PROCEEDINGS OF SCIENCE

Production of heavy flavours at CMS

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Recent CMS results on production of heavy hadrons are presented, including the measurement of total charm production cross section in pp collisions at $\sqrt{s} = 7$ TeV and the observation of simultaneous production of $\Upsilon(1S)$ meson and Z boson in pp collisions at $\sqrt{s} = 13$ TeV.

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1. Introduction

The purpose of this proceeding is to present a review of the most recent analyses published by the CMS collaboration [1] in the field of Heavy Flavour production. We will discuss the following three analyses: "Measurement of double-differential and total charm cross section at 7 TeV" [3], "Measurement of B meson production fractions in pp collisions at 13 TeV" [4], and "Measurements of $\Upsilon(1S)$ production in association with a Z boson at 13 TeV" [5].

2. Measurement of double-differential and total charm cross section at 7 TeV

2.1 Motivations

The study of charm-quark production is essential for testing Quantum Chromodynamics (QCD), as the charm-quark mass is close to the QCD scale parameter (Λ_{QCD}). For this reason, charm production occurs in a transition region between perturbative and non-perturbative regimes, making theoretical predictions particularly challenging.

Up to now the best theoretical predictions are calculated at next-to-leading plus next-to-leading logarithm (NLO+NLL) accuracy, as in the FONLL framework [2], for differential cross sections while total cross sections σ are available at next-to-next-to-leading order (NNLO). To validate these theoretical predictions (Fig. 1) experimental measurements are therefore necessary.

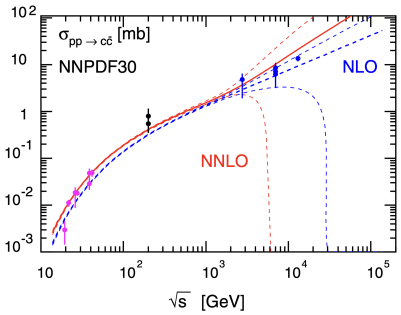

Figure 1: Example of theoretical predictions for the $c\bar{c}$ production cross section in pp collisions at NLO and NNLO using the NNPDF3.0 parton distribution functions. [6]

All experiments can measure cross sections only within their fiducial volumes, so the total cross section can be obtained only through extrapolations, which rely on certain theoretical assumptions. State-of-the-art results have so far assumed charm fragmentation universality. However, recent measurements indicate that charm fragmentation is not universal [7], highlighting the need to account for this effect in the cross-section extrapolation. This has been made possible thanks to a new technique known as ddFONLL.

2.2 D^* reconstruction and differential cross section

To measure the $c\bar{c}$ production cross section, the analysis starts from the measurement of the D^{*+} meson production cross section. The D^{*+} is reconstructed through the decay chain:

$$D^{*+} \to D^0 \pi_s^+ \to K^- \pi^+ \pi_s^+, \tag{1}$$

where the kaon–pion charge combination is unambiguously determined by the charge of the soft pion (π_s). The observable of interest is $\Delta m = m(D^{*+}) - m(D^0)$, which is expected to be measured with excellent resolution, thereby significantly reducing the combinatorial background.

The analysis is based on proton–proton collision data collected at $\sqrt{s} = 7\,\text{TeV}$ in 2010, corresponding to an integrated luminosity of about $3.0\,\text{nb}^{-1}$, and made available through the CMS Open Data portal. A dedicated low-p_T tracking algorithm, available during the data-taking, allowed the reconstruction of charged tracks down to approximately 70 MeV. Events were selected with zero-bias and minimum-bias triggers, as well as with single-electron and single-muon triggers. In the latter cases, to avoid potential biases, events in which the triggered lepton defined the primary vertex were excluded. Multiple D^{*+} candidates per event were accepted, as they may originate from different primary vertices.

The reconstruction strategy required the D^0 meson to be built from two oppositely charged tracks, identified as kaon and pion candidates. A common-vertex fit of the two tracks was performed, with a requirement on the vertex-fit probability p-value $> 1\%$. The soft pion was required to originate from the same primary vertex as the D^0 and to satisfy $p_T > 70\,\text{MeV}$.

The signal extraction relied on a background subtraction method. Right-charge combinations ($K^{\mp}\pi^{\pm}\pi^{\pm}$) contain both genuine D^{*+} decays and combinatorial background, while wrong-charge combinations ($K^{\mp}\pi^{\mp}\pi^{\pm}$) represent purely combinatorial background. The background distribution was normalized to match the integral in the sideband regions, and the signal yield was obtained by integrating the distribution in the background-subtracted signal region, as illustrated in Fig. 2.

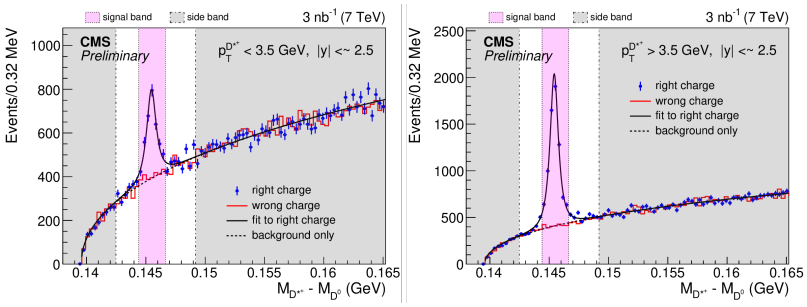

Figure 2: $\Delta m = m(D^{*+}) - m(D^0)$ distributions in two p_T intervals. The right-charge data (blue points) are compared with the wrong-charge distribution (red histogram), normalized in the shaded sideband regions (gray bands). The pink band marks the mass window used for the final signal extraction. [3]

This procedure is repeated for different p_T ($[0, +\infty]$) and $|y|$ ($[0, 2.5]$) bins, and the D^{*+} yield is used to calculate the differential cross section $\frac{d\sigma}{dp_T dy}$ (an example is shown in Figure 3 left). The results are found to be in agreement with PYTHIA predictions (globally scaled to the data) and FONLL predictions. The differential cross section is then integrated to obtain the total fiducial cross section measured by CMS:

$$\sigma^{\text{CMS}}_{\text{fiducial}} = 1.28^{+0.22}_{-0.22}\,\text{mb} \tag{2}$$

2.3 Total charm cross section

The CMS results are combined with those from LHCb to cover a rapidity range up to $|y| = 4.5$, and the uncovered $|y|$ regions are estimated using ddFONLL (3 right), a new technique based on

FONLL in which the "universal" fragmentation fraction is replaced by a p_T-dependent hadron-production fraction directly obtained from LHC measurements (more details are available at [8]).

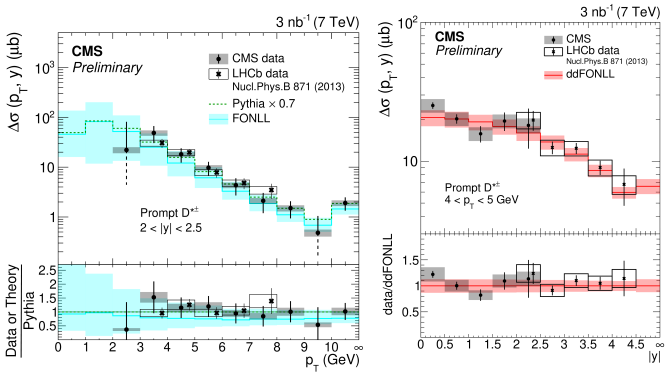

Figure 3: (left) Double-differential prompt-D^{*+} cross section versus p_T bins for $|y| < 0.5$, with data points and theoretical predictions. (right) The $D^{*+} + D^{*-}$ cross sections are shown as a function of $|y|$ bins for $4 < p_T < 5GeV$. Data are compared to the data-driven FONLL (red bands). [3]

The total $c\bar{c}$ cross section is then calculated as:

$$\sigma_{c\bar{c}} = \frac{\Delta_{D^+}^{\text{data}}(\text{measured PS}) + \Delta_{D^+}^{\text{ddFONLL}}(\text{unmeasured PS})}{2\, f_{D^{*+}}^{pp}}, \tag{3}$$

where $\Delta_{D^+}^{\text{data}}$ is the measured yield in the accessible phase space (PS), $\Delta_{D^+}^{\text{ddFONLL}}$ accounts for the extrapolation to the unmeasured phase space using ddFONLL, and $f_{D^{*+}}^{pp}$ is the $c \to D^{*+}$ fragmentation fraction. Using this procedure, the resulting cross section is $\sigma_{c\bar{c}} = 9.39^{+1.35}_{-1.49}$ mb, which is compatible with NNLO predictions.

3. Measurement of B meson production fractions in pp collisions at 13 TeV

3.1 Motivations

The measurement of b-quark fragmentation fractions [4], i.e., the probabilities for a b quark to hadronize into a specific hadron (e.g., B^+, B^0, B_s), and in particular the ratios of these probabilities, known as Production Fraction Ratios (PFRs), is crucial for several analyses. For instance, they enter the determination of the branching ratio of $B_s \to \mu^+\mu^-$ and constitute one of its main sources of uncertainty. Several results have already been obtained, for example by CMS [10] and LHCb [11], and a dependence on p_T has been observed, making it particularly interesting to investigate with higher statistics.

3.2 Overview

The CMS analysis we will discuss was performed using the data collected by CMS in 2018 through the B-Parking dataset [9]. This dataset consists of events collected with a single-muon trigger operating at a variable rate, increased in steps as the Physics Stream bandwidth decreases. The idea is that if the muon originates from the decay of a B meson, there is one additional B meson in the event, ensuring an essentially unbiased sample. Using this approach, approximately 10

billion unbiased decays of hadrons containing b quarks, corresponding to an integrated luminosity of $41.5 fb^{-1}$, were collected. The CMS analysis is divided into two channels: the hadronic open-charm channel, which aims at measuring the PFR values by studying B meson decays into D mesons, and the charmonium channel, which investigates decays into J/ψ and can probe the p_T dependence of the PFR as well as the relative PFR (defined later).

3.2.1 Hadronic open-charm

The hadronic open-charm channel explores decays of $B^+ \to \pi^+ \bar{D}^0 (K^+\pi^-)$, $B^0 \to \pi^+ D^- (K^+\pi^-\pi^-)$, $B_s^0 \to \pi^+ D_s^- (\pi^- \phi(K^+K^-))$, applying both standard kinematic selections (p_T, η, vertex probability) and BDT-based selections to further suppress the combinatorial background. The invariant mass distributions and the final fits are shown in Fig. 4. The main formula used for the calculation of the PFRs is:

$$\frac{f_s}{f_d} = \frac{\mathcal{B}(B^0 \to \pi^+ D^-)}{\mathcal{B}(B_s^0 \to \pi^+ D_s^-)} \frac{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^- \to \pi^- \phi(K^+K^-))} \frac{N_{\text{corr}}(B_s^0)}{N_{\text{corr}}(B^0)}, \tag{4}$$

where N_{corr} denotes the efficiency-corrected yield. However, in the case of PFRs involving f_s, the branching fraction $\mathcal{B}(B_s^0 \to \pi^+ D_s^-)$ cannot be directly used since it is itself determined under assumptions on the PFRs. Therefore, in Eq. 4 we multiply and divide by $\mathcal{B}(B^0 \to K^+ D^-)$ and replace the ratio $\mathcal{B}(B^0 \to K^+ D^-)/\mathcal{B}(B_s^0 \to \pi^+ D_s^-)$ with a result derived from theory.

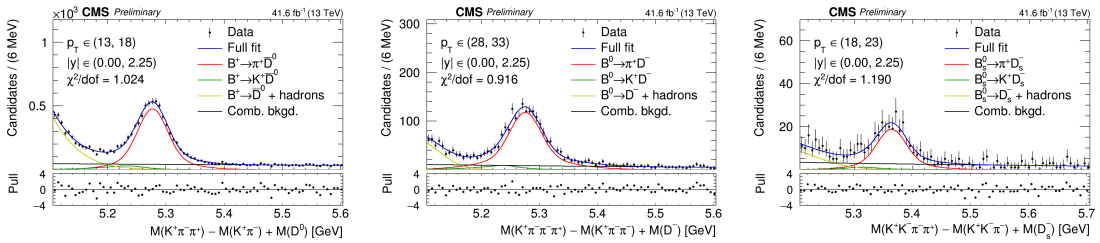

Figure 4: Distribution of the B candidate invariant mass in the hadronic open-charm channel, corrected for the D meson one. The left, middle, and right panels show the B^+, B^0, and B_s^0 decays, respectively. [4]

3.2.2 Charmonium

In the charmonium channel we study decays of $B^+ \to J/\Psi K^+$, $B^0 \to J/\Psi K^*(K\pi)$, $B_s^0 \to J/\Psi \phi(KK)$, applying only kinematic selections. In this case, we can directly measure only

$$\frac{f_d}{f_u} = \frac{\mathcal{B}(B^+ \to J/\psi K^+)}{\mathcal{B}(B^0 \to J/\psi K^*(K\pi))} \frac{N_{\text{corr}}(B^0)}{N_{\text{corr}}(B^+)}, \tag{5}$$

for reasons similar to those discussed previously. As for the other two PFRs, we can only extract the so-called PFR ratios, defined as

$$R_s^{(d)} = \frac{N_{\text{corr}}(B_s^0)}{N_{\text{corr}}(B^+(B^0))}, \tag{6}$$

which can be used to study trends in p_T or rapidity, and can later be converted into PFRs by incorporating input from the hadronic open-charm channel. Since the J/ψ is reconstructed through its decay into two muons, we can exploit both the unbiased side of the parking dataset (probe) and the triggered-muon side (test).

3.3 Results

From the hadronic open-charm channel we are able to extract f_s/f_d and f_s/f_u:

$$\begin{aligned} f_s/f_u &= 0.227 \pm 0.011\,(\text{stat}) \pm 0.017\,(\text{syst}), \\ f_s/f_d &= 0.224 \pm 0.011\,(\text{stat}) \pm 0.014\,(\text{syst}). \end{aligned} \tag{7}$$

the latter being compatible with the LEP result $f_s/f_d = 0.249 \pm 0.023$. From the charmonium channel we can study the p_T and η dependence. The results do not exhibit any statistically significant dependence on p_T or $|y|$, and are consistent with the previous CMS measurement [PRL 131 (2023) 121901], as shown in Fig. 5 (left). By combining all channels, we obtain a value of $f_d/f_u = 0.98 \pm 0.05$, consistent with the Standard Model and previous CMS results. Finally, by combining the two channels we can convert the relative PFRs into absolute PFRs, with the results illustrated in Fig. 5 (right).

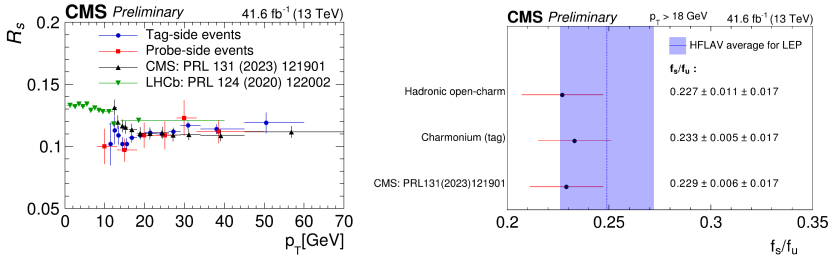

Figure 5: (left) Distribution of relative PFR (R_s) as a function of p_T compared with previous CMS and LHCB results. (right) Summary of f_s/f_u for the two channel and the previous CMS result. [4]

4. Measurements of $\Upsilon(1S)$ production in association with a Z boson at 13 TeV

4.1 Motivations

Heavy quarkonium production in hadronic collisions is not yet fully understood. Several models describe it, but they are sometimes competing, and the tensions among them become more pronounced when quarkonia are produced in association with electroweak bosons. For these reasons, the goal of this analysis is the measurement of the fiducial cross section for Z + $\Upsilon(1S)$, along with the determination of the effective Double Parton Scattering (DPS) cross section (σ_{eff}).

4.2 Analysis Overview

The analysis uses data collected by CMS during Run 2 (2016–2018), corresponding to an integrated luminosity of $\sim 138 fb^{-1}$. In these data, we search for the associated production of a Z boson and an Υ meson, reconstructing both through their decays into two muons, and using the channel $Z \to 4\mu$ as normalization. The final invariant mass distributions for the Υ and Z candidates are shown in Fig. 6 (left&center). A two-dimensional extended unbinned maximum likelihood fit is performed to extract the expected signal yields. Among the Υ states, only the $\Upsilon(1S)$ is found with a significance greater than 5σ (34.6 ± 9.0 observed events). To separate the contributions from DPS and single parton scattering (SPS), we perform a simultaneous fit of the rapidity (Δy)

and azimuthal angle ($\Delta\phi$) separations between the Z and $\Upsilon(1S)$ candidates, using Monte Carlo simulations as templates. The extracted yields are:

- $N^{SPS}_{Z+\Upsilon(1S)} = 1.7 \pm 8.7$
- $N^{DPS}_{Z+\Upsilon(1S)} = 32.9 \pm 8.7$

These numbers enter the calculation of the fiducial cross section ratio as:

$$R_{Z+\Upsilon(1S)} = \left(\frac{N^{\text{SPS}}_{Z+\Upsilon(1S)}}{\epsilon^{\text{SPS}}_{Z+\Upsilon(1S)}} + \frac{N^{\text{DPS}}_{Z+\Upsilon(1S)}}{\epsilon^{\text{DPS}}_{Z+\Upsilon(1S)}} \right) \frac{\epsilon_{Z\to 4\mu}}{N_{Z\to 4\mu}}, \tag{8}$$

where ϵ are efficiencies computed from MC simulations and $N_{Z\to 4\mu}$ the number of events in the control channel. In turn, the fiducial cross section ratio for the DPS contribution is used to compute the effective cross section as:

$$\sigma_{\text{eff}} = \frac{\sigma(\Upsilon(1S))}{R^{DPS}_{Z+\Upsilon(1S)}} \frac{B(Z\to\mu\mu)B(\Upsilon(1S)\to\mu\mu)}{B(Z\to 4\mu)}, \tag{9}$$

where $\sigma(\Upsilon(1S))$ is $\Upsilon(1S)$ production section is taken from data-constrained theory [12, 13]. The result is $\sigma_{eff} = 13.0^{+7.9}_{-3.5}$ mb. Using the same strategy, σ_{eff} has also been measured as a function of the transverse momentum of the $\Upsilon(1S)$ and of the Z boson, yielding the distributions shown in Fig. 6 (right). These results can serve as inputs to constrain double parton distribution functions in multiparton interactions.

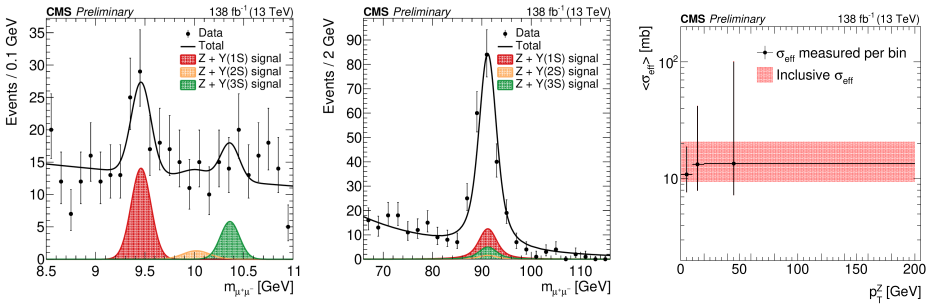

Figure 6: (left&center) Invariant mass distributions of Υ and Z candidates. (right) Measurement of σ_{eff} in bins of the Z boson p_T. [5]

5. Summary

In conclusion, in this proceeding we have discussed three recent analyses published by CMS: the measurement of the cc production cross section, the measurement of the associated production cross section of Upsilon and Z via double parton scattering, and the measurement of the b fragmentation fraction ratio. All results are consistent with the Standard Model predictions.

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