Soft QCD and CEP at LHCb

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Abstract. Besides its $b$ and $c$ quark physics programme, due to the experiment’s unique geometry, LHCb also provides a suitable environment for QCD and central exclusive production measurements in a unique forward pseudorapidity range. The latest results on inelastic cross-section for proton-proton collisions and the central exclusive production of $J/\psi$ and $\psi(2S)$ vector mesons, both at $\sqrt{s} = 13$ TeV at LHCb are presented.

1. Introduction
The LHCb experiment [1] was designed for studies of very rare decays of $b$ and $c$ flavoured hadrons. The detector is a single arm forward spectrometer instrumented with tracking, calorimetry and particle identification in the pseudorapidity range $2 < \eta < 5$. In 2015, a new set of scintillators (HeRSCHeL detector) [2] were implemented on both sides of the LHCb interaction point with the goal of enhancing studies of diffractive physics. Due to this extension, LHCb has sensitivity to particles in the regions $-10 < \eta < -5$, $-3.5 < \eta < -1.5$ and $1.5 < \eta < 10$. All these particularities make LHCb well suited for both QCD and central exclusive production (CEP) studies in the forward region, complementary to other LHC experiments. In this paper, results from two measurements will be discussed, both using pp collisions data at $\sqrt{s} = 13$ TeV center-of-mass energy, collected by LHCb during Run 2.

2. Measurement of the inelastic pp cross-section at $\sqrt{s} = 13$ TeV
In this section, the inelastic cross-section for proton-proton collision at $\sqrt{s} = 13$ TeV at LHCb is presented [3]. The measurement is performed for the fiducial region of the LHCb detector ($2 < \eta < 5$) and then extrapolated to the full phase-space with data collected for both field orientations of the LHCb dipole magnet, the data samples consisting of 691 milion events in 49 runs from 8 LHC fills, recorded in 2015.

2.1. Fiducial cross-section
The fiducial cross-section is defined as the cross-section for pp collisions with at least one long-lived prompt ($\Delta t > 30$ ps and produced directly in the primary collisions) charged particle with $p > 2$ GeV/c and produced in the LHCb acceptance. Assuming that the number of inelastic interactions per event are described through a Poisson distribution, the fiducial cross-section is calculated following this expression

$$\sigma_{acc} = \frac{(\mu - \mu_{bkg})N_{evt}}{L_{tot}}$$  (1)
where $\mu - \mu_{bkg}$ is the average number of interactions per event, $N_{evt}$ is the number of collected events and $L_{tot}$ is the integrated luminosity. The result for this first measurement is:

$$\sigma_{acc} = 62.2 \pm 0.2 \pm 2.5 \text{ mb} \quad (2)$$

where the first uncertainty represents the total (statistical and systematic) uncertainty and the second one is due to the determination of the integrated luminosity.

2.2. Extrapolation to full phase-space

The extrapolation from the fiducial cross-section to the total inelastic cross-section is performed using the following relation:

$$\sigma_{inel} = F_T \sigma_{acc} = \sum X \sigma_X \quad (3)$$

where $F_T$ is the extrapolation factor determined from generator-level simulations and $X$ represents the non-diffractive (ND), single-diffractive (SD) and double-diffractive (DD) processes. Neglecting the interference effects between the contributions, the total inelastic cross-section is measured to be:

$$\sigma_{inel} = 75.4 \pm 3.0 \pm 4.5 \text{ mb} \quad (4)$$

with the first uncertainty due to experimental uncertainty of the fiducial cross-section and the second one due to extrapolation to the full phase-space. In Figure 1, a comparison of the inelastic cross-sections at different energies obtained at ALICE [4], ATLAS [5], [6], [7], [8] and TOTEM [9], [10], [11], [12], [13], [14] are shown. The new LHCb measurement at $\sqrt{s} = 13$ TeV is in good agreement with ATLAS [8] and TOTEM [14] measurements at the same energy.

3. Central exclusive production of $J/\psi$ and $\psi(2S)$ vector mesons in pp collision at $\sqrt{s} = 13$ TeV

Central exclusive production processes in high energy proton-proton collisions offer a promising framework to study aspects of both QCD and New Physics signals. These processes are elastic, colliding protons interact via colorless objects (e.g. photons, pomerons) exchange. The two protons lose energy but survive the collision intact remaining inside the beampipe (unlike the quarks/gluons the photon is colour-singlet object, therefore can naturally lead to exclusive final state, with intact outgoing protons), a system of mass $X$ being produced with its decay products present in the fiducial region of the detector. The low multiplicity of the final state and the absence of activity, or large “rapidity gap”, either side of the central system provides
a distinctive signature of the CEP process. This paper presents cross-section measurements for central exclusive production of charmonia in \(2 < y < 4.5\) rapidity range using the LHCb forward extension, HeRSCheL detector [2] and following the same analysis method as in reference [15].

### 3.1. Exclusive production of \(J/\psi\) and \(\psi(2S)\) vector mesons

For this study, a data set corresponding to an integrated luminosity of \(L = 204 \pm 8\) pb\(^{-1}\) at \(\sqrt{s} = 13\) TeV is used. The event selection requirements are listed in Table 1.

#### Table 1: Candidate selection criteria

| Hardware | Software |
|----------|----------|
| \(< 30 \) deposits | \(< 10\) reconstructed tracks |
| \(p_T(\mu) > 200\) MeV | 1 muon |

#### Offline selection

- 2 reconstructed muons in \(2 < \eta < 4.5\) \(\pm 65\) MeV/c\(^2\) from \(J/\psi\) or \(\psi(2S)\) mass \(p_T^2 < 0.8\) GeV\(^2\)

![Figure 2: Invariant mass distribution of the dimuonic candidates with the vertical lines indicating the mass windows of the \(J/\psi\) and \(\psi(2S)\) vector mesons [16].](image1)

![Figure 3: Transverse momentum squared distribution for the dimuonic candidates with (lower) and without (upper) HeRSCheL veto applied [16].](image2)

In Figure 2 the invariant mass of the dimuonic candidates is shown. The background sources considered are: the non-resonant dimuon production coming from photon-photon fusion, the feed-down of \(\chi_s\) or \(\psi(2S)\) produced in association with the \(J/\psi\) vector meson and the non-exclusive events where a proton dissociates but the remnants are undetected. The number of non-exclusive events is determined through the squared tranverse momentum distribution of the \(J/\psi\) and \(\psi(2S)\) vector mesons. Figure 3 illustrates the \(p_T^2\) distributions of the dimuonic candidates with and without the HeRSCheL requirement. The number of electromagnetic CEP events is obtained by fitting the \(p_T^2\) distributions with a signal shape taken from simulated events and an inelastic background modelled by the sum of two exponential functions. The fraction of non-exclusive events coming from proton dissociation is determined through the \(p_T^2\) distributions of the two vector mesons after the electromagnetic nonresonant and feed-down backgrounds are substracted.
3.2. Cross-sections

The differential cross-section as a function of rapidity for both \( J/\psi \) and \( \psi(2S) \) are shown in figure 5 compared to approximate NLO theoretical calculations [17] where a good agreement is observed. Summing the differential results over all bins, measurements of the product of the cross-sections and branching fractions, where both muons are within the fiducial region, are obtained:

\[
\sigma_{(J/\psi \rightarrow \mu^+\mu^-)}(2.0 < \eta_\mu < 4.5) = 399 \pm 16 \pm 10 \pm 16 \text{ pb} \tag{5}
\]
\[
\sigma_{(\psi(2S) \rightarrow \mu^+\mu^-)}(2.0 < \eta_\mu < 4.5) = 10.2 \pm 1.0 \pm 0.3 \pm 0.4 \text{ pb}
\]

The first uncertainties are statistical, the second are systematic, and the third are due to the luminosity determination. This measurement is linked with the photoproduction cross-section using the formula from reference [18]

\[
\sigma_{pp \rightarrow p\gamma\gamma} = r(W_\pm)k_\pm \frac{dn}{dk_\pm} \sigma_{\gamma p \rightarrow \gamma p}(W_\pm) + r(W_-)k_- \frac{dn}{dk_-} \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow \gamma p}(W_-)
\tag{6}
\]

where \( r(W_\pm) \) is the gap survival factor, \( k_\pm \) is the photon energy, \( \frac{dn}{dk_\pm} \) is the photon flux and \( W_\pm^2 = 2k_\pm \sqrt{s} \) is the invariant mass of the photon-proton system. By using equation 6 the photoproduction cross-section values are computed and the results for the two vector mesons are shown in figure 6 for 7 and 13 TeV at LHCb compared to H1 [20], ZEUS [21] and ALICE [22] results. In the plots, a good agreement between 13 TeV and 7 TeV data is observed, however the 13 TeV data extends the W reach at almost 2 TeV. At higher energies, a deviation from the H1 data to describe the \( J/\psi \) data is observed, but in contrast a good agreement of the data with the JMRT prediction can be seen.
4. Conclusions
In these proceedings the latest results on the measurement of the inelastic proton-proton cross-section with at least one prompt long-lived charged particle in the pseudorapidity range $2 < \eta < 5$ and the central exclusive production of $J/\psi$ and $\psi(2S)$ vector mesons at $\sqrt{s} = 13$ TeV have been presented showing the physics potential of LHCb in the QCD domain. The implementation of the HeRSCheL subdetector has increased the sensitivity of LHCb to central exclusive production and reduced the background uncertainties compared to the previous analysis. Both measurements were compared with similar results from other LHC experiments, the agreement between the results was highlighted through plots.

5. References
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