EXCLUSIVE PRODUCTION OF VECTOR MESONS AT THE LHCb*

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Studies of the central exclusive production (CEP) of vector mesons in pp collisions at the LHCb are reported. A search is performed for the CEP of charmonium pairs using data corresponding to an integrated luminosity of 3 fb^{-1} collected at centre-of-mass energies of 7 and 8 TeV. Pairs of $J/\psi\, J/\psi$ and $J/\psi\psi(2S)$ are observed in the absence of any other activity inside the LHCb acceptance and the measured cross sections are consistent with theoretical expectations. A study of CEP of $\Upsilon(nS)$ states based on the same data is presented. The $\Upsilon(1S)$ cross section is measured as a function of rapidity and is found to be in good agreement with the Standard Model predictions. The CEP of J/ψ and $\psi(2S)$ mesons is measured at $\sqrt{s} = 13$ TeV and backgrounds are significantly reduced compared to previous measurements through the use of forward shower counters.

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1. Introduction

Central exclusive production (CEP) [1] in pp collisions is a diffractive process characterized by an elastic interaction between protons through the exchange of a colorless object (photons or Pomerons). Some perturbative Quantum Chromodynamics (QCD) models predict that the cross sections for such processes have a strong dependence on the gluon Parton Distribution Function (PDF). Therefore, measurements of CEP provide tests of the interplay of the hard and soft regimes of QCD.

The LHCb Collaboration has measured exclusive processes in pp and PbPb collisions at different centre-of-mass energies [2–7]. In this report, we present details of the observation of charmonium pairs [4] and $\Upsilon(nS)$ states [5] produced exclusively at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, and the measurement of CEP of J/ψ and $\psi(2S)$ at $\sqrt{s} = 13$ TeV [6].

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2. The LHCb experiment

The LHCb detector [8] is a single-arm forward spectrometer covering the pseudorapidity range of $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector leverages a high-precision tracking system which includes a silicon-strip vertex detector (VELO) surrounding the proton–proton interaction region with sensitivity to charged particles in the pseudorapidity ranges of $-3.5 < \eta < -1.5$ and $1.5 < \eta < 5$. Photon candidates are identified by a calorimeter system including scintillating-pad (SPD) and pre-shower detectors and an electromagnetic calorimeter. The SPD also provides a measurement of the charged-particle multiplicity. Muons are identified by a muon system composed of alternating layers of iron and multiwire proportional chambers. The trigger consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage which applies a full event reconstruction. The pseudorapidity coverage is further extended to $-10 < \eta < -5$ and $5 < \eta < 10$ by the HeRSCheL subdetector [9], a system of forward shower counters consisting of five planes of scintillators split in four quadrants.

3. Exclusive production of charmonium pairs

The CEP of charmonium pairs is studied using data corresponding to integrated luminosities of 0.9 fb^{-1} collected in 2011 at $\sqrt{s} = 7$ TeV and 2.0 fb^{-1} collected in 2012 at $\sqrt{s} = 8$ TeV. The process signature is an event containing four muons, at most two photons, and no other activity. The dimeson system must be in the rapidity fiducial region of $2.0 < y < 4.5$. The masses of the dimuons must be within -200 MeV and $+65$ MeV of the known J/ψ or $\psi(2S)$ masses. The resulting mass distributions are shown in Fig. 1.

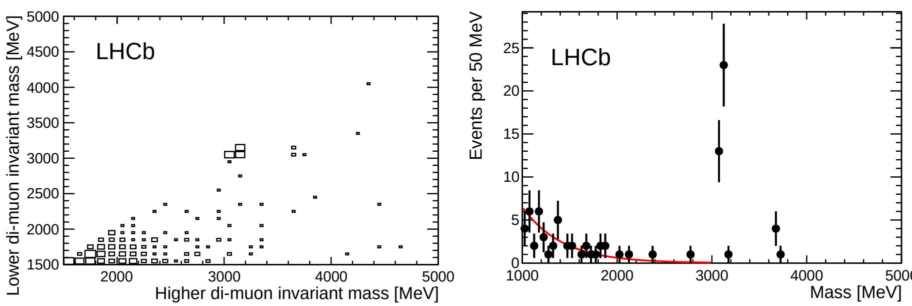

Fig. 1. Invariant masses of pairs of the oppositely charged muons in events with exactly four tracks (left) and invariant mass of the second pair of tracks when the first pair has a mass consistent with the J/ψ or $\psi(2S)$ meson (right).

The non-resonant background is considered for the $J/\psi J/\psi$ analysis only and is calculated by fitting an exponential to the non-signal region in Fig. 1 and extrapolating the fit to the signal region. The feed-down from $\psi(2S)$ is estimated using simulated events normalized by control samples. Acceptance and efficiency corrections are applied and systematic uncertainties are estimated using simulation and data-driven methods. The fiducial cross sections are measured to be:

$$\begin{aligned} \sigma^{J/\psi J/\psi} &= 58 \pm 10(\text{stat.}) \pm 6(\text{syst.})\ \text{pb}\,, & \sigma^{\chi_{c0}\chi_{c0}} &< 69\ \text{nb}\,, \\ \sigma^{J/\psi\psi(2S)} &= 63^{+27}_{-18}(\text{stat.}) \pm 10(\text{syst.})\ \text{pb}\,, & \sigma^{\chi_{c1}\chi_{c1}} &< 45\ \text{pb}\,, \\ \sigma^{\psi(2S)\psi(2S)} &< 237\ \text{pb}\,, & \sigma^{\chi_{c2}\chi_{c2}} &< 141\ \text{pb}\,, \end{aligned}$$

where the upper limits are set at the 90% confidence level. The cross sections are quoted without accounting for the contribution of inelastic production. An attempt is made to quantify the elastic fraction in the $J/\psi J/\psi$ sample using its p_T^2 distribution to allow comparison with theory.

4. Exclusive production of $\varUpsilon(nS)$ states

The CEP of $\varUpsilon(nS)$ is studied using data collected in 2011 and 2012 corresponding to an integrated luminosity of 2.9 fb^{-1} at centre-of-mass energies of 7 TeV and 8 TeV. The process signature is an event containing two muons and no other activity. It is required that both muons lie in the pseudorapidity range of $2 < \eta(\mu) < 4.5$ and that the reconstructed $\varUpsilon(nS)$ lies in the rapidity range of $2 < y(\varUpsilon) < 4.5$. The dimuon mass must lie within 9 GeV and 20 GeV, while its p_T^2 must be less than 2 GeV^2. Events are vetoed if there is additional activity in the form of extra tracks or excessive deposits in the SPD. Figure 2 shows the resulting mass (left) and p_T^2 (right) distributions.

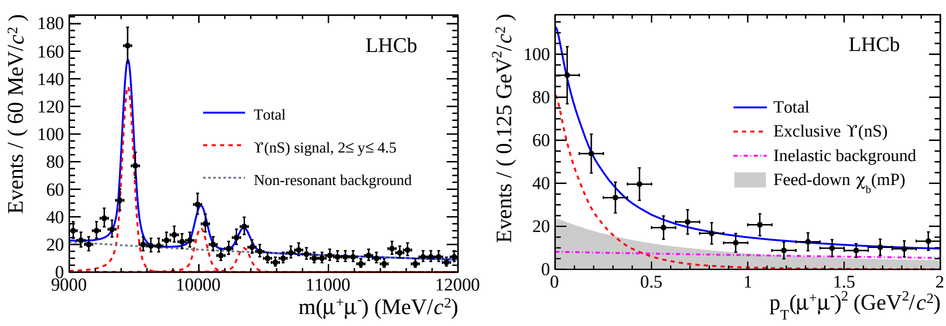

Fig. 2. Invariant mass (left) and p_T^2 (right) distributions of the dimuon candidates.

A fit is performed on the dimuon mass distribution to estimate non-resonant background (Fig. 2). Resonances are modelled with double-sided Crystal Ball functions [10], while the non-resonant contribution is modelled with an exponential shape. The feed-down from χ_b is estimated using a combination of data and simulation. The contribution from non-exclusive events is estimated from a fit to the dimuons' p_{T}^2 distribution after subtracting the non-resonant contribution (Fig. 2, right plot). The number of selected events is corrected by the effective luminosity, efficiencies, and purity to calculate the total (below) and differential (Fig. 3) fiducial cross sections:

$$\sigma(pp \to p\Upsilon(1S)p) = 9.0 \pm 2.1 \pm 1.7 \text{ pb}, \qquad \sigma(pp \to p\Upsilon(3S)p) < 3.4 \text{ pb},$$
$$\sigma(pp \to p\Upsilon(2S)p) = 1.3 \pm 0.8 \pm 0.3 \text{ pb},$$

where the first uncertainties are statistical and the second are systematic. The upper limit is set at the 95% confidence level.

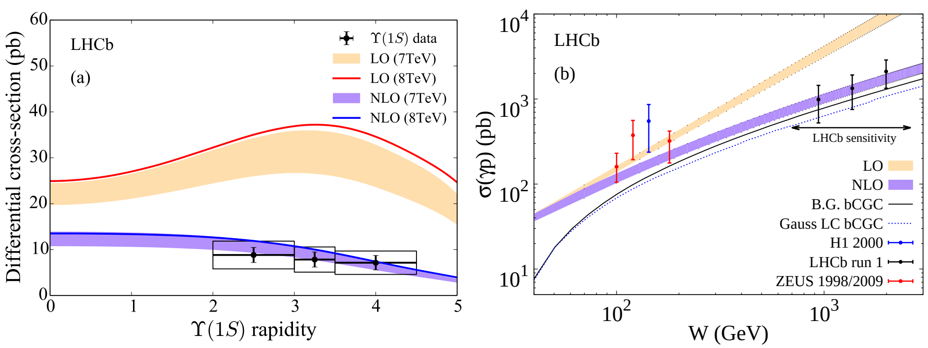

Fig. 3. Left: differential cross section w.r.t. the meson rapidity. Right: photon–proton cross section w.r.t. the energy of the photon–proton centre-of-mass energy.

5. Exclusive production of J/ψ and $\psi(2S)$

The CEP of J/ψ and $\psi(2S)$ is studied using data collected in 2015, corresponding to an integrated luminosity of 0.2 fb^{-1} at $\sqrt{s} = 13$ TeV. The signature for these processes is an event containing two muons and no other activity. Two reconstructed muons are required in the region of $2.0 < \eta < 4.5$, with an invariant mass within ± 65 MeV of the known J/ψ or $\psi(2S)$ mass [11] and $p_{\mathrm{T}}^2 < 0.8$ GeV^2 for the dimuon. Events with additional VELO tracks or photons or with significant activity in HeRSCheL are vetoed.

The non-resonant background is determined from the fit shown in Fig. 4, where the signals are modelled with two Crystal Ball functions [10] and the non-resonant background, with a sum of two exponential functions. The $\psi(2S)$ feed-down background in the J/ψ selection is determined using simulated events normalized to data control samples, while the χ_c feed-down is

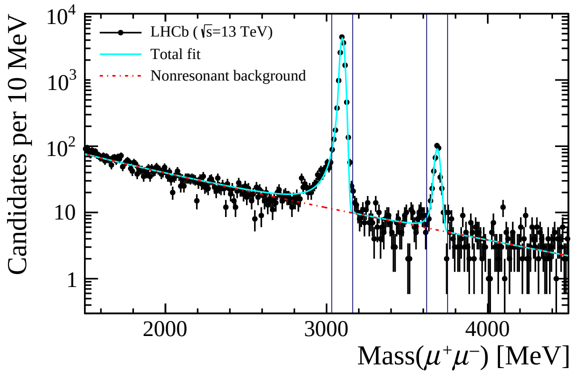

Fig. 4. Invariant mass distribution of dimuon candidates. The J/ψ and $\psi(2S)$ mass windows are indicated by the vertical lines.

determined using a data calibration sample which contains events without the requirement of zero photons. The non-exclusive fraction is determined through a fit to the p_{T}^2 distribution of the J/ψ and $\psi(2S)$ candidates after subtracting the non-resonant contribution. The number of selected events is corrected by the effective luminosity, efficiencies, and purity to calculate the total (below) and differential (Fig. 5) fiducial cross sections:

$$\begin{aligned} \sigma_{J/\psi\to\mu^+\mu^-}(2<\eta<4.5) &= 435\pm18\pm17\pm16\ \text{pb}\,, \\ \sigma_{\psi(2S)\to\mu^+\mu^-}(2<\eta<4.5) &= 11.1\pm1.1\pm0.3\pm0.4\ \text{pb}\,. \end{aligned}$$

The first uncertainties are statistical, the second are systematic, and the third are due to the luminosity determination.

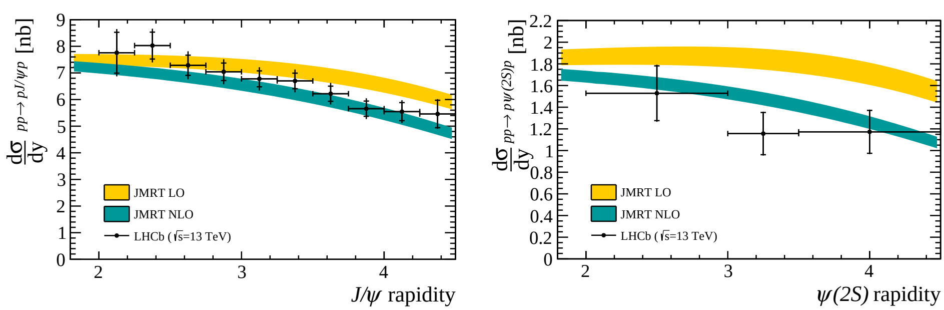

Fig. 5. Differential cross sections compared to LO and NLO theory JMRT predictions [12, 13] for the J/ψ (left) and $\psi(2S)$ (right) mesons. The inner error bar represents the statistical uncertainty, while the outer represents the total uncertainty.

6. Conclusions

The exclusive production of pairs of $J/\psi J/\psi$ and $J/\psi\psi(2S)$ is observed and the measurements are in agreement with preliminary theoretical predictions. No signal is observed for the production of pairs of P-wave charmonia and upper limits on the cross sections are set. The exclusive cross section for $\Upsilon(nS)$ production at 7 and 8 TeV is presented, and a differential cross section is extracted as a function of the meson rapidity. The results are compared to theoretical predictions and a strong preference for NLO predictions is seen. The cross sections for exclusive J/ψ and $\psi(2S)$ production using scintillators to reduce backgrounds are measured and compared to theory. The measurements are found to be in better agreement with NLO predictions.

REFERENCES

[1] M. Albrow, T. Coughlin, J. Forshaw, *Prog. Part. Nucl. Phys.* **65**, 149 (2010).

[2] LHCb Collaboration (R. Aaij *et al.*), *J. Phys. G: Nucl. Part. Phys.* **40**, 045001 (2013), arXiv:1301.7084 [hep-ex].

[3] LHCb Collaboration (R. Aaij *et al.*), *J. Phys. G: Nucl. Part. Phys.* **41**, 055002 (2014), arXiv:1401.3288 [hep-ex].

[4] LHCb Collaboration (R. Aaij *et al.*), *J. Phys. G: Nucl. Part. Phys.* **41**, 115002 (2014), arXiv:1407.5973 [hep-ex].

[5] LHCb Collaboration (R. Aaij *et al.*), *J. High Energy Phys.* **2015**, 084 (2015), arXiv:1505.08139 [hep-ex].

[6] LHCb Collaboration (R. Aaij *et al.*), *J. High Energy Phys.* **2018**, 167 (2018), arXiv:1806.04079 [hep-ex].

[7] LHCb Collaboration, LHCb-CONF-2018-003, 2018.

[8] LHCb Collaboration (A.A. Alves Jr. *et al.*), *J. Instrum.* **3**, S08005 (2008).

[9] K. Carvalho Akiba *et al.*, *J. Instrum.* **13**, P04017 (2018), arXiv:1801.04281 [physics.ins-det].

[10] T. Skwarnicki, Ph.D. Thesis, Institute of Nuclear Physics, Kraków, 1986, DESY-F31-86-02.

[11] Particle Data Group Collaboration (C. Patrignani *et al.*), *Chinese Phys. C* **40**, 100001 (2016) and 2017 update.

[12] S. Jones, A.D. Martin, M.G. Ryskin, T. Teubner, *J. High Energy Phys.* **2013**, 085 (2013), arXiv:1307.7099 [hep-ph].

[13] S.P. Jones, A.D. Martin, M.G. Ryskin, T. Teubner, *J. Phys. G: Nucl. Part. Phys.* **41**, 055009 (2014), arXiv:1312.6795 [hep-ph].