Central exclusive quarkonia production in the forward region at LHCb

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Abstract. The LHCb detector and LHC running conditions are ideally suited to measure central exclusive production. Recent results of central exclusive production of J/Ψ, Ψ(2S) and double charmonium are presented. Results are consistent with theoretical expectations. Prospects for measurements of central exclusive production with a new detector installed for the next running period are discussed.

1. Introduction
Central exclusive production (CEP), pp → pXp, in which the protons remain intact and the system X is produced with a rapidity gap on either side, proceeds via the exchange of colourless, neutral particles, either photons or combinations of gluons, for example pomerons. Experimentally, this leads to a unique signature with a small number of particles in the detector, either produced directly or as decay products, and two rapidity gaps that extend to the outgoing protons. The outgoing protons are not detected but escape through the beam-pipe. CEP allows the study of quantum chromodynamics (QCD) and the pomeron. Furthermore, it allows searches for exotic states in a low-background experimental environment and to probe the gluon distribution of the proton.

2. LHCb detector and running conditions
The LHCb detector [1] is a single-arm forward spectrometer, fully instrumented in the pseudorapidity range 2 < η < 5 (‘forward region’). The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the pp interaction region. The VELO has sensitivity to charged particles with momenta above 100 MeV/c in the range 3.5 < η < 1.5 (‘backward region’), while extending the sensitivity of the forward region to 1.5 < η < 5. Though tracks in the backward region have no momentum measurement, the backward acceptance provides an efficient veto for charged particles.

The running conditions at LHCb are well suited for CEP measurements because the experiment is operated at a low number of interactions per beam crossing. The data used in the analyses presented below correspond to an integrated luminosity of about 1 fb⁻¹ collected in 2011 at a centre-of-mass energy √s = 7 TeV and 2 fb⁻¹ collected in 2012 at √s = 8 TeV.

3. Exclusive J/Ψ and Ψ(2S) production
Exclusive J/Ψ and Ψ(2S) meson production in hadron collisions proceed at leading order via the exchange of a photon and a pomeron, which at sufficiently hard scales can be described by two
Figure 1. Feynman diagrams for the central exclusive production of a) charmonium through photon-pomeron fusion and d) double charmonium through double pomeron exchange. Typical diagrams for inelastic background from b) additional gluon radiation or c) proton dissociation.

gluons as shown in Fig. 1 a). Measurements of exclusive J/Ψ and Ψ(2S) production thus provide a test of QCD and help to understand the pomeron, which plays a critical role in the description of diffraction and soft processes. The measurements are sensitive to saturation effects [2] and probe x, the fractional momentum of the parton, down to 5 · 10^{-6} in the pseudorapidity range of LHCb.

The analysis is based on about 1 fb^{-1} of data collected at √s = 7 TeV [3]. Events are selected with two muons and no other track in the VELO. Furthermore, it is required that there is no reconstructed photon. This ensures two rapidity gaps which sum to 3.5 units in the forward region and one to two units, depending on the vertex position, in the backward region. Muon pairs are combined to form meson candidates. Their transverse momentum squared is required to be \( p_T^2 < 0.8 \text{ GeV}^2/c^2 \) to reduce inelastic background, and their invariant masses must lie within 65 MeV/c^2 of their PDG values [4]. 55,985 J/Ψ and 1565 Ψ(2S) candidates are found.

Figure 2. Invariant mass distribution of muon pairs after the selection requirements. The horizontally (diagonally) hatched regions show the J/Ψ (Ψ(2S)) signal and side-band regions. The data are fitted (solid curve) with Crystal Ball functions for the signals and an exponential function for the non-resonant background (dashed curve) [3].

Three background components are considered: non-resonant background, feed-down from exclusive production of other mesons, and inelastic production of mesons with additional
gluon radiation or proton dissociation shown in Fig. 1b) and c). The di-muon invariant mass distribution is shown in Fig. 2. It is fitted with Crystal Ball functions [5] to describe the resonant contributions and an exponential for the non-resonant background. Within the mass range of the analysis the non-resonant background is estimated to amount to \((0.8 \pm 0.1)\%\) for \(J/\Psi\) and \((17.0 \pm 0.3)\%\) for \(\Upsilon(2S)\) candidates.

Exclusively produced \(\chi_c\) or \(\Upsilon(2S)\) mesons can feed down to mimic an exclusive \(J/\Psi\) decay when the particles produced in association with the \(J/\Psi\) are not detected. Their contribution is estimated using simulated events normalised to an enriched background sample in the data. The feed-down from \(\chi_c\) and \(\Upsilon(2S)\) is estimated to account for \((7.6 \pm 0.9)\%\) and \((2.5 \pm 0.2)\%\) of the \(J/\Psi\) candidates respectively. Feed-down into the \(\Upsilon(2S)\) selection is expected to be very small, and mainly due to \(\chi_c(2P)\) or \(X(3872)\) decays. It is estimated from data, by relaxing the requirement on the number of photons, to be \((2 \pm 2)\%\).

The largest background is due to inelastic production of \(J/\Psi\) and \(\Upsilon(2S)\) mesons with additional gluon radiation or proton dissociation where the additional particles are not detected in LHCb. Since the inelastic background has a higher \(p_T\) than the signal the background contribution is determined by a fit to the \(p_T^2\) distribution of the meson. In Regge theory, it is assumed that elastic \(J/\Psi\) and \(\Upsilon(2S)\) meson production follows an exponential \(d\sigma/dt \propto \exp(bst)\), where \(t \sim p_T^2\) is the four-momentum transfer squared at the proton-pomeron vertex and \(b\) a constant for a given process. The assumption that the signal and inelastic background can be parametrised by an exponential was tested by the H1 collaboration and found to hold for low \(p_T\) [6]. Fitting the \(p_T^2\) distribution with three components, an exponential for elastic CEP, an exponential for the inelastic background, and the feed-down component from data, allows the signal fraction to be extracted (Fig. 3). The slopes found from the fit are in good agreement with expectations from HERA using Regge theory for the extrapolation in energy. The signal fraction is measured to be \((59 \pm 1)\%\) for \(J/\Psi\) and \((52 \pm 7)\%\) for \(\Upsilon(2S)\) with \(p_T^2 < 0.8\text{GeV}^2/c^2\).

![Figure 3](image-url)

**Figure 3.** Transverse momentum squared distributions for (a) \(J/\Psi\) and (b) \(\Upsilon(2S)\) candidates, where the non-resonant background contribution has been subtracted using side-bands. The points are data, the solid curve is the total fit, the other curves describe the signal and the backgrounds from feed-down and inelastic events [3].

The cross-section times branching fraction to two muons, with pseudorapidities between 2.0 and 4.5, is determined in ten bins of meson rapidity, \(y\). The efficiencies for tracking, muon identification and trigger are determined from data, the selection efficiency from simulation. The number of visible proton-proton interactions per beam crossing, \(n\), is assumed to follow a Poisson distribution, \(P(n) = \mu^n \exp(\mu)/n!\), where \(\mu\) is the average number of visible interactions. Averaged over the data-taking period, the efficiency for a single interaction is then found to be

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\[ \epsilon_{\text{single}} = (24.1 \pm 0.3)\% \]

The cross-sections times branching fraction to two muons having pseudorapidities between 2.0 and 4.5 are measured to be:

\[ \sigma(J/\Psi \rightarrow \mu\mu) = 291 \pm 7(\text{stat}) \pm 19(\text{syst})\text{pb} \]
\[ \sigma(\Psi(2S) \rightarrow \mu\mu) = 6.5 \pm 0.9(\text{stat}) \pm 0.4(\text{syst})\text{pb}. \]

The differential distributions are presented in Fig. 4, where the error bars indicate the uncorrelated statistical uncertainties and the band is the total uncertainty. The systematic uncertainties are mostly correlated between bins. The measurements are compared to leading and next-to-leading order predictions [7]. Better agreement is observed between data and the NLO prediction than between data and the LO prediction.

Exclusive production of J/\Psi in pp collisions is related to photoproduction through

\[ \frac{d\sigma(pp)}{dy} = r_+ k_+ \frac{dn}{dk_+} \sigma(\gamma p)(W_+) + r_- k_- \frac{dn}{dk_-} \sigma(\gamma p)(W_-) \]

where \(dn/dk\) are photon fluxes for photons of energy \(k \approx (M(J/\Psi)/2)\exp(|y|)\), \(W_\pm\) the \(\gamma p\) centre of mass energy, \((W_\pm)^2 = 2k_\pm s\), and \(r_\pm\) are absorptive corrections. The LHCb results cannot unambiguously determine the photoproduction cross-section due to contributions from both \(W_+\) and \(W_-\), corresponding to the photon being either an emitter or a target, respectively. A model-dependent determination of \(\sigma(\gamma p \rightarrow J/\Psi p(W_{(+/-)})\) is obtained from the LHCb differential cross-section measurement, assuming the power-law result from a fit to the HERA data [6] for \(\sigma(\gamma p \rightarrow J/\Psi p(W_{(-/+)}))\) as shown in Fig. 5. Here, the LHCb data is shown together with HERA and fixed target photoproduction results and the power-law fit from [6]. There are two correlated points for each LHCb measurement. Deviations from the power law dependence are observed at the energies probed by the LHCb measurements. These can be explained by higher order corrections or saturation effects.

4. Double charmonium production

Cross-sections and invariant mass spectra of charmonium pairs are sensitive to the presence of additional particles in the decay chain such as glueballs or tetraquarks [9]. LHCb has measured the inclusive production of J/\Psi pairs [8] to be in broad agreement with the QCD predictions,
Figure 5. Photoproduction cross-section as a function of the centre-of-mass of the photon-proton system with the power-law fit from superimposed [6]. The LHCb data points for $W_+ (W_-)$ are derived assuming the power-law fit for $W_- (W_+)$ and are correlated. The uncertainties are correlated between bins [8].

although the invariant mass distribution of the di-meson system is shifted to higher values in data. In the inclusive case, this shift could be an indication of double parton scattering (DPS) effects [10]. The principal production mechanism for the CEP of two charmonia is through double pomeron exchange (DPE) as shown in Fig. 1 d).

CEP of $J/\Psi J/\Psi, J/\Psi\Psi(2S)$ and $\Psi(2S)\Psi(2S)$ are examined using a data sample corresponding to an integrated luminosity of about 3 fb$^{-1}$ [11]. The $J/\Psi$ and $\Psi(2S)$ mesons are identified through their decays to two muons. The selection of $J/\Psi$ or $\Psi(2S)$ candidates requires four reconstructed tracks, three of them identified as muons, and no other activity in the event. The invariant masses of oppositely charged muon candidates is shown in Fig. 6 a). Accumulations of events are apparent around the $J/\Psi$ and $\Psi(2S)$ masses.

Figure 6 b) shows the higher mass combination when asking that the lower mass combination is consistent with the $J/\Psi$ mass. There are 37 $J/\Psi J/\Psi, 5 J/\Psi\Psi(2S)$ and no $\Psi(2S)\Psi(2S)$ candidates. The only substantial feed-down background to the $J/\Psi J/\Psi$ signal comes from $J/\Psi\Psi(2S)$ where $\Psi(2S)\rightarrow J/\Psi X$ with $X$ unreconstructed.

The cross-section, at an average energy of 7.6 TeV, for the di-meson system to be in the rapidity range 2.0 < y < 4.5 with no other charged or neutral energy inside the LHCb acceptance are measured to be

$$\sigma(J/\Psi J/\Psi) = 58 \pm 10(\text{stat}) \pm 6(\text{syst}) \text{pb}$$

$$\sigma(\Psi(2S)\Psi(2S)) = 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst}) \text{pb}$$

$$\sigma(J/\Psi\Psi(2S)) < 237(\text{syst}) \text{pb}.$$ 

The upper bound for the cross-section for $J/\Psi\Psi(2S)$ production is given at a 90% CL.

Similarly to the previous analysis, the elastic fraction is estimated from the $p_T^2$ distribution. It is shown in the left plot of Fig. 7 a) for the $J/\Psi J/\Psi$ candidates. Central exclusive events peak below 1 GeV$^2$/c$^2$ while the tail to higher values is characteristic of inelastic production. A maximum likelihood fit is performed to the sum of two exponentials, $f_{el}b_{el}\exp(-b_{el}p_T^2) + (1 -$
Figure 6. Invariant masses (a) of pairs of oppositely charged muons in events with exactly four tracks and invariant mass of the second pair of tracks (b) where the first pair has a mass consistent with the J/Ψ or Ψ(2S) meson [11].

\[ f_{el} |b_b \exp(-b_b p_T^2) \], where \( b_s, b_b \) are the slopes for the signal and background and \( f_{el} \) is the fraction of elastic events. Due to the small sample size, the value of \( b_b \) is constrained using the distribution for exclusive dimuon candidates whose invariant mass lies in the range 6 to 9 GeV/c\(^2\). Their \( p_T^2 \) distribution is shown in the first bin of Fig. 7b). It has a prominent peak in the first bin corresponding to the electromagnetic two-photon exchange process, \( pp \rightarrow p\mu^+\mu^-p \). The tail to larger values is characteristic of events with proton dissociation. Only the region \( 1.5 < p_T^2 < 10 \) GeV/c\(^2\) is used in the fit to determine the slope \( b_b = 0.29 \pm 0.02 \) GeV\(^{-2}\)c\(^2\). With \( b_b \) fixed the fit to the signal distribution yields \( b_s = 2.9 \pm 1.3 \) GeV\(^{-2}\)c\(^2\) and \( f_{el} = 0.42 \pm 0.13 \). Using this signal fraction the cross-section for exclusive production of J/Ψ J/Ψ is found to be \( 24 \pm 9 \) pb. This is in agreement with theoretical calculations [12] which predict cross-sections between 6 and 34 pb.

Figure 7. Transverse momentum squared distribution of a) candidates for exclusively produced J/Ψ J/Ψ and b) dimuons with invariant mass between 6 and 9 GeV/c\(^2\). The curves are fits to the data as described in the text [11].

5. Shower counters
The coverage of the LHCb detector is the limiting factor for the precision of CEP measurements. During the LHC shutdown new forward shower counters (FSC) have been installed, significantly extending the rapidity coverage in the very forward and backward region \( 5 < |\eta| < 8 \). The FSCs...
consist of five stations with four retractable plastic scintillator plates placed on either side of the interaction point at 7.5 m, 19 m and 114 m from the interaction region. A schematic of one station in the closed and open configuration is shown in Fig. 8. Information from this new detector will greatly improve LHCb's ability to separate elastic from inelastic events and help to understand the shape of the background. Furthermore, a veto on the activity in the FSCs will be used in the trigger allowing a more efficient triggering mechanism for CEP events.

Figure 8. Drawings of one plane of the forward shower counters which were installed around the beam-pipe, in the LHC tunnel, on either side of the interaction point. The picture shows the support structure, scintillators and PMTs, which can be retracted from the beam-line.

6. Conclusions
The design of the LHCb detector makes it well suited to the study of central exclusive production. It has excellent particle identification and the ability to trigger on low multiplicity events and low transverse momentum objects. Measurements of differential cross-sections for exclusive J/Ψ and Ψ(2S) have been discussed. They agree with the shapes predicted by next-to-leading order predictions. A clear signal for double charmonium production in the absence of other activity in the LHCb acceptance is observed. It is estimated that (42 ± 13)% of these events are elastically produced.

The additional instrumentation of the LHCb detector with forward shower counters will significantly increase the coverage of the detector and will allow more precise exclusive measurements in the next running period. The signal of these counters can be used as a veto in the trigger and help to further reduce the inelastic background. The uncertainty on this background is presently the dominant systematic uncertainty.

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