PROCEEDINGS OF SCIENCE

Exclusive J/ψ and $\psi(2S)$ production in pp collisions at $\sqrt{s} = 7$ TeV.

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Exclusive J/ψ and $\psi(2S)$ vector meson production has been observed in the dimuon channel using the LHCb detector. The cross-section times branching fractions to two muons with pseudo-rapidities between 2.0 and 4.5 are measured and are found to be in good agreement with results from previous experiments and theoretical predictions. The J/ψ photoproduction cross-section is reported as a function of the photon-proton centre-of-mass energy, and is shown to be consistent with measurements obtained at HERA with power law behaviour.

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1. Motivation

Most experimental analyses of proton-proton collisions are concerned with inelastic collisions where two partons interact, the proton disintegrates and, at LHC energies, there are typically hundreds of final state particles. On the other hand, elastic collisions are usually investigated through $pp \to pp$ scattering. However a third class of interactions, *central exclusive production*, exists. This is an elastic process, in the sense that the protons remain intact, yet which also produces other final state particles. Two examples of these are discussed here: $pp \to pJ/\psi p$ and $pp \to p\psi(2S)p$.

Experimentally these are unusual events; they are devoid of all activity save for the decay products of the vector mesons. Theoretically they are of great interest as they involve the exchange of colourless objects, which for the strong force, requires multiple gluons. These processes therefore test QCD in an experimentally clean environment and are sensitive to new phenomena such as odderons [3] or saturation effects.

The Feynman diagram for exclusive J/ψ production is shown in Fig. 1a. One proton interacts via a photon propagator, the other through a pomeron (two gluons). At leading order the cross-section, σ, for $\gamma^* p \to J/\psi p$ can be written[1, 2]

$$\left.\frac{d\sigma_{\gamma p \to J/\psi p}}{dt}\right|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

with $\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4$ where Q^2 is the virtuality of the photon. The gluon PDF enters squared, and so in principle, this process has high sensitivity to, and can be used to constrain, the gluon PDF.

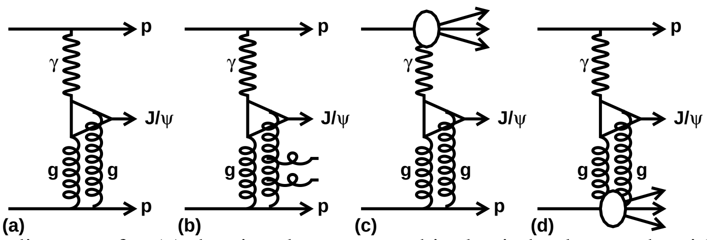

Figure 1: Feynman diagrams for (a) the signal process and inelastic backgrounds with (b) additional gluon radiations and (c,d) proton dissociation.

2. The LHCb detector and selection of central exclusive events

This note presents results [4] from the LHCb detector operating on the LHC collider using 37 pb^{-1} of data collected at $\sqrt{s} = 7$ TeV during 2010. LHCb is fully instrumented with tracking and calorimetry between pseudo-rapidities, $2 < \eta < 5$ and can trigger on muons with transverse momentum, p_T down to 400 MeV. The VELO, a silicon microstrip detector, surrounds the interaction region and provides additional sensitivity to charged particles in the region $-3.5 < \eta < -1.5$. The experimental signature is two identified muons in the event and no other activity in the approximate 5 units of pseudo-rapidity in which charged particles can be registered. This condition also rejects beam-crossings with multiple proton interactions; in the low-luminosity conditions of LHCb, about 20% of proton-collisions occur in single interaction beam crossings.

The invariant mass of reconstructed muon pairs in otherwise empty events, in the J/ψ and $\psi(2S)$ mass region is shown in Fig. 2. The non-resonant background is very small and is mainly due to the QED production of muon pairs through di-photon fusion.

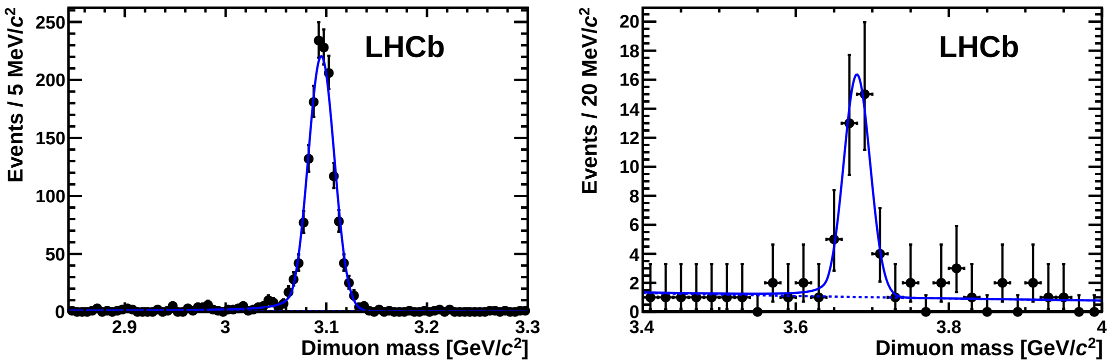

Figure 2: Invariant mass of reconstructed muon pairs in the (left) $J\psi$ and (right) $\psi(2S)$ mass regions. . The dotted line represents the non-resonant background.

3. Cross-section calculation

The cross-section for J/ψ and $\psi(2S)$ mesons which decay to two muon with both muons in the pseudorapidity range $2 < \eta < 4.5$ is calculated using

$$\sigma = \frac{pN}{\varepsilon(\varepsilon_{single}L)}$$

where N is the number of events within 65 MeV of the known meson mass, p is the purity of the sample, ε the trigger, reconstruction and selection efficiency, L is the luminosity and ε_{single} is the efficiency for the beam crossing to have no other visible proton-proton interaction.

The efficiency has been determined from simulated events produced using the STARLIGHT [5] and SUPERCHIC [6] generators which have been passed through a full detector simulation. Comparisons of the detector response in data and simulation using a large sample of inclusively produced J/ψ lead to an overall systematic uncertainty on the cross-section of 7% due to the knowledge of ε.

The luminosity has been determined with an accuracy of 3.5% [7]. 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 μ is the average number of visible interactions and varied up to a maximum of 2.5. Averaged over the data-taking period, the efficiency for having one single proton-proton interaction, $\varepsilon_{single} = 21.1 \pm 0.1\%$.

Three backgrounds sources have been considered. Firstly, the non-resonant contribution amounts to 0.8 ± 0.1 for the J/ψ analysis and 16 ± 3 for the $\psi(2S)$. Secondly, for the J/ψ analysis, feed-down via $\chi_c \to J/\psi + \gamma$ and $\psi(2S) \to J/\psi + X$ are estimated to account for $9.0 \pm 0.8\%$ and $1.8 \pm 0.3\%$, respectively and have been evaluated using simulated events normalised to χ_c and $\psi(2S)$ signal yields obtained in data. The third and least well understood background, comes from the inelastic production of J/ψ and $\psi(2S)$ mesons; events which involve additional gluon radiations or in which the proton dissociates (see Fig. 1(b,c,d)).

The inelastic contribution has been estimated using the shape of the J/ψ transverse momentum distribution. The signal contribution is taken from SUPERCHIC. The background is taken from data, extrapolating the shape of the distribution for identified inelastic J/ψ events which contain additional tracks. The result of the fit is shown in the left plot of Fig. 3; below 900 MeV, the elastic fraction is $70 \pm 7\%$ where the uncertainty includes a statistical and a systematic component. The latter is obtained by varying the signal and background template shapes.

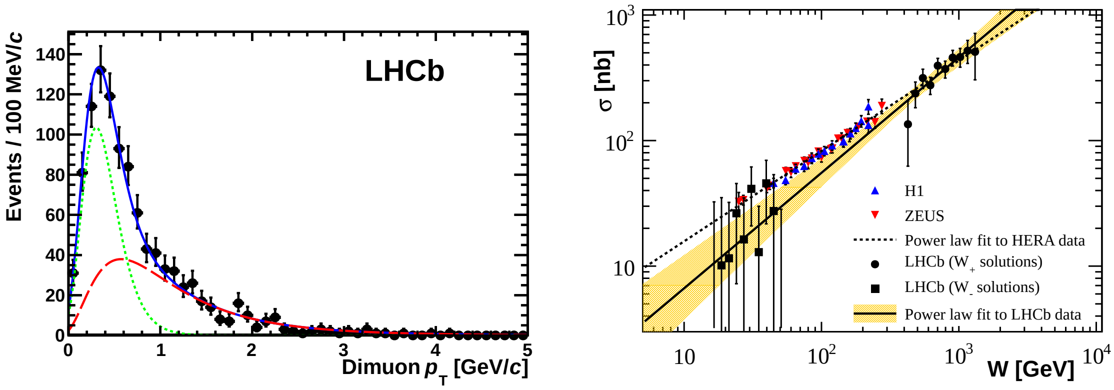

Figure 3: Left: Exclusive J/ψ candidates fitted with an elastic component from simulation (dotted), and an inelastic component from data (dashed). Right: J/ψ photo-production cross-section as a function of photon-proton centre-of-mass showing HERA data points and derived quantities from the LHCb results.

4. Results

The cross-sections times branching fractions to two muons with pseudorapidities between 2.0 and 4.5 are measured to be

$$\sigma_{pp\to J/\psi(\to\mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 307 \pm 21 \pm 36 \text{ pb},$$
$$\sigma_{pp\to\psi(2S)(\to\mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 7.8 \pm 1.3 \pm 1.0 \text{ pb}.$$

which agree with the predictions of STARLIGHT [5], SUPERCHIC [6], Gonçalves and Machado [8], and Motyka and Watt [9], and is lower than the predictions of Schäfer and Szczurek [10]. The differential cross-section for J/ψ has been calculated in ten bins of rapidity, y, using acceptance factors calculated with STARLIGHT. The results are given in Table 4.

Our results can be compared to J/ψ photoproduction results from HERA [11]. In their case, the photon radiates from the electron while in ours, it can come from either proton, leading to a two-fold ambiguity in the cross-sections which are related through

$$\frac{d\sigma}{dy}_{pp\to pJ/\psi p} = r(y)\left[k_+\frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi p}(W_+) + k_-\frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi p}(W_-)\right], \tag{4.1}$$

where W is the photon-proton centre-of-mass, the photon energy is $k_\pm \approx (m_{J/\psi}/2)\exp(\pm|y|)$, the photon flux is dn/dk and r is a gap-survival correction factor. The LHCb data is fit assuming a power law dependence of the form $\sigma(W) = aW^\delta$ where W is the photon-proton centre-of-mass. Then, inserting these fitted values for one of the two solutions on the right-hand-side of the equation above, leads to an estimate for the other. This is shown in the right plot of Fig. 3, and compared to previous HERA results in a different kinematic regime. With current statistics, both are consistent.

Table 1: Cross-section measurements (nb) as a function of J/ψ rapidity.

Rapidity	2.00-2.25	2.25-2.50	2.50-2.75	2.75-3.00
$\frac{d\sigma}{dy}(J/\psi)$	$3.2 \pm 0.8 \pm 0.9$	$4.5 \pm 0.5 \pm 0.8$	$5.3 \pm 0.4 \pm 0.9$	$4.4 \pm 0.3 \pm 0.7$
Rapidity	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00
$\frac{d\sigma}{dy}(J/\psi)$	$5.5 \pm 0.3 \pm 0.8$	$4.8 \pm 0.3 \pm 0.7$	$5.2 \pm 0.3 \pm 0.8$	$4.8 \pm 0.4 \pm 0.8$
Rapidity	4.00-4.25	4.25-4.50		
$\frac{d\sigma}{dy}(J/\psi)$	$4.7 \pm 0.5 \pm 0.9$	$4.1 \pm 0.9 \pm 1.3$		

5. Conclusions and Outlook

The cross-sections for exclusive J/ψ and $\psi(2S)$ mesons have been measured in the forward region at $\sqrt{s} = 7$ TeV using LHCb data. The results agree with several theoretical predictions. The differential cross-section for J/ψ mesons is consistent with previous results from HERA in a different energy regime, although the current uncertainties are large and do not allow us distinguish between models with and without saturation effects [8, 9]. A factor 100 times as much data, taken at $\sqrt{s} = 7$ and 8 TeV, is currently under analysis and will allow more precise tests of theory. Due to the luminosity levelling employed by LHCb, the average number of visible proton-proton interactions remains at about 1.5, despite the increase in luminosity. Coupled with the ability of LHCb to trigger on low momentum particles, this will allow a range of measurements of central exclusive production using over 3 fb $^{-1}$ of data.

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PoS(DIS 2013)082