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New CMS results on heavy flavour production and flavour anomalies

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The CMS experiment has recently measured bottom quark hadronization fractions using 61.6 fb^{-1} of proton-proton collisions at $\sqrt{s}$ = 13 TeV over a range of B hadron transverse momentum and rapidity, confirming the observed p_T dependence of the ratio f_s/f_u first measured by the LHCb experiment. Additionally, a new measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction by CMS is described which is in closer agreement with the standard model than previous results based on the 2020 combination of ATLAS, LHCb, and CMS analyses.

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1. Introduction

Proton colliders have proven to be an important tool in the study of bottom hadrons due to the large b-quark production cross section and have so far been the primary facilities at which the properties of B_s^0 mesons, Λ_b^0 baryons and other b-flavored baryons have been studied in detail. Essential to many of these studies are measurements of rare decay branching fractions but determining these precisely requires knowledge of the initial numbers of weakly decaying b-hadrons in a sample. Specifically, the number of B meson decays observed in a final state X, is related to several experimental quantities, including a branching fraction of interest:

$$N_X = \sigma_b \cdot A \cdot f_q \cdot \mathcal{B}(B_q \to X) \cdot \epsilon_X \tag{1}$$

with an analogous expression for weakly decaying b-barysons such as Λ_b or Ξ_b. In either case, σ_b is the bottom quark production cross section, A is the experimental acceptance for trigger and event reconstruction, and ϵ_X is the trigger and reconstruction efficiency for the decay of interest. It is the hadronization fractions, f_q, that quantify the probabilities that a bottom quark will, through the process of hadronization followed by decays of intermediate resonances, form one of the weakly decaying b mesons or baryons. Hadronization fractions, and ratios of hadronization fractions, are therefore essential inputs when measuring branching fractions of rare b decays and their ratios.

Historically, bottom quark hadronization fractions were first measured at LEP and then subsequently measured in proton-antiproton collisions at the Tevatron [1]. The comparison, shown in Table 1, suggested disagreements at the level of 2σ and although not highly significant, led to speculation that hadronization fractions may depend on the environment in which bottom hadrons are formed. The possibility of environmental dependence has been recognized as a potential limiting factor in the precision measurement of B_s^0 branching fractions, including $B_s^0 \to \mu^+\mu^-$.

Quantity		LEP (Z decays)	Tevatron
B^+ or B^0 fraction	$f_u = f_d$	0.407 ± 0.007	0.344 ± 0.021
B_s^0 fraction	f_s	0.101 ± 0.008	0.115 ± 0.013
b-baryon fraction	f_{baryon}	0.085 ± 0.011	0.198 ± 0.046
ratio	f_s/f_d	0.249 ± 0.023	0.334 ± 0.040

Table 1: Bottom quark hadronization fractions and ratios of hadronization fractions measured at LEP and the Tevatron as of 2018 [1].

More recently, the analysis of large samples of inclusive semi-leptonic decays by the LHCb collaboration found a significant dependence of f_{Λ_b} on $p_T(\Lambda_b^0)$, and a weaker but still significant p_T dependence of the ratio $f_s/(f_u + f_d)$ [2]. This observation motivates new measurements carried out using the CMS detector [3] of bottom quark hadronization fractions in proton-proton collisions over a range of p_T and rapidity.

2. New CMS Measurement of f_s/f_u

Although rare, events containing decays of B mesons to final states that include $J/\psi \to \mu^+\mu^-$ can be selected with high purity by level-1 and high-level triggers. Recently, the CMS experiment

PoS(FPCP2023)054

has used this approach to measure ratios of b-meson hadronization fractions by reconstructing $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, and $B_s^0 \to J/\psi\phi$ with $K^{*0} \to K^-\pi^+$ and $\phi \to K^+K^-$ [4]. These final states were reconstructed in 61.1 fb^{-1} of proton-proton collisions collected in 2018 at a center-of-mass energy of 13 TeV using a di-muon trigger with the requirement of an additional track consistent with production at a common displaced secondary vertex. Specifically, pairs of oppositely charged muons with $p_T > 4$ GeV, $|\eta| < 2.5$ and with invariant mass in the vicinity of the J/ψ resonance were selected if they were consistent with production at a displaced secondary vertex, with the transverse distance from the primary to the secondary vertex at least three times its uncertainty. An additional track with $p_T > 1.2$ GeV and transverse impact parameter significance larger than 2 was then required to also be consistent with production at the J/ψ vertex.

Within this sample of events, the B^+, B^0, and B_s^0 decays were reconstructed by imposing additional quality criteria on the di-muon candidate, and selecting high-purity tracks with at least 5 hits in the silicon tracker, one of which was in the pixel layers. All final-state particles were then fit to a common secondary vertex with the di-muon invariant mass constrained to the world-average [4]. The associated primary vertex was then re-fit with any tracks in the B candidate removed and the distance between the primary and secondary vertices was required to be greater than 5 times its uncertainty. The final sample of B candidates was selected by requiring their p_T to be in the range 12 to 70 GeV and $|y| < 2.4$.

The yields of reconstructed B mesons were determined in 12 bins of p_T, integrated over rapidity, and in 7 bins of $|y|$, integrated over p_T, by fitting the invariant mass distributions of the final state particles. Figure 1 shows examples of these fits for the 20-23 GeV range of p_T. The functions used to describe the invariant mass distributions consist of two Gaussians with a

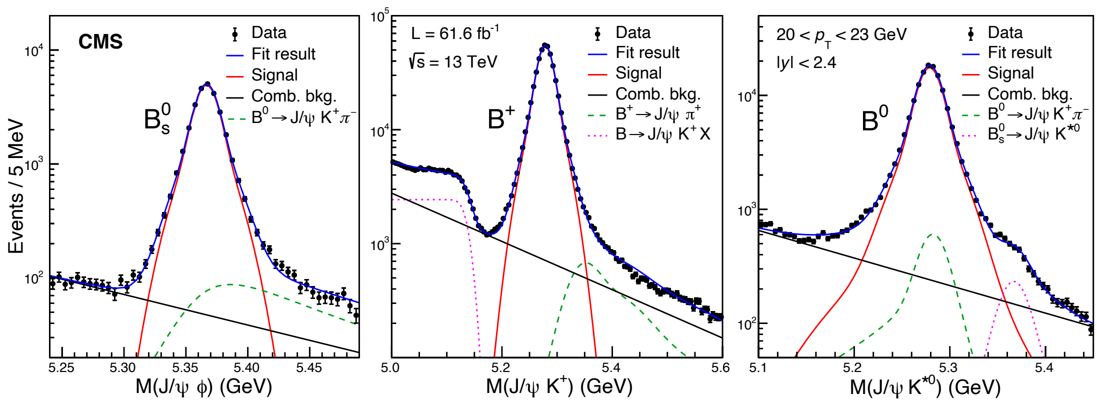

Figure 1: Invariant mass distributions of the $J/\psi\phi$, $J/\psi K^+$, and $J/\psi K^{*0}$ final states for the range of transverse momentum $20 < p_T < 23$ GeV [4].

common mean and independent widths to describe the signal, an exponential function to describe the combinatorial background, and shapes determined from simulation to describe reflections such as $B^0 \to J/\psi K^+\pi^-$ in the $B_s^0 \to J/\psi\phi$ sample, $B^+ \to J/\psi\pi^+$ in the $B^+ \to J/\psi K^+$ sample, and both $B^0 \to J/\psi K^+\pi^-$ and $B_s^0 \to J/\psi K^{*0}$ in the $B^0 \to J/\psi K^{*0}$ sample. Additionally, partially reconstructed B decays in the $B^+ \to J/\psi K^+$ sample were described by an error function. In principle, ratios of hadronization fractions can be determined from the measured yields of b-hadrons provided the branching fractions to the observed final states are known. This is the case for $\mathcal{B}(B^0 \to J/\psi K^{*0})$ and $\mathcal{B}(B^+ \to J/\psi K^+)$, which have been measured precisely by the BaBar [6] and Belle [7] experiments, but the most precise measurement of $\mathcal{B}(B_s^0 \to J/\psi\phi)$, made by the LHCb experiment [8], is highly correlated with their measurement of the ratio f_s/f_d. Thus, CMS prefers to measure ratios of the products of hadronization fractions and branching fractions,

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

$$\mathcal{R}_s = \frac{f_s}{f_u}\frac{\mathcal{B}(B_s^0 \to J/\psi\phi)\mathcal{B}(\phi \to K^- K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = \frac{N_{B_s^0 \to J/\psi\phi}\epsilon_{B^+ \to J/\psi K^+}}{N_{B^+ \to J/\psi K^+}\epsilon_{B^0 \to J/\psi\phi}} \tag{3}$$

which are still sensitive to any p_T and y dependence, and may be used to determine the hadronization fractions when sufficiently precise independent branching fraction measurements become available.

The efficiency corrected ratios of the measured B_s^0 and B^+ yields as functions of p_T and $|y|$ are shown in Figure 2 and agree well with measurements made by the LHCb experiment in the region of p_T where they overlap, while no significant dependence of $\mathcal{R}_s$ on rapidity is observed over the range $|y| < 2.4$. These measurements confirm the dependence of $\mathcal{R}_s$ on p_T observed by LHCb at

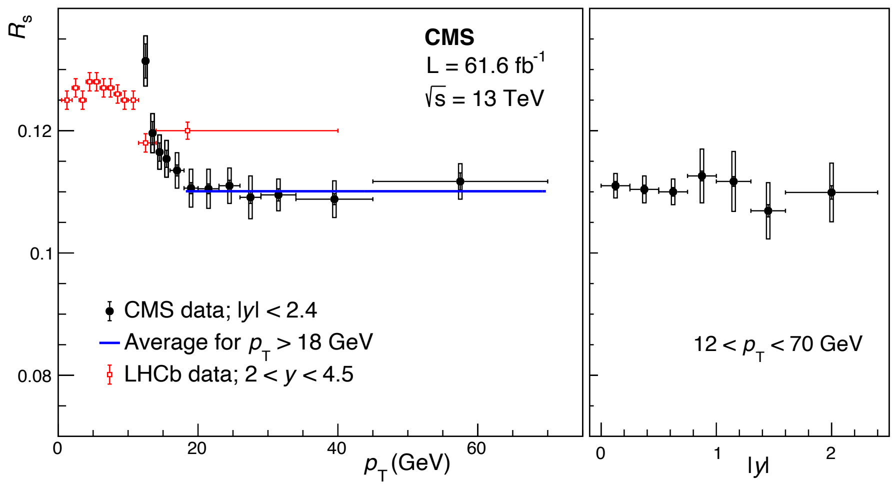

Figure 2: Efficiency-corrected ratio of B_s^0 and B^+ yields ($\mathcal{R}_s$) as functions of p_T (left) and $|y|$ (right) compared with previous LHCb measurements (red). Statistical uncertainties are represented by vertical error bars, while bin-to-bin systematic uncertainties are represented by vertical boxes [4].

low p_T and show that the ratio reaches an asymptotic value of $\mathcal{R}_s = 0.1102 \pm 0.0027$ when averaged over measurements with $p_T > 18$ GeV. The ratio f_d/f_u is also determined as a function of p_T and $|y|$ using the measured ratios $\mathcal{R}_d$ and the independently determined branching fractions and is found to be consistent with unity over the ranges of p_T and $|y|$ considered.

In principle, the ratio f_s/f_u could also be determined precisely if uncorrelated estimates of the branching fractions were available, but this may only be feasible for $\mathcal{B}(B_s^0 \to J/\psi\phi)$ by analysing B_s^0 decays collected at e^+e^- colliders operating at the $\Upsilon(5S)$ resonance. Nevertheless, there is reason to expect that the ratio of branching fractions for the hadronic decays $B_s^0 \to D_s^+\pi^-$ and $B^0 \to D^- K^+$ can be calculated with a precision of about 5% [9] which would allow for an independent measurement of f_s/f_u using these all-hadronic final states. Although this presents a challenge for proton collider experiments, as there is no lepton in the final state on which to trigger, CMS has recently collected large samples of unbiased b decays from the QCD production of $b\bar{b}$ in which one of the quarks forms a b-hadron that decays semi-leptonically. This sample, collected in 2018 and corresponding to an integrated luminosity of 41.6 fb^{-1}, contains approximately 10^{10} events that were triggered by the presence of a single displaced muon [10]. Jets opposite the muon used in the trigger are free from any trigger bias and are found to have a b-purity of 60-90%, estimated by reconstructing the decay $B \to D^{*+}\mu^-\overline{\nu}_\mu$. Thus, it should be possible that in the future, a precise, independent measurement of f_s/f_u could be made by the CMS experiment.

3. New CMS Measurement of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$

In 2020, discrepancy with standard model predictions emerged in the field of heavy flavour physics when the ATLAS, LHCb, and CMS experiments combined their respective likelihood functions to obtain improved limits on the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ branching fractions [11]. The result, shown in Figure 3, suggested that the measured branching fraction $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ deviated from the standard model expectation at the level of about 2σ. This apparent discrepancy motivated an improved analysis of these branching fractions by the CMS experiment using the full 140 fb^{-1} data sample collected at $\sqrt{s} = 13$ TeV in 2016-2018 [12].

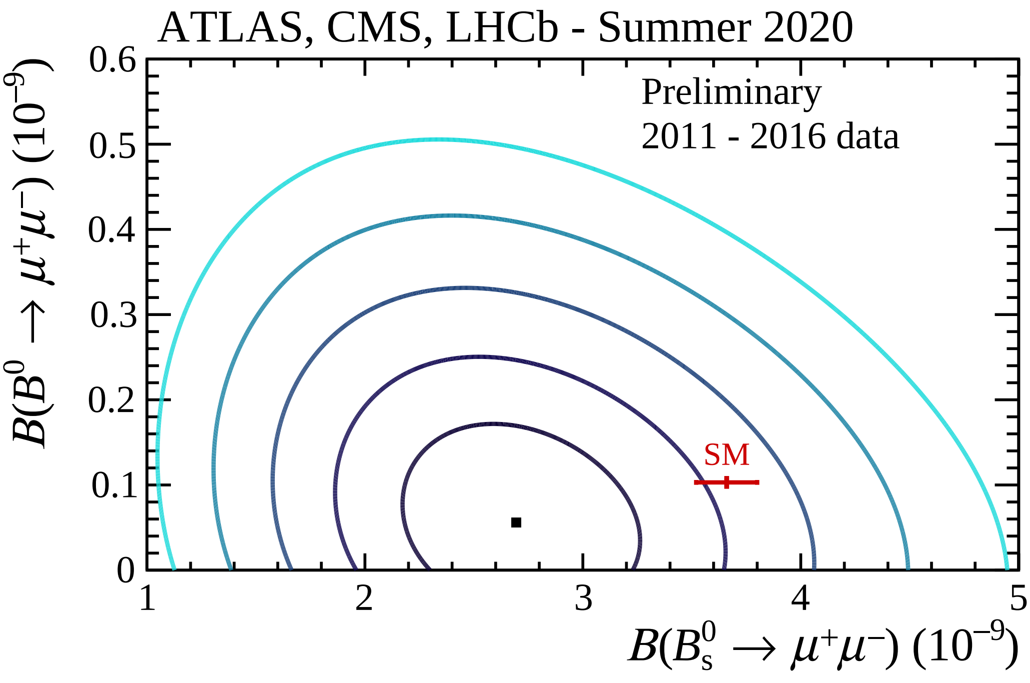

Figure 3: Likelihood contours of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and $\mathcal{B}(B^0 \to \mu^+\mu^-)$ from the combination of the ATLAS, CMS, and LHCb experiments. Contours correspond to values of $-2\Delta \log \mathcal{L} = 2.3, 6.2, 11.8, 19.3$, and 30.2, while the red point shows the expected standard model prediction, with uncertainties [11].

The branching fraction $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ was measured from the ratios of the $B^0_s \to \mu^+\mu^-$ and $B^+ \to J/\psi K^+$ yields and reconstruction efficiencies using

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+)\frac{N_{B^0_s\to\mu^+\mu^-}}{N_{B^+\to J/\psi K^+}}\frac{\epsilon_{B^+\to J/\psi K^+}}{\epsilon_{B^0_s\to\mu^+\mu^-}}\frac{f_u}{f_s} \tag{4}$$

in which f_u/f_s is the ratio of the b-quark hadronization fractions. The measurement was also performed relative to the yield of $B^0_s \to J/\psi\phi$ decays which, although less precise given our current knowledge of this branching fraction, removes the dependence of the measurement on the ratio of hadronization fractions. Events used in this analysis were collected using a trigger that required the presence of two muons with $|\eta| < 1.5$ that formed a secondary vertex and had an invariant mass that was either in the range $2.9 - 3.3$ GeV, in the vicinity of the J/ψ, or in the B^0_s signal region, $4.5 - 6.0$ GeV. Offline event selection imposed tighter muon identification requirements, including matching high-quality tracks found in the inner detector with $p_T > 4$ GeV and $|\eta| < 1.4$. The $B^+ \to J/\psi K^+$ selection required the presence of an additional track with $p_T > 1$ GeV and $|\eta| < 2.5$.

The sample of selected events is dominated by backgrounds composed primarily of independent semi-leptonic decays of two heavy quarks, and partially reconstructed semi-leptonic decays of b-hadrons. These backgrounds can be distinguished from the $B^0_s \to \mu^+\mu^-$ and $B^+ \to J/\psi K^+$ signals using the distinct geometry of these decay topologies by means of a multivariate analysis (MVA). Inputs to the MVA include angles between the B candidate momentum and the vector joining primary and secondary vertices, secondary vertex fit quality, the displacement of the secondary vertex from the primary vertex, and a class of observables sensitive to additional decay products that would be present in semi-leptonic decays of bottom and charm hadrons. The MVA was trained using simulated $B^0_s \to \mu^+\mu^-$ signal events and background events selected in data from the invariant mass sidebands above and below the expected B^0_s signal. The performance of the MVA on data was evaluated using an independent control sample of $B^+ \to J/\psi K^+$ events for which the kaon p_T was required to be less than 1.5 GeV in order to more accurately represent the kinematics of the $B^0_s \to \mu^+\mu^-$ signal, with a scale factor introduced to account for the difference in opening angle of the muons. A correction to the MVA selection efficiency was derived from the ratio of observed $B^+ \to J/\psi K^+$ selection efficiencies in data and Monte Carlo which was then applied to the $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ efficiencies. A second method reweighted simulated $B \to \mu^+\mu^-$ events to more closely match the data using a multivariate event classifier that used the same inputs as the MVA selection. The difference between these two methods, which agree at the level of $1 - 2\sigma$, was used to define the systematic uncertainty associated with the MVA selection.

The B^0_s and B^0 signal yields were determined from un-binned maximum likelihood fits to the di-muon invariant mass distributions that were performed separately in 16 distinct categories, based on data taking period, MVA discriminant output, and pseudorapidity of the most forward muon. The $B \to \mu^+\mu^-$ signals were modelled using crystal ball functions, combinatorial background was described well by a linear function, and backgrounds from semi-leptonic B decays were constrained to shapes determined from Monte Carlo. Peaking background from charmless hadronic two-body B decays with $K^\pm$ or $\pi^\pm$ in the final state, were constrained to shapes obtained from Monte Carlo simulations normalized to the $B^+ \to J/\psi K^+$ control sample using measured branching fractions [5]. These fake signal rates were measured using $K^0_S \to \pi^+\pi^-$ and $\phi \to K^+K^-$ control samples, and were found to be consistent with those predicted by Monte Carlo simulations. Figure 4 shows examples of the resulting fit for two distinct ranges of the MVA output.

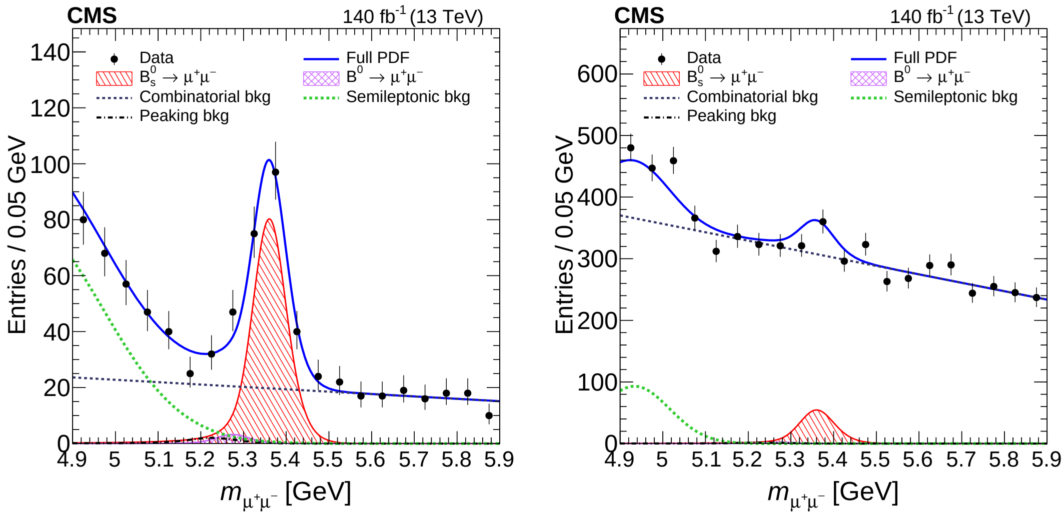

Figure 4: Projections of the di-muon invariant mass for two ranges of the MVA discriminant output, $d_{MVA} > 0.99$ (left) and $0.90 < d_{MVA} < 0.99$ (right) [12].

Branching fractions for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ were calculated from the event yields determined from the un-binned likelihood fits to the signal and the $B^+ \to J/\psi K^+$ normalization sample, assuming the standard model value for the B_s^0 lifetime of 1.61 ps, and the external inputs $\mathcal{B}(B^+ \to J/\psi K^+) = (1.020 \pm 0.019) \times 10^{-3}$, $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033) \times 10^{-2}$ [5], and $f_s/f_u = 0.231 \pm 0.008$. The ratio of hadronization fractions used was determined from the observed distribution of B_s^0 transverse momentum in this sample and the p_T-dependent measurement of f_s/f_u made by LHCb [8] which agrees with the previously described CMS result in the p_T range of interest. The profile likelihood of the resulting branching fractions, shown in Figure 5, is seen to be in closer agreement with the standard model than the previous combined result. The resulting $B_s^0 \to \mu^+\mu^-$ branching fraction was

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = [3.83^{+0.38}_{-0.36}(\mathrm{stat})^{+0.19}_{-0.16}(\mathrm{syst})^{+0.14}_{-0.13}(f_s/f_u)] \times 10^{-9}$$

where the systematic uncertainty is dominated by the MVA modelling, kaon tracking efficiency, and trigger efficiencies. The $B^0 \to \mu^+\mu^-$ branching fraction was also constrained to be $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ at the 95% confidence level. Using the $B_s^0 \to J/\psi\phi$ decay as an alternative normalization channel gives

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = [4.02^{+0.40}_{-0.38}(\mathrm{stat})^{+0.28}_{-0.23}(\mathrm{syst})^{+0.18}_{-0.15}(\mathcal{B})] \times 10^{-9}$$

which does not depend on the ratio of hadronization fractions, but is limited by the uncertainty on the branching fraction of the normalization channel. In the future, this may be reduced by an independent measurements of $\mathcal{B}(B_s^0 \to J/\psi\phi)$ at e^+e^- collider experiments operating at the $\Upsilon(5S)$ resonance.

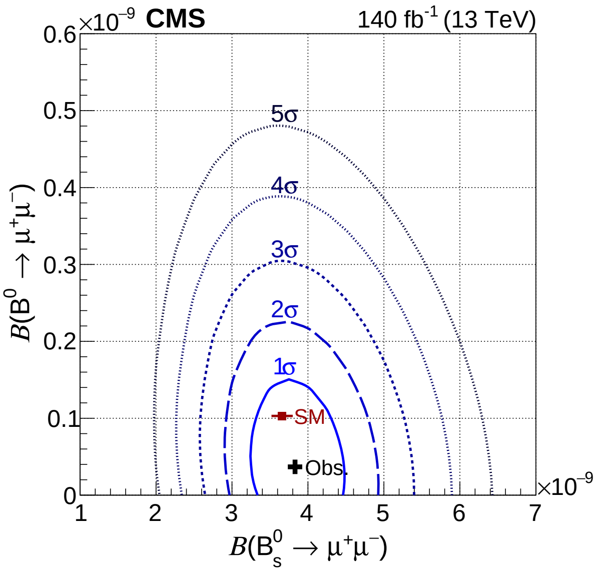

Figure 5: Profile likelihood as a function of $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ and $\mathcal{B}(B^0 \to \mu^+\mu^-)$ with contours representing confidence levels. The black point indicates the position of the observed minimum and the red point represents the expected branching fractions based on the standard model [12].

Many of the selection criteria are highly correlated with the decay time distributions of B candidates. In particular, it is the heavy B^0_s CP eigenstate that decays to $\mu^+\mu^-$ and its measured lifetime is expected to differ from lifetime measurements obtained from the analysis of a different mixture of CP eigenstates. Thus, the effective $B^0_s \to \mu^+\mu^-$ lifetime was also measured in the sample of selected events by means of a simultaneous fit to the distributions of invariant mass, the decay time, and the decay time uncertainty. Biases in this lifetime measurement were quantified by performing the same analysis on $B^+ \to J/\psi K^+$ decays and comparing the result with predictions from simulations. In this way, the effective lifetime of the $B^0_s \to \mu^+\mu^-$ decay sample was determined to be $\tau = 1.83^{+0.23}_{-0.20}(\text{stat})^{+0.04}_{-0.04}(\text{syst})$ ps where the systematic uncertainty is dominated by the fit bias and by the modelling of the MVA selection efficiency. The lifetime-dependent scale factor for the $B^0_s \to \mu^+\mu^-$ branching fraction is parameterized by a linear function,

$$s_B = 1.577 - 0.358\tau$$

and hence, the measured lifetime shifts the observed $B^0_s \to \mu^+\mu^-$ branching fraction to slightly smaller values, albeit with a larger uncertainty.

4. Conclusions

Hadron colliders provide a unique environment in which to study the production and decay of B^0_s mesons. Recent measurements have now demonstrated the dependence of the B^0_s hadronization fraction on p_T and the analysis by CMS extends this to $p_T < 70$ GeV, observing an asymptotic behaviour above 18 GeV with no dependence on rapidity. The significance of a recently observed deviation from the standard model in the $B^0_s \to \mu^+\mu^-$ branching fraction at the 2σ level is greatly reduced by the new CMS measurement which is now the most precise single measurement to date. The results obtained for the $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions, and for the effective lifetime in the $B^0_s \to \mu^+\mu^-$ sample, are found to be consistent with the standard model.

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PoS(FPCP2023)054