

Central Exclusive Production in pp collisions at LHCb

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Abstract.

Central Exclusive Production (CEP) is a unique process at hadron machines in which particles are produced via colourless propagators, and several measurements at the LHC are directly comparable with past and future electron-ion colliders. LHCb have measured the cross-sections for the CEP of vector mesons, J/ψ , $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$, which are photo-produced. In the double Pomeron exchange process, preliminary measurements have been made of $\chi_{c0}, \chi_{c1}, \chi_{c2}$ meson production while the first observations of the CEP of pairs of charmonia, $J/\psi J/\psi$ and $J/\psi \psi(2S)$, have been made and limits obtained on the pair production of other charmonia.

1 Introduction

Central exclusive production (CEP) at the LHC is characterised by an isolated system of particles surrounded by two rapidity gaps that extend down to the intact colliding protons; see [1] and the papers referenced in [2] for a recent survey of the field. The lack of additional activity signals the presence of colourless propagators: two photons; two Pomerons; or a photon and a Pomeron. LHC results on photon-photon and photon-Pomeron fusion are directly comparable with past and future electron-ion colliders. For example, in J/ψ CEP at LHC central rapidities, parton fractional momenta, x , of about 5×10^{-4} are probed, similar to that examined at HERA. However, at the forward rapidities accessible to the LHCb experiment, this x reach extends to 5×10^{-6} . Looking to the near future, measurements (for example of ρ production at 13 TeV) will probe x values an order of magnitude smaller, where phenomena such as saturation may become observable.

The LHCb detector [3] is suited to studying CEP as it is fully instrumented with tracking, calorimetry and particle identification in the pseudorapidity, η , range between 2 and 5. In addition, charged activity in the backward region, in the approximate range $-3.5 < \eta < -1.5$, can be vetoed due to the presence of a silicon strip detector that surrounds the interaction point. LHCb is designed to trigger on particles produced at low transverse momentum. CEP events are selected by triggering on muons with transverse momentum, p_T , above 400 MeV/c or electromagnetic or hadronic energy above 1000 MeV, in coincidence with a total event charged multiplicity of less than 10 as recorded by a scintillating pad detector. A further advantage of LHCb for CEP is the low number of proton-proton interactions (typically 1.5) per beam crossing. Consequently about 20% of the total luminosity has a single interaction and is suitable for searching for the CEP signature of low multiplicity and large rapidity gaps.

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The LHCb measurements of CEP to date have concentrated on final states with muons. In this report, I concentrate on measurements of the photoproduction of single charmonium and bottomium as well as the production of double charmonia, which is principally produced by double Pomeron exchange. The single charmonium measurements use almost 1 fb^{-1} of data taken at $\sqrt{s} = 7 \text{ TeV}$, while the other measurements add an additional 2 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$. Preliminary results, based on 37 pb^{-1} of data, are also available on χ_c production and dimuons produced by the QED process [4].

2 Photoproduction of J/ψ and $\psi(2S)$ mesons

Candidates for J/ψ mesons produced through CEP are selected [5] by requiring two identified muons inside the LHCb acceptance and no photons or additional tracks in either forward or backward directions. The p_T^2 of the dimuon is required to be below $0.8 \text{ GeV}^2/c^2$, and its invariant mass to be within $65 \text{ MeV}/c^2$ of the known J/ψ or $\psi(2S)$ masses. The invariant mass of all candidates (with the mass requirement removed) is shown in Fig.1(a). The non-resonant background, due to the QED production of dimuons via photon propagators, is modelled with an exponential function and is estimated to account for $(0.8 \pm 0.1)\%$ of the J/ψ and $(16 \pm 3)\%$ of the $\psi(2S)$ sample. Feed-down backgrounds inside the J/ψ mass window, amounting to $(10.1 \pm 0.9)\%$, are due to χ_c or $\psi(2S)$ mesons decaying to J/ψ and photons that are undetected due to being very soft or going outside the detector acceptance. Inelastic J/ψ or $\psi(2S)$ production, in which the proton dissociates but does not produce activity inside the LHCb acceptance, is assessed by fitting the $t \approx p_T^2$ distribution and assuming that $d\sigma/dt$ can be modelled by two exponentials for signal and background, as assumed in Regge theory and observed at HERA [6, 7]. The fitted parameters for the exponentials are consistent with those found at HERA, having corrected for kinematic differences. In total, $(59.2 \pm 1.2)\%$ of the J/ψ sample and $(52 \pm 7)\%$ of the $\psi(2S)$ sample is estimated to be exclusively produced.

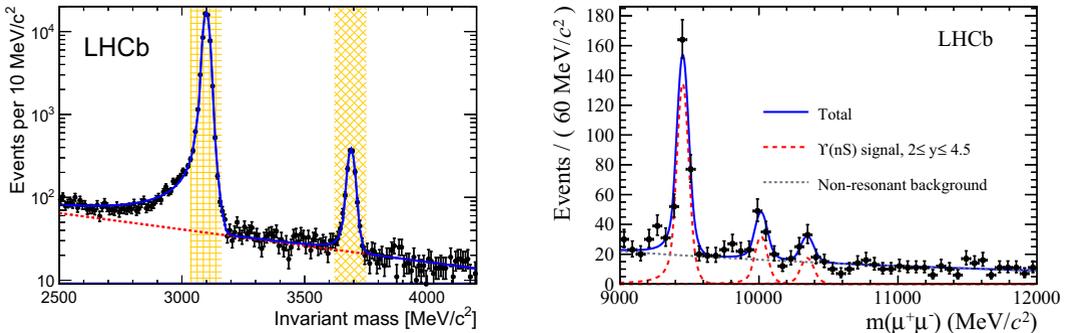


Figure 1. Invariant mass of dimuons in (a, left) the charmonium analysis [5] with the J/ψ and $\psi(2S)$ windows indicated and (b, right) the bottomonium analysis [15].

The cross-section for CEP charmonia is determined from the estimated number of CEP events dividing by the luminosity and correcting for the detector efficiency and acceptance, the former being determined with tag-and-probe techniques in data while the latter is found from simulated events. The total cross-sections are given in Table 1 while differential cross-sections as a function of rapidity are shown in Fig. 2(a,c) compared to LO and approximate NLO predictions from [8]. Results on the total cross-section have been compared to other predictions [9–13] and all agree with the data. A photoproduction cross-section can be derived from these results once rapidity gap corrections and

photon flux factors are included. A two-fold ambiguity is present due to not knowing which of the protons the photon was radiated from. This can be resolved in a model-dependent way by assuming the H1 derived power-law ¹ for one of the solutions. The (model-dependent) cross-section derived is shown in Fig. 2(b,d), compared to results from HERA, fixed target collisions, and proton-lead collisions at ALICE [14], in which the aforementioned ambiguity can be resolved.

Table 1. Total cross-section results for charmonia and bottomonia states.

Quantity measured	Kinematic region	Measurement (pb)
$\sigma(pp \rightarrow pJ/\psi p) \cdot BR(J/\psi \rightarrow \mu\mu)$	$2 < \eta_\mu, y_{J/\psi} < 4.5$	$291 \pm 7 \pm 19$ [5]
$\sigma(pp \rightarrow p\psi(2S)p) \cdot BR(\psi(2S) \rightarrow \mu\mu)$	$2 < \eta_\mu, y_{\psi(2S)} < 4.5$	$6.5 \pm 0.9 \pm 0.4$ [5]
$\sigma(pp \rightarrow p\Upsilon(1S)p)$	$2 < \eta_\mu, y_{\Upsilon(1S)} < 4.5$	$9.0 \pm 2.1 \pm 1.7$ [15]
$\sigma(pp \rightarrow p\Upsilon(2S)p)$	$2 < \eta_\mu, y_{\Upsilon(2S)} < 4.5$	$1.3 \pm 0.8 \pm 0.3$ [15]
$\sigma(pp \rightarrow p\Upsilon(3S)p)$	$2 < \eta_\mu, y_{\Upsilon(3S)} < 4.5$	< 3.4 at 95% c.l. [15]
$\sigma(J/\psi J/\psi)$	$2 < y_{J/\psi J/\psi} < 4.5$	$58 \pm 10 \pm 6$ [20]
$\sigma(J/\psi\psi(2S))$	$2 < y_{J/\psi\psi(2S)} < 4.5$	$63^{+27}_{-18} \pm 10$ [20]
$\sigma(\psi(2S)\psi(2S))$	$2 < y_{\psi(2S)\psi(2S)} < 4.5$	< 237 at 90% c.l. [20]
$\sigma(\chi_{c0}\chi_{c0})$	$2 < y_{\chi_{c0}\chi_{c0}} < 4.5$	< 69000 at 90% c.l. [20]
$\sigma(\chi_{c1}\chi_{c1})$	$2 < y_{\chi_{c1}\chi_{c1}} < 4.5$	< 45 at 90% c.l. [20]
$\sigma(\chi_{c2}\chi_{c2})$	$2 < y_{\chi_{c2}\chi_{c2}} < 4.5$	< 141 at 90% c.l. [20]

3 Photoproduction of Υ mesons

Candidates for Υ mesons produced through CEP are selected [15] by requiring two muons in LHCb and no other charged tracks. The muon pair must have $p_T^2 < 2 \text{ GeV}^2/c^2$ and an invariant mass between 9 and 20 GeV/c^2 , which allows the shape of the QED non-resonant components to be determined at the same time as the fit to the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. The distribution of candidates is shown in Fig.1(b).

Feed-down backgrounds coming from the various χ_b states are estimated to contribute $39 \pm 7\%$ of the total signal yield. As in the charmonium analysis, inelastic Υ production is assessed by fitting the $t \approx p_T^2$ distribution, but with the signal shape given by the SUPERCHIC generator[13]. After subtraction of the χ_b component, $(54 \pm 11)\%$ is assessed to be exclusively produced; thus of the total Υ yield, one third is CEP.

After correcting for the detection efficiency, found using simulated events, and taking account of the luminosity, the cross-sections are determined and reported in Table 1. The low statistics and sizeable background impact on the significance of the 2S and 3S states. However, there are sufficient statistics to divide the 1S state into three bins of rapidity, which are plotted in Fig.2(e). Compared to the charmonium analysis, the difference between the LO and NLO predictions is large and the data show a clear preference for the latter. A photoproduction cross-section can be derived from these results. Here, the smaller of the two ambiguous solutions (that contributes between 5% and 20%) is ignored. The result is shown in Fig.2(f) showing good consistency with HERA results [16, 17].

4 Production of pairs of charmonia

The pair production of charmonia has been observed inclusively in a previous LHCb analysis [18], where tetraquark contributions or double parton scattering (DPS) may play an important role. The

¹The power-law for J/ψ is taken from [6] while for $\psi(2S)$, I use $R(W) = \sigma(\psi(2S))/\sigma(J/\psi) = 0.166$ from [7].

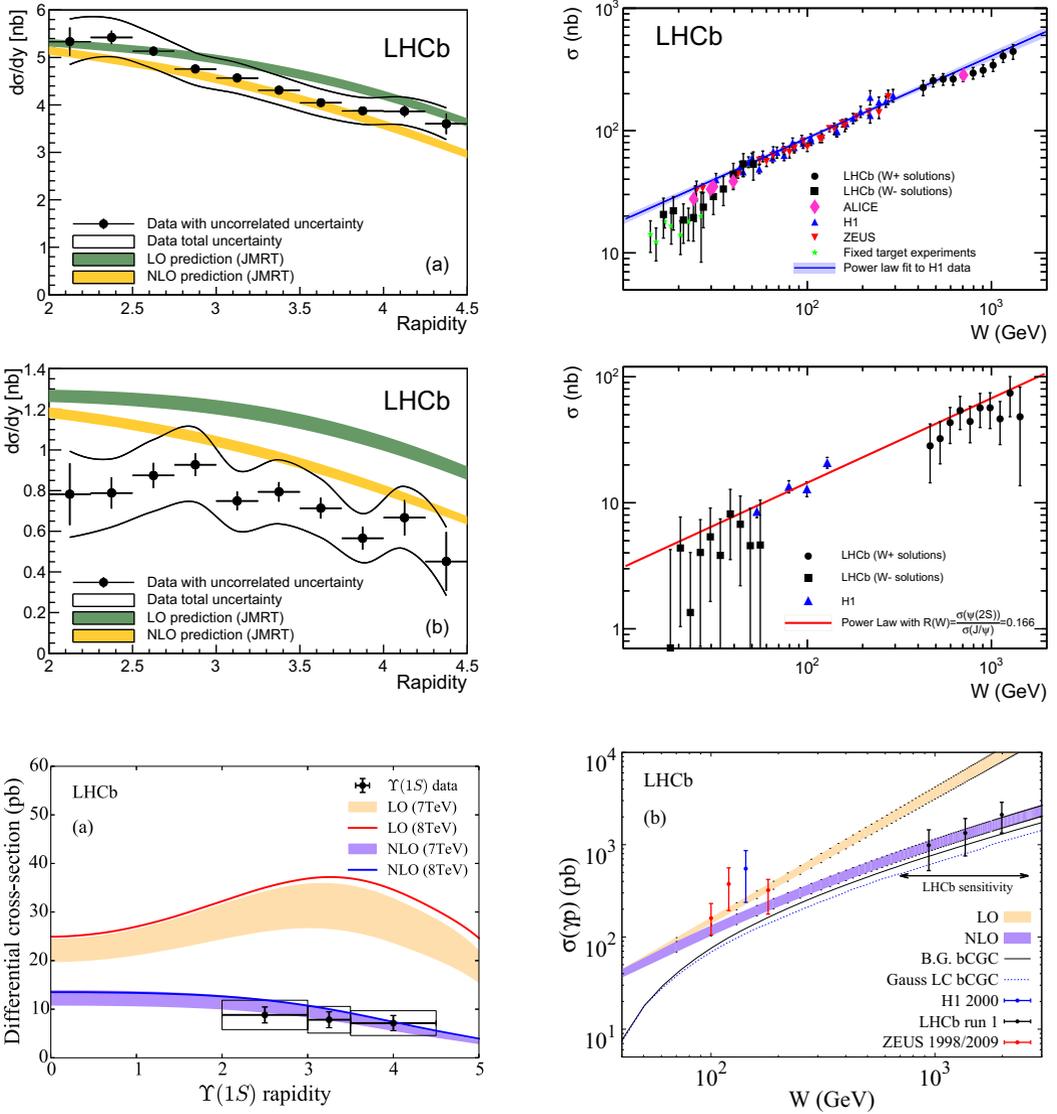


Figure 2. Differential cross-sections for exclusively produced (a, top left) J/ψ , (c, middle left) $\psi(2S)$, and (e, bottom left) Υ , compared to LO and NLO predictions [8]. Compilation of photoproduction cross-sections from various experiments for (b, top right) J/ψ , (d, middle right) $\psi(2S)$, (f, bottom right) Υ . The LHCb results are model-dependent as explained in the text.

contribution of DPS in CEP is minimal and the process proceeds dominantly through double Pomeron exchange. The cross-section for CEP of $J/\psi J/\psi$ inside the LHCb acceptance is predicted to lie in the range 2-20 pb, depending on the model used for the soft survival factor and the gluon PDF that enters with the fourth power [19].

The selection of the CEP of charmonia pairs [20] requires exactly four tracks, at least three of which are identified as muons. The invariant masses of two unlike-sign pairs of muons is required to be consistent with that of the J/ψ or $\psi(2S)$ mesons. The pairwise combinations are shown in Fig.3(a); 37 candidates are consistent with $J/\psi J/\psi$ production and 5 are consistent with $J/\psi\psi(2S)$. The invariant mass of the four tracks is shown in Fig.3(b) and agrees qualitatively with the spectrum observed inclusively [18]. The signal is only seen when there are precisely 4 tracks in the event; it is not present when additional tracks are present in the detector. After accounting for efficiency and luminosity, the cross-section for pairs of charmonia produced in the absence of other charged or neutral activity in LHCb is determined and given in Table 1.

Because of the low statistics, it is difficult to assess how often proton dissociation occurs. A fit to the t distribution suggests $(42 \pm 13)\%$ of the sample is CEP implying an exclusive cross-section for $J/\psi J/\psi$ inside the LHCb acceptance of (24 ± 9) pb, in broad agreement with the predictions.

The analysis is also sensitive to the production of pairs of χ_c mesons, which would be visible through their decays to a J/ψ meson and a photon. Searches are made for additional photons in events with two J/ψ candidates. A single event is consistent with $\chi_{c0}\chi_{c0}$ production but is also consistent with partially reconstructed $J/\psi\psi(2S)$ production. Limits are set on pairs of tensor meson charmonia and are given in Table 1.

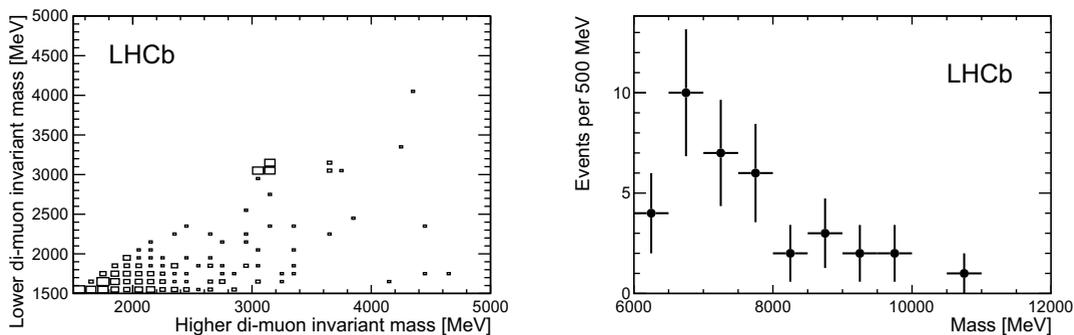


Figure 3. Invariant mass of (a, left) dimuon pairs (b, right) the $J/\psi J/\psi$ system [20].

5 Future projects

Experimentally, LHCb is sensitive to about 5.5 units in pseudorapidity allowing modest rapidity gap sizes to be identified. The identification of CEP events would be significantly aided if the veto region could be increased. To this end, for Run 2 forward shower counters, consisting of five planes of scintillators, have been installed in the LHC tunnel at distances of up to 115 m from the interaction point. These will provide a veto over at least an extra 6 units in pseudorapidity.

The photoproduction predictions have a strong dependence on the gluon PDF at low x , although large scale uncertainties are also present. Recent theoretical work [21] has shown an improvement in understanding these effects and thus CEP of vector mesons, particularly Υ , may provide an important method for constraining the gluon PDF in the poorly understood low- x region [22].

Reductions in the hadronic trigger thresholds for Run 2 will also allow LHCb to extend these studies to investigate the photoproduction of light vector mesons, ρ , ω and ϕ , accessing x values

below 10^{-6} . It will also facilitate studies of the DPE production of pairs of pions and kaons, a region of great interest for light meson spectroscopy [23].

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