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Addendum: Dielectron production in proton–proton and proton–lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

ALICE Collaboration*

Abstract

This is an addendum to the article "Dielectron production in proton–proton and proton–lead collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV" published in Phys. Rev. C **102** no. 5, (2020) 055204 [1]. We update the extracted charm cross section at midrapidity given in Table 3 and Figure 4 (left) of the original publication with the fragmentation fractions of charm quarks in pp collisions published in Ref. [2].

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*See Appendix A for the list of collaboration members

In Ref. [1] the production cross section of charm and anti-charm ($\mathrm{c\overline{c}}$) quark pairs was measured at midrapidity using a template fit to the measured dielectron yield in the invariant mass (m_{ee}) region $1.1 < m_{\mathrm{ee}} < 2.7$ GeV/c^2, the so-called intermediate mass range (IMR). The fit was performed simultaneously in the m_{ee} and dielectron transverse momentum ($p_{\mathrm{T,ee}} < 8$ GeV/c) dimensions, using either POWHEG [3–6] or PYTHIA 6 [7] as event generators for the templates of the charm and beauty components. Both generators give different shapes of the dielectron spectrum as a function of m_{ee} and $p_{\mathrm{T,ee}}$, however, they describe the data well after the fit. To further extract the $\mathrm{c\overline{c}}$ and $\mathrm{b\overline{b}}$ cross sections at midrapidity, an extrapolation from the IMR to full phase space was performed using the functional shape given by the generators. To obtain the cross section, the probability of a charm or beauty quark fragmenting into hadrons, and those decaying with an electron in the final state was used to calculate the heavy-quark ($\mathrm{Q\overline{Q}}$) cross sections from the heavy-flavour dielectron cross section. These so-called effective branching ratios $\mathrm{BR(Q \to e)}$ are a convolution of the fragmentation fractions (FF) of the heavy quarks and the decay branching ratios of open heavy-flavour hadrons into electrons. In the case of beauty, the effective branching ratios implemented in PYTHIA 6 were used [8]. For charm, the central value of $\Gamma(\mathrm{c \to l + X})/\Gamma(\mathrm{c \to X})$ from the 2020 edition of the PDG [9] was used, i.e. 9.6%.

With the measured FF in pp collisions at $\sqrt{s} = 5.02$ TeV at the LHC [2], the effective branching ratio of charm quarks into electrons can be reevaluated. This first measurement at LHC energies also extends the previous measurements by including the FF of the $\Xi_{\mathrm{c}}{}^{0}$. For the fragmentation fraction of charm quarks into Ξ_{c}^{+} baryons, $f(\mathrm{c} \to \Xi_{\mathrm{c}}^{+})$, the same value as for $f(\mathrm{c} \to \Xi_{\mathrm{c}}^{0})$ is used, assuming isospin symmetry. This is confirmed by measurements in pp collisions at $\sqrt{s} = 13$ TeV [10]. The values used are summarised in Table 1. Listed are the fragmentation fractions of c quarks into charm hadrons ($\mathrm{H_c}$) [2], together with their branching ratios into electrons based on Ref. [11]. In the last column, the product of both is calculated, giving the probability of $\mathrm{c \to H_c \to e}$ for each charm hadron species. The absolute probability for a c quark to produce an electron after fragmentation and decay is then given by the sum over these values and amounts to $7.33^{+0.61}_{-0.66}$%. This does not include the contribution of Ω_{c}^{0}, leading to an additional uncertainty of -0.52%. This is added in quadrature to the lower uncertainty resulting in $\mathrm{BR(c \to e)} = 7.33^{+0.61}_{-0.84}$, which corresponds to $0.54^{+0.09}_{-0.12}$% for the $\mathrm{c\overline{c} \to e^+e^-}$ case.

Table 1: The charm quark fragmentation fractions into charm hadrons $f(\mathrm{c \to H_c})$ from Ref. [2] are listed together with the respective branching ratios of the hadrons into electron $\mathrm{BR(H_c \to e)}$ from Ref. [11], as well as their product. The systematic and statistical uncertainties of $f(\mathrm{c \to H_c})$ are added in quadrature, assuming they are uncorrelated. If available, the inclusive values for of the branching ratios with electrons in the final state are used. In the case of Ξ_{c}^{+} and Ξ_{c}^{0} only one decay with an electron in the final state is measured. In these cases, the BR for the respective channel is used.

$\mathrm{H_c}$	$f(\mathrm{c \to H_c})[\%]$	$\mathrm{BR(H_c \to e)}[\%]$	$f \times \mathrm{BR}[\%]$
D^0	$39.1 \pm 1.7(\mathrm{stat})^{+2.5}_{-2.3}(\mathrm{syst})$	6.49 ± 0.11	$2.54^{+0.20}_{-0.27}$
D^+	$17.3 \pm 1.8(\mathrm{stat})^{+1.7}_{-1.7}(\mathrm{syst})$	16.07 ± 0.3	$2.78^{+0.40}_{-0.45}$
D_{s}^{+}	$7.3 \pm 1.0(\mathrm{stat})^{+1.9}_{-0.1}(\mathrm{syst})$	6.33 ± 0.15	$0.46^{+0.14}_{-0.09}$
Λ_{c}^{+}	$20.4 \pm 1.3(\mathrm{stat})^{+1.6}_{-1.6}(\mathrm{syst})$	4.06 ± 0.13	$0.83^{+0.09}_{-0.09}$
Ξ_{c}^{0}	$8.0 \pm 1.2(\mathrm{stat})^{+2.5}_{-2.3}(\mathrm{syst})$	1.94 ± 0.55	$0.16^{+0.05}_{-0.05}$
Ξ_{c}^{+}	$8.0 \pm 1.2(\mathrm{stat})^{+2.5}_{-2.3}(\mathrm{syst})$	7 ± 4	$0.56^{+0.37}_{-0.37}$
			$7.33^{+0.61}_{-0.66}$

The comparison with the previously used value of $\mathrm{BR(c \to e)} = 9.6$% leads to a larger $\mathrm{c\overline{c}}$ production cross section at midrapidity ($\mathrm{d}\sigma_{\mathrm{c\overline{c}}}/\mathrm{d}y|_{y=0}$) by a factor 1.72 as the change in $\mathrm{BR(c \to e)}$ enters the final results squared. The previously assigned uncertainty on $\mathrm{BR(c\overline{c} \to e^+e^-)}$ was 22%, which is now reevaluated to $^{+23}_{-17}$%. The $\mathrm{c\overline{c}}$ cross sections in pp collisions at $\sqrt{s} = 7$ and 13 TeV [8, 12] can be updated with the same procedure. The reevaluated $\mathrm{c\bar{c}}$ production cross sections at midrapidity are summarised in Table 2. Note that with respect to Refs. [1, 8, 12] only the $\mathrm{c\bar{c}}$ cross sections change.

Table 2: $\mathrm{c\bar{c}}$ production cross sections at midrapidity extracted at different collision energies using the event generators PYTHIA 6 and POWHEG with an effective branching ratio of charm quarks to electrons based on fragmentation fractions measured by the ALICE collaboration [2].

$\sqrt{s}$ (TeV)	$\sigma_{\mathrm{c\bar{c}}}\vert_{y=0}$ (μb)	
	PYTHIA	POWHEG
5.02	$900 \pm 105(\mathrm{stat}) \pm 45(\mathrm{syst})\ ^{+208}_{-152}\ (\mathrm{BR})$	$1299 \pm 137(\mathrm{stat}) \pm 65(\mathrm{syst})\ ^{+300}_{-220}\ (\mathrm{BR})$
7	$1468 \pm 211(\mathrm{stat}) \pm 249(\mathrm{syst})\ ^{+339}_{-248}\ (\mathrm{BR})$	$2150 \pm 266(\mathrm{stat}) \pm 366(\mathrm{syst})\ ^{+497}_{-363}\ (\mathrm{BR})$
13	$1674 \pm 237(\mathrm{stat}) \pm 241(\mathrm{syst})\ ^{+387}_{-283}\ (\mathrm{BR})$	$2435 \pm 316(\mathrm{stat}) \pm 351(\mathrm{syst})\ ^{+562}_{-411}\ (\mathrm{BR})$

The compilation of the measured $\mathrm{c\bar{c}}$ cross sections as a function of $\sqrt{s}$ is shown in Fig. 1, together with the complementary measurement of the charm production cross sections at midrapidity in the fully reconstructed charm hadron channels in pp collisions at $\sqrt{s} = 5.02$ and 7 TeV [2], as well as 13 TeV [10]. Within uncertainties the dielectron measurements are consistent with the results using charm hadrons. The measurements are compared to predictions calculated in the fixed-order next-to-leading-log (FONLL) approach [13–16]. Shifting up the data points coherently, the $\sqrt{s}$ dependence of the cross section is unchanged with respect to the original publication and described by the FONLL calculations. While consistent with FONLL predictions within uncertainties, the measurements tend to be on the upper edge of the theoretical uncertainty band. Calculations at next-to-next-to-leading-order (NNLO) predict a consistently higher $\mathrm{c\bar{c}}$ cross section as a function of $\sqrt{s}$ [17, 18]. The smaller uncertainties however increase the tension with the measurements.

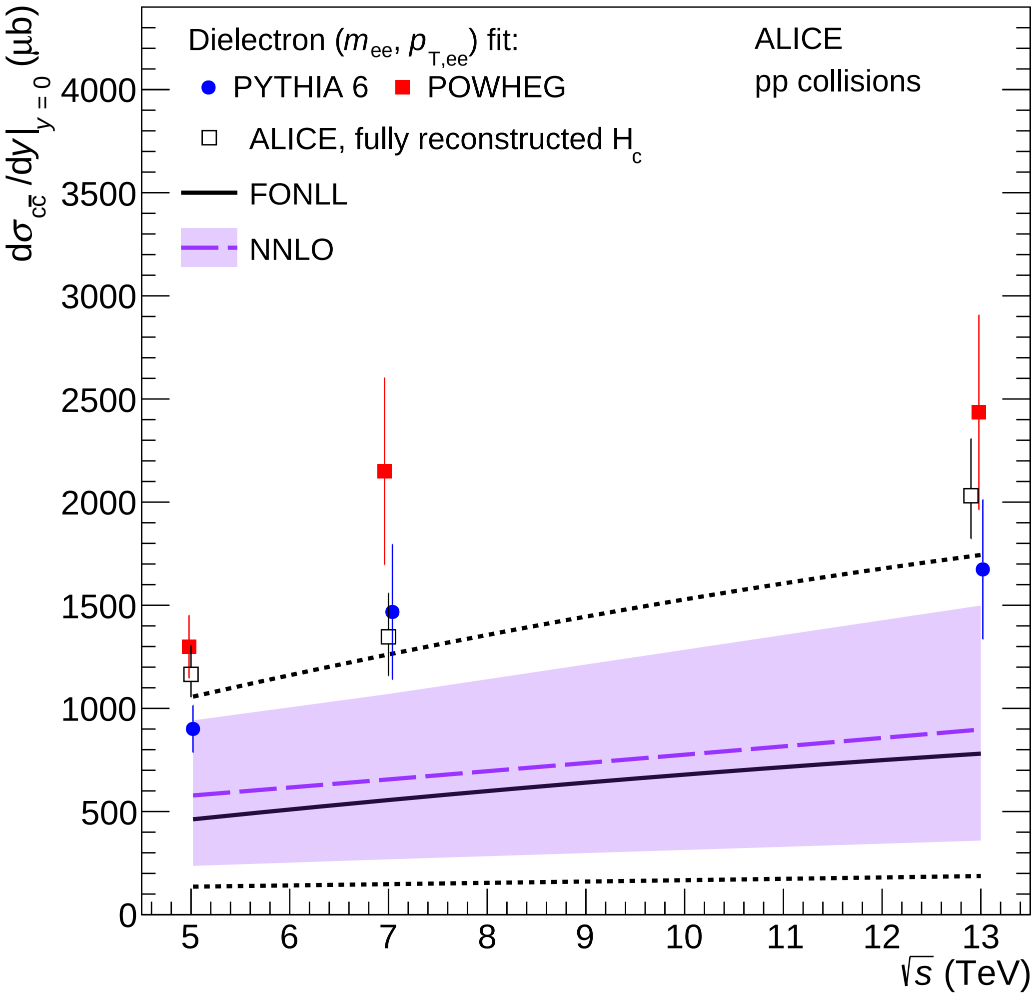

Figure 1: (Colour online) Cross sections at midrapidity for $c\bar{c}$ production as a function of $\sqrt{s}$ in pp collisions. The coloured markers represent the measured midrapidity cross sections at $\sqrt{s}$ = 5.02, 7, and 13 TeV which are derived using either PYTHIA 6 (blue circles) or POWHEG (red squares) simulations [1, 8, 12]. The systematic and statistical uncertainty of the data points are summed in quadrature and represented by vertical bars. The measurements in the dielectron analysis are compared to measurements performed with fully reconstructed charm hadrons (H_c) at the same energies (open markers) [2, 10]. In addition, measurements are compared to FONLL calculations (black solid line) [13–16] with corresponding model uncertainties (dashed lines), with next-to-next-to-leading-order (NNLO) calculations (magenta) [17, 18].

As for the beauty sector, enhanced baryon-to-meson ratios for beauty hadrons [19] and non-prompt charm hadrons [20] have been measured in hadronic collisions at the LHC compared to results in e^+e^- collisions at lower energies. Since the semi-leptonic branching ratios of the different beauty hadrons are very close to each other, these observations affect only the dielectron pairs involving at least one charm hadron decay ($b \to c \to e$). Since no decays were forced in the creation of the templates, the fragmentation and decay in the relevant PYTHIA version are responsible for reproducing the measurements. A reweighting was performed to study the validity of the utilized templates to extract the cross sections. It was found that the overall effect on the shape of the beauty template is negligible in the phase space where the measurement is sensitive to the beauty production.

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