame has been defined. In this analysis [4], two different choices of the spin-quantization frame have been used: the helicity frame (HX) and the Collins-Soper frame (CS).

The event sample is obtained from pp collisions at $\sqrt{s} = 7$ TeV with an integrated luminosity of 1 fb^{-1}. The event selection relies upon the use of a dedicated muon hardware trigger and a software trigger which refines the dimuon selection.The reconstruction of $\psi(2S)$ from the kinematic properties of the two muons is then performed and finally a cut is applied on the pseudo-decay time of the $\psi(2S)$, to reduce the non-prompt contamination from 20% to 3%. A mass fit in 5 p_T and 5 y (rapidity) bins of the $\psi(2S)$, labeled $p_T^{\psi 2}$ and y$^{\psi 2}$ hereafter, is performed to extract the signal yield. After background subtraction, efficiency corrections obtained from simulated events are applied and a bin-by-bin likelihood is constructed.

The three polarisation parameters are obtained in each $(p_T^{\psi 2}, y^{\psi 2})$ bin for the two choices of polarisation frames. Systematic and statistical errors are of the same magnitude (5% to 100% depending on the $(p_T^{\psi 2}, y^{\psi 2})$ bin). Within errors and over the accessible kinematic range, $\lambda_{\theta\phi}$ and λ_ϕ are compatible with 0.
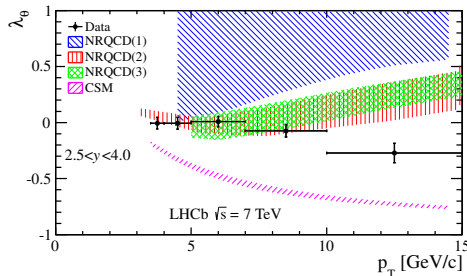
Figure 1. Polarisation parameter λ_θ in the HX frame as a function of $p_T^{\psi 2}$ for $y^{\psi 2}$ in the range [2.5,4.0]. The error bars represent the sum in quadrature of statistical and systematic uncertainties.

The λ_θ parameter in the HX frame does not show any large polarisation (longitudinal or transverse) effect which contradicts, at high $p_T^{\psi 2}$, most QCD-based models (Fig. 1). A frame-invariant polarisation parameter built from λ_θ and λ_ϕ is consistent with a negative polarisation with no strong $p_T^{\psi 2}$ and $y^{\psi 2}$ dependence. All results are consistent, within errors, between the HX and the CS choices of the polarisation frame.

3. Evidence for the decay X(3872)$\rightarrow \psi$(2S)γ

The X(3872) is the first exotic state discovered by Belle in 2003. Since its discovery, the nature of this state has been investigated with no strong conclusion. In this analysis [5], the decay X(3872)$\rightarrow\psi$(2S)γ is searched for. The X(3872)$\rightarrow J/\psi\,\gamma$ decay is also investigated and the ratio of the two X(3872) branching fractions is measured. The value of this ratio is predicted by several models describing the X(3872) nature. The predictions range from ≈ 0 for a $D\bar{D}^*$ molecule to ≈ 15 for a pure charmonium state.

The data sample corresponds to the full statistics recorded by LHCb during Run1, i.e. to integrated luminosities of 1 fb^{-1} at $\sqrt{s}$ = 7 TeV and 2 fb^{-1} at $\sqrt{s}$ = 8 TeV. This also holds for the other analyses presented in the remainder of this document. The X(3872) particle is searched for in the $B^+ \to X(3872)K^+$ decay. The event selection is similar to that presented in the previous section except that the dimuon is requested to be non-prompt. The accompanying kaon is distinguished from a pion using the (RICH based) charged particle identification system and kinematic cuts are applied to ensure that the dimuon and the kaon are coming from the same displaced vertex. The dimuon invariant mass is constrained to be in the ψ(2S) or J/ψ mass range. A photon is identified in the calorimeters as an electromagnetic cluster with no charged track pointing to it. Photons from $\pi^0 \to \gamma\gamma$ decays (main background to the isolated photons) are rejected if, when combined to other photons in the event, their invariant mass is within 25 MeV of the π^0 mass.

The signal yield of the $B^+ \to X(3872)K^+$ decays followed by X(3872)$\to \psi\gamma$ ($\psi \equiv\psi$(2S) or J/ψ) is determined from a two-dimensional unbinned maximum likelihood fit in the ($\psi\gamma K^+$, $\psi\gamma$) invariant mass plane. In the ψ(2S) channel, the X(3872) signal is observed with a significance of 4.4 standard deviations. The measured yields are corrected for efficiencies ($\epsilon_{J/\psi}, \epsilon_{\psi(2S)}$). Their ratio, determined from simulated events with similar topologies, is found to be 5.25 $\pm$ 0.04. The large value of this ratio is mainly due to the differences in the photon kinematics. The dominant systematic errors are coming from the X(3872) yield determination and the photon reconstruction ($\approx$ 6-7% each). The ratio of branching fractions is measured to be 2.46 $\pm$ 0.64 (stat) $\pm$ 0.29 (syst). This value agrees with expectations for both a pure charmonium and a molecular-charmonium mixture but does not support a pure $D\bar{D}^*$ molecular interpretation of the X(3872) state.

4. Observation of the resonant character of the Z(4430)⁻ state

The Z(4430)⁻ state has been the topic of many debates in the past years. Its existence and its nature are still controversial. In this analysis [6], we study the $B^0 \to \psi(2S)\pi^- K^+$ decay where the $\psi(2S)$ is observed through its decay to a pair of muons. In this decay channel , the dominant background to a $Z(4430)^- \to \psi(2S)\pi^-$ decay comes from the many $K^{*0} \to K^+\pi^-$ decays through their reflections in the mass peak. This study is a four-dimensional amplitude analysis where the amplitude depends on $(m^2_{K^+\pi_-}, m^2_{\psi(2S)\pi_-}, \cos\theta_{\psi(2S)}, \phi)$ where $\theta_{\psi(2S)}$ is the $\psi(2S)$ helicity angle and ϕ the angle between the K^{*0} and $\psi(2S)$ planes in the B^0 rest frame.

The B^0 selection uses similar techniques as that described in Section 3. The amplitude model includes all known K^{*0} resonances in various spin states (J=0,1,2,3) with nominal mass at or slightly above kinematic limits. The fits with all K^* components give a significance of 18.7 σ and $M_{Z^-} = 4475 \pm 7\,\text{MeV}, \Gamma_{Z^-} = 172 \pm 13\,\text{MeV}, f_{Z^-}$ (amplitude fraction) $= (5.9 \pm 0.9)\%$, compatible with the latest Belle results. The significance goes down to 13.9 σ when all systematics are included. These systematics are obtained by varying the major components of the amplitude fits: K^* models, K^* S-wave representation, K^* masses and width, etc. Added in quadrature, the systematic errors are: (+15,-25) MeV for M_{Z^-}, (+37,-34) MeV for Γ_{Z^-} and (+1.5,-3.3) % for f_{Z^-}. The spin-parity of the Z(4430)⁻ is found to be 1⁺ with a very high significance.

An additional fit is performed where the Z(4430)⁻ amplitude is represented as a combination of independent complex amplitudes (Re $A^{Z(4430)^-}$, Im $A^{Z(4430)^-}$) at six equidistant points in the $m^2_{\psi(2S)\pi^-}$ range. The resulting Argand diagram, shown in Fig. 2, exhibits a quasi circular pattern, characteristic of a resonance.
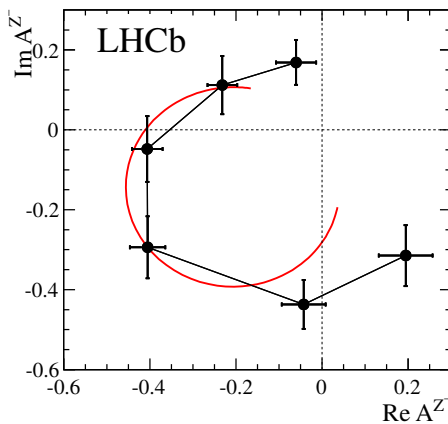

Figure 2. Fitted values of the Z^- amplitude in six $m^2_{\psi(2S)\pi^-}$ bins. The curve is the prediction from the Breit-Wigner formula with a resonance mass (width) of 4475 (172) MeV.

5. χ_b meson production

Feed-down contributions from P-wave quarkonium states to S-wave quarkonium states might be of crucial importance for the comparison between experimental results and theory. This analysis [7] studies the χ_b production in LHCb using the data sample described in Section 3 and measures the fraction of $\Upsilon(nS)$ originating from χ_b decays.

Prompt muon pairs are selected with each muon having a p_T larger than 1 GeV. Further cuts refine the quality and the purity of the muons. An identification purity ranging between 75% and 98% according to the muon p_T is achieved. Cuts improving the two-prong common vertex and the compatibility of this vertex with the primary vertex are applied. Three very clean peaks, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$, are observed in the $m_{\mu\mu}$ mass distribution. For each of these 3 states, the yield is obtained from an unbinned maximum likelihood fit.

Photons reconstructed using the electromagnetic calorimeter are combined to each muon pair having an invariant mass within 150 MeV of one of the Υ states to form a χ_b. A transverse energy cut of 600 MeV, information from the PS and SPD detectors and rejection of electromagnetic clusters matched to the extrapolation of a charge track are applied to improve the quality of photons. The reconstructed χ_b mass is corrected by replacing the reconstructed Υ mass by its known value. The χ_b yield is determined from an extended maximum likelihood fit. In the fit, the χ_{b0} contribution of the multiplet is neglected and the χ_{b1} and χ_{b2} contributions are set to be equal. This assumption is needed since the χ_b mass resolution does not allow to separate these two states. The assumption on the relative χ_{b1}/χ_{b2} contribution and the electromagnetic calorimeter energy scale are entering as the dominant systematic errors on the measurement of the χ_b (3P) mass. This mass is measured to be $10511.3 \pm 1.7\,(\text{stat}) \pm 2.4\,(\text{syst})$ MeV.

The 'feed-down fractions' $R_{\Upsilon(nS)}^{\chi_b(mP)}$ of Υ originating from radiative χ_b decays are determined by computing the ratio of the Υ and χ_b yields in each p_{T}^{Υ} bin and for each decay: $\chi_b(mP) \to \Upsilon(nS)\gamma$ with m $\geq$ n. In this ratio, most of the systematic errors cancel. The remaining systematic errors are dominated by the uncertainties related to the photon reconstruction at low p_{T} and the various assumptions made in the χ_b mass fits: χ_{b1}/χ_{b2} ratio, p_{T} dependence on the mass fits and modelling of the mass resolution. The results of the feed-down fractions, for each Υ state as a function of their p_{T} are represented in the three plots of Figure 3. Contributions to the Υ(nS) production from radiative decays of χ_b(mP) states are far from negligible.
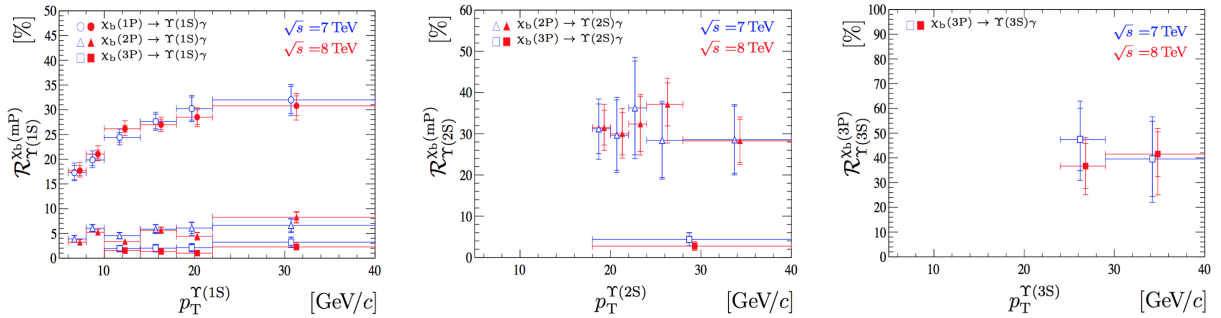

Figure 3. Feed-down fractions $R_{\Upsilon(nS)}^{\chi_b(mP)}$ as a function of p_{T}^{Υ}. Open (solid) symbols correspond to data collected at $\sqrt{s}$=7(8) TeV respectively. Inner error bars represent statistical uncertainties while outer error bars represent the sum in quadrature of statistical and systematic uncertainties.

6. Conclusions

Four analyses in the sector of quarkonium production and exotic states, all based on the excellent reconstruction of muon pairs in LHCb, have been presented. These results bring improved knowledge and/or increased precision on the various topics considered. Given the sizes of the statistical errors, at the level of the systematic errors in most cases, new data expected soon with the start of Run2 will be most welcome.

References
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