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# CMS results on the hadron production fractions ratios

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**Summary.** — The recent CMS measurement of the dependence of the hadron production fraction ratios $f_s/f_u$ and $f_d/f_u$ on $B$ meson kinematic variables, in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$, is reported and the significant scope of this result is discussed.

## 1. – Introduction to the context in which the CMS result is inserted

The proton-proton ($pp$) collisions at the LHC produce copious pairs of $b$ and $\bar{b}$ quarks that undergo a process, referred to as fragmentation or hadronization, resulting in the creation of any of the beauty hadrons. The hadron production fractions (also known as fragmentation functions) are defined as the probabilities for a beauty quark to hadronize to beauty hadrons. The fractions of $B^+$, $B^0$ and $B_s^0$ mesons are denoted by $f_u$, $f_d$ and $f_s$, respectively. Thanks to the B-factories many of the $B^+$ and $B^0$ branching fractions are well known, namely at a very good level of precision, thus allowing further precision measurements at both B-factories and hadron colliders. This is not the case for the $B_s^0$ meson and, consequently, precision $B_s^0$ branching fractions at hadron colliders rely on ratios to $B^+$ and $B^0$ decay modes, thus requiring the knowledge of $f_s/f_u$ and $f_d/f_u$ ratios, respectively. Measuring the relative production of $b$ hadrons is not only important for the studies about the underlying QCD and eventually the nature of the strong interaction, but the $f_s/f_u$ ratio is also an essential input and a dominant source of systematic uncertainty in the $B_s^0$ branching fractions' measurements at hadron colliders. As a relevant example, the measurement of the branching fraction of the rare decay $B_s^0 \to \mu^+\mu^-$, that is used to search physics beyond the Standard Model, is currently limited by the uncertainty in $f_s/f_u$ (see refs. [1-4]). The isospin symmetry implies that $f_u = f_d$ and thus $f_s/f_u = f_s/f_d$.

(*) On behalf of the CMS Collaboration.

By exploiting $Z$ boson decays, a variety of measurements by the LEP experiments have been combined to obtain the ratio $f_s/f_d$ [5]. Afterwards, the measurements by CDF (in the central pseudorapidity interval $|\eta| < 1$) in $p\bar{p}$ collisions [6] and ATLAS (for $|\eta| < 2.5$) in $pp$ collisions at $\sqrt{s} = 7\,\text{TeV}$ [7], were found to be compatible with the LEP result and without any evidence of dependence on the $p_T$ of the $B$ meson. In absence of contradicting evidence, the production fractions in different collisions environments have been considered universal and thus averaged.

However, in the second part of the last decade, a set of measurements performed by LHCb have seriously questioned this universality picture. An evidence of the $p_T$ dependence of $f_s/f_d$ [8] and a clear indication of the $p_T$ dependence of $f_{\Lambda_b^0}/f_d$ [9] were later confirmed —even strengthened— by LHCb in ref. [10].

The $p_T$ dependence of $f_s/f_u$ has been investigated in detail by LHCb in a more recent analysis based on the whole statistics integrated in Runs 1 and 2 (*i.e.*, considering the $\sqrt{s} = 7, 8$ and 13 TeV datasets all together), and covering the full forward region ($2.0 < |\eta| < 6.4$) [11]. As a result a $p_T$ dependence was observed with a statistical significance of 6.0 $\sigma$ whereas no evidence for an $\eta$ dependence was found. The $p_T$ dependency is driven by the $\sqrt{s} = 13\,\text{TeV}$ sample ($8.7\,\sigma$) while those for the other collision energies are not significant when considered separately. This brings also to evidence for an increase of $f_s/f_u$ as a function of the collision energy, the two-sided significance being $4.8\,\sigma$ with respect to no energy dependence hypothesis. To be precise, LHCb effectively measures the ratio $\mathcal{R}$ of efficiency-corrected yields of $B_s^0 \to J/\psi\phi$ and $B^+ \to J/\psi K^+$ reconstructed signals: no attempt is made to measure the absolute $f_s/f_u$ value because of the large uncertainty on the $B_s^0 \to J/\psi\phi$ branching fraction. These results have been confirmed in a subsequent re-analysis presented in ref. [12]; for instance the measured double ratio when comparing Run 2 *vs.* Run 1 brings to $(f_s/f_d)_2/(f_s/f_d)_1 = 1.064 \pm 0.007$.

The new CMS results [13], to be presented below (sect. **2**), address the study of the $f_s/f_u$ ratio and its possible dependence on $B$ meson kinematic variables, in a kinematic region ($p_T > 12\,\text{GeV}$ and $|y| < 2.4$) approximately complementary to that of the LHCb detector, by using a data sample of $pp$ collisions collected in 2018 at $\sqrt{s} = 13\,\text{TeV}$ and corresponding to an integrated luminosity of $61.6\,\text{fb}^{-1}$. Furthermore, a first test of the isospin invariance in $B$ meson production in $pp$ collisions is performed by measuring the $f_d/f_u$ ratio. At the time of the HADRON 2023 conference the paper in ref. [13] was not published yet and just the paper draft [14] was available.

## 2. – Setup and methods of the CMS analysis

The $B^+$, $B^0$ and $B_s^0$ mesons are reconstructed using the $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$ decay channels (charged-conjugate states are implicitly included), with the intermediate resonances reconstructed in the decay modes $J/\psi \to \mu^+\mu^-$, $\phi(1020) \to K^+K^-$ and $K^{*0}(892) \to K^+\pi^-$. Since CMS [15] lacks a hadronic particle identification there are always two possible combinations for each $K^{*0}$ candidate ($K^+\pi^-$ and $\pi^+K^-$) and therefore an arbitration criterion is applied (the one with the invariant mass closest to the nominal $K^{*0}$ mass is kept). A swapped signal component (with swapped $\pi$-$K$ mass assignments) survives with a 12 % yield's size relative to the unswapped signal (as estimated from simulation) and is kept in the fit model to extract $B^0$ yield.

It is worthy to focus on the kind of observables that are effectively measured, namely the two following efficiency-corrected yield ratios, and for each one we show that

—theoretically— they are directly proportional to the corresponding production fraction ratio:

$$\mathcal{R}_s = \frac{N_{B_s^0}}{N_{B^+}} \cdot \frac{\epsilon_{B^+}}{\epsilon_{B_s^0}}, \quad \mathcal{R}_s = \frac{f_s}{f_u} \cdot \frac{\mathcal{B}(B_s^0 \to J/\psi\phi)\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(B^+ \to J/\psi K^+)}, \tag{1}$$

$$\mathcal{R}_d = \frac{N_{B^0}}{N_{B^+}} \cdot \frac{\epsilon_{B^+}}{\epsilon_{B^0}}, \quad \mathcal{R}_d = \frac{f_d}{f_u} \cdot \frac{\mathcal{B}(B^0 \to J/\psi K^{*0})\mathcal{B}(K^{*0} \to K^+\pi^-)}{\mathcal{B}(B^+ \to J/\psi K^+)}. \tag{2}$$

In principle, from eq. (1) it would be possible to extract the $f_s/f_u$ ratio, however the world-average value for the $B_s^0 \to J/\psi\phi$ branching fraction is dominated by the LHCb result (with which we want to compare our results) that used $B^+ \to J/\psi K^+$ as normalization channel and therefore depends —in turn— on the $f_s/f_u$ ratio. To avoid this evident circularity we report the measurement of the $\mathcal{R}_s$ rather than of $f_s/f_u$.

For what concerns $f_d/f_u$ the situation is even more tricky. The involved branching fractions in the expression on the right of eq. (2) are independently obtained from —B-factories based— high-precision measurements that assume strong isospin symmetry. Initially, reporting the $f_d/f_u$ ratio (instead of $\mathcal{R}_d$), that is expected to be independent of kinematic variables and equal to unity because of isospin symmetry, provides a "calibration mode" to corroborate the correctness of the $\mathcal{R}_s$ measurement. Furthermore the measured $\mathcal{R}_d$ —once converted into the $f_d/f_u$ observable— can be even used to probe the isospin symmetry invariance in $B$ meson production provided that the needed branching fractions ratio $\mathcal{B}(B^+ \to J/\psi K^+)/\mathcal{B}(B^0 \to J/\psi K^{*0})$ is evaluated without the isospin invariance assumption. This is obtainable by proceeding as follows:

a) for $\mathcal{B}(B^0 \to J/\psi K^{*0})$, the world-average value [16] is considered; it assumes isospin invariance: $\mathcal{R}^{\pm,0} = \mathcal{B}(\Upsilon(4S) \to B^+B^-)/\mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0) = 1$ for the B-factories results;

b) for $\mathcal{B}(B^+ \to J/\psi K^+)$, its most precise measurement [17] is considered after correcting it for the assumption in ref. [17] $\mathcal{R}^{\pm,0} = 1.058 \pm 0.024$ (borrowed from ref. [5]) in order to make it compatible with the branching fractions that assume $\mathcal{R}^{\pm,0} = 1$;

c) lastly, following ref. [18], the ratio of branching fractions is scaled by the correction factor, namely it is divided by the most recent value $\mathcal{R}^{\pm,0} = 1.059 \pm 0.027$ (borrowed from ref. [19]), in order to remove the isospin conservation assumption.

The signal candidates from the three decay modes $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^*0$ and $B_s^0 \to J/\psi\phi$ have been extracted filtering events by means of a displaced dimuon-plus-track high level trigger and applying a set of offline selection criteria presented in ref. [13]. This CMS paper discusses —in detail— how the $N_{B^+}$, $N_{B^0}$ and $N_{B_s^0}$ yields are extracted from the unbinned maximum likelihood fits of the $J/\psi K^+$, $J/\psi K^*0$ and $J/\psi\phi$ invariant mass distributions, and how the two efficiency ratios $\epsilon_{B^+}/\epsilon_{B_s^0}$ and $\epsilon_{B^+}/\epsilon_{B^0}$ are estimated by using simulated samples. Yields and efficiency ratios are given for 12 different $p_T^B$-bins (integrated over $|y^B|$) and 7 $|y^B|$-bins (integrated over $p_T^B$).

The $\mathcal{R}_s$ and $\mathcal{R}_d$ measurements are affected by systematic uncertainties in the determination of the fitted signal yields and in the evaluation of the efficiency ratios. The systematic uncertainties can be divided in bin-by-bin and global (*i.e.*, equal for every bin) ones and are discussed in detail in ref. [13].

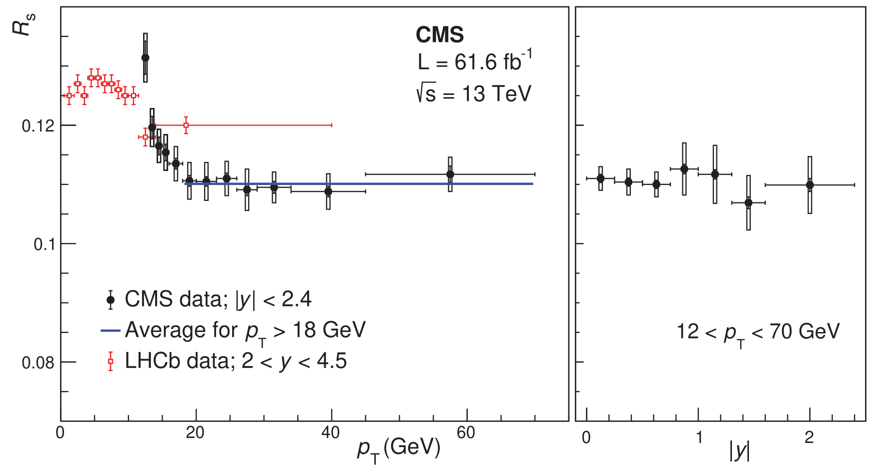


Fig. 1. – The efficiency-corrected yield ratio $\mathcal{R}_s$ as a function of $p_T^B$ (left) and $|y^B|$ (right) from ref. [13]; $\mathcal{R}_s$ is directly proportional to $f_s/f_u$ as discussed in the text. The LHCb measurement [11] is reported as well. The vertical bars (boxes) represent the statistical (bin-to-bin systematic) uncertainties, whereas the horizontal bars show the bin widths. A global uncertainty of 2.3%, associated to track reconstruction and found to be independent of $p_T^B$ and $|y^B|$, is not graphically represented. The blue line represents the average for $p_T^B > 18\,\text{GeV}$.

## 3. – Discussion of the CMS results

In fig. 1 the efficiency-corrected yield ratio $\mathcal{R}_s$ is shown as a function of the transverse momentum and the rapidity of the $B$ meson. While no dependence on the rapidity is seen, a strong variation is observed at low $p_T^B$ (namely in the 12–18 GeV range), followed by a flat trend for higher $p_T^B$ values; $\langle \mathcal{R}_s \rangle = 0.1102 \pm 0.0027$ is the average value for $p_T^B > 18\,\text{GeV}$. The LHCb results of ref. [11] are also reported: the measurement appears to be compatible with the CMS data, thus supporting the $p_T^B$ dependence.

In fig. 2 the $f_d/f_u$ ratio is shown as a function of the same two kinematic variables. No dependence on the transverse momentum and the rapidity of the $B$ meson is observed. The average value over all the $p_T^B$-bins is $\langle f_d/f_u \rangle = 0.998 \pm 0.063$, with this uncertainty including all contributions; it is consistent with unity within the 6 % precision of the measurement. This is the first direct measurement of isospin invariance in $B$ meson production at hadron colliders.

In summary, at the LHC the ratios of hadron production fractions are probed in different rapidity regions and center-of-mass energies as reported by LHCb [11,12], ATLAS [7] and now CMS [13]. The CMS result shows, for $|y^B| < 2.4$ and $12 < p_T^B < 70\,\text{GeV}$, that the ratio $\mathcal{R}_s \propto f_s/f_u$ decreases as $p_T^B$ increases up to $p_T^B \sim 18\,\text{GeV}$, and then flattens out at higher $p_T^B$ values, with the "asymptotic" value which also agrees with the LEP value at high $p_T^B$. This observation is only possible because of the larger central acceptance in $p_T^B$ compared to the LHCb results, and the much better statistical precision compared to the ATLAS result. The $\mathcal{R}_s$ result with its $p_T^B$-dependency behaviour is a crucial input to measurements by ATLAS and CMS of the $B_s^0 \to \mu^+\mu^-$ branching fraction.

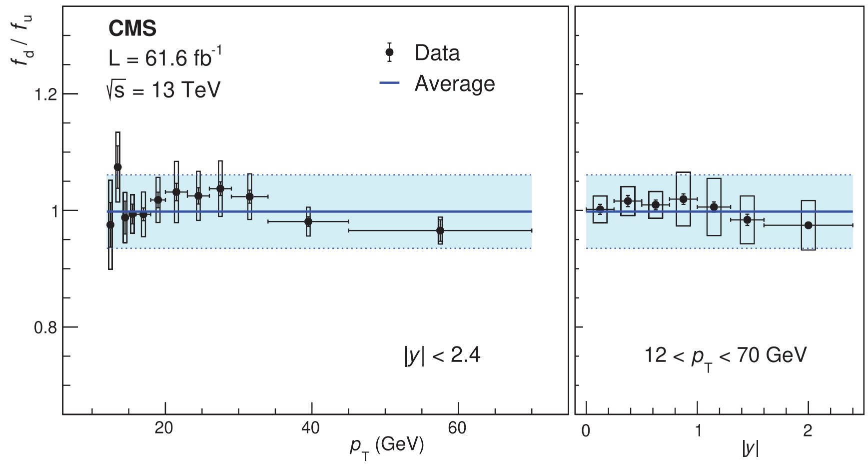


Fig. 2. – The $f_d/f_u$ ratio as a function of $p_T^B$ (left) and $|y^B|$ (right) from ref. [13]; it is derived from the efficiency-corrected yield ratio $\mathcal{R}_d$ as discussed in the text. The vertical bars (boxes) represent the statistical (bin-to-bin systematic) uncertainties, whereas the horizontal bars show the bin widths. The horizontal blue line and band represent the average value and uncertainty. The global uncertainty of 5.7 % is included in the blue bands but not in the individual data points.

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