THE RECENT HEAVY FLAVOUR RESULTS FROM CMS*

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Received 13 April 2025, accepted 28 April 2025,
published online 26 June 2025

The CMS experiment has delivered numerous significant measurements using data from LHC Run 2 and the ongoing Run 3. This report explains key components of the CMS detector relevant to heavy-flavour physics. The short introduction to CP violation in $B_s \to J/\psi\phi(1020)$ is given, followed by the recent CMS results, confirming the CP violation in this channel. The search for CP violation in $D_s \to K^0_{\mathrm{S}}K^0_{\mathrm{S}}$ channel is presented. In addition, the most important information on selected recent CMS heavy-flavour physics results is highlighted. It includes: measurement of $B_s \to J/\psi K_{\mathrm{S}}$ effective lifetime, test of lepton flavour universality with $R_{J/\psi}$, and search for rare decays in $D^0 \to \mu^+\mu^-$. Finally, the CMS measurements of $B/B_s \to \mu^+\mu^-$ are reminded.

DOI:10.5506/APhysPolBSupp.18.5-A16

1. The CMS experiment

The Compact Muon Solenoid (CMS) [1, 2] is a general-purpose experiment for precise measurements and discoveries at high-energy frontier provided by the LHC. Among the many CMS analyses, those related to heavy-flavour physics — studies of particles containing b or c quark — play a prominent role.

The central component of the CMS detector is a large (13 m long and 6 m in diameter) solenoid providing a strong uniform magnetic field of 3.8 T inside, and about 2 T outside solenoid, in the return yoke. Essential for heavy-flavour studies are the muon system and central tracking system. The muon system is equipped with gaseous detectors and covers pseudorapidity up to $|\eta| < 2.4$. Located after the calorimeters, it identifies muons and provides

* Presented at the 31$^{\mathrm{st}}$ Cracow Epiphany Conference on the *Recent LHC Results*, Kraków, Poland, 13–17 January, 2025.

initial track measurements and triggering. The central tracking system is composed of a silicon pixel detector and a silicon strip detector. It provides vertex resolution with a precision down to 15 μm. The typical transverse impact parameter resolution is 20–75 μm. The tracker coverage for track reconstruction is limited to $|\eta| < 2.5$. The CMS combines reconstruction of tracks in the muon system and in the inner tracker. It results in track transverse momentum resolution of $\sigma_{p_\mathrm{T}}/p_\mathrm{T} \approx 1\%$ in the barrel, degrading to 3% in endcaps. The precision of reconstruction is dominated by the tracker.

The CMS trigger is a two-level trigger [3]. The Level-1 trigger is implemented in custom programmable devices. With a frequency of 40 MHz, it processes coarse-grade data from the muon and calorimeter systems and finally reconstructs muons, electrons/photons, jets (and τ candidates), and energy sums. The Level-1 output rate is exceeding 110 kHz and is constrained by detector readout capabilities. Among the reconstructed objects, muons are of primary interest for heavy-flavour physics, due to possible $b \to c\mu X$, $c \to s\mu X$ transitions as well as cascade $b \to c \to \mu$ decays. Muons provide a clear signature for triggering and, contrary to electrons, allow to apply relatively soft momentum thresholds. Currently, CMS reserves more than 10% of Level-1 bandwidth to multi-muon trigger which permits to trigger on opposite-charge dimuons with transverse momenta as low as 4 GeV (with some additional constraints on $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$, η — pseudorapidity, φ — azimuthal angle) and even lower — depending on muon pseudorapidity and luminosity conditions. In addition, CMS triggers on single muons with a standard transverse momentum threshold of 22 GeV, which is too high for B-physics. In this case, the special low-momentum trigger, working only on high-quality reconstructed muons in the barrel region is introduced, with a threshold of 11 GeV, further relaxed depending on instantaneous luminosity. The second trigger level is the High-Level Trigger (HLT), implemented on a large computer farm. It accesses full granularity data from the whole detector, including the tracker, with a reconstruction quality similar to offline. The main trigger strategy is to confirm inclusive measurements from Level-1 (with various thresholds) and extend it with additional trigger paths optimized for the process under study. The HLT output rate depends on local storage availability, transmission bandwidth to main storage, and the event size ($\mathcal{O}(1\,\mathrm{MB/ev})$ for full events). Since the performance of data taking and reconstruction depends on a number of interactions occurring during a single bunch–bunch collision, LHC is optimizing beam conditions applying the so-called lumi-leveling procedure. Instead of delivering the maximal possible instantaneous luminosity, the average number of interactions is kept constant (up to pileup of 64), limiting the instantaneous luminosity to an effective value of $2.1 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. For a typical long LHC fill, the lumi-leveling period which may last about 7–8 hours is followed by a lumi-decay period, when the luminosity exponentially decreases. Due to limited processing resources, CMS is dividing triggers into so-called *core* triggers and *parking* triggers [4]. The core triggers are scheduled for immediate prompt reconstruction of primary datasets, while parked data are reconstructed in idle time (*e.g.* delayed reconstruction during machine shutdowns). During the lumi-decay period it is also possible to lower trigger threshold to acquire softer data, important for B-physics. The typical HLT trigger rate (2024) for core triggers is about 2.7 kHz and up to 4.7 kHz for parked data. Moreover, CMS collects data with so-called scouting triggers, where only objects reconstructed at the trigger level are stored. This results in a small event size $\mathcal{O}(10\,\mathrm{kB/ev})$ and a high event rate of approximately 24 kHz.

In the case of B-physics, the interest is often in signatures with at least two, typically low-p_{T} muons, thus the double muon parking is the core of the B-physics program. The important HLT trigger is based on two muons, one with $p_{\mathrm{T}} > 4\,\mathrm{GeV}$, the second with $p_{\mathrm{T}} > 3\,\mathrm{GeV}$ which should form a common vertex and should have a dimuon invariant mass below 8.5 GeV. The contribution of such a trigger to the HLT bandwidth is $\mathcal{O}(1\,\mathrm{kHz})$. Most of heavy-flavour results presented in this report are based on a selection of Run 2 data (2015–2018) when LHC delivered to CMS an integral luminosity of about $164\,\mathrm{fb}^{-1}$. The luminosity acquired so far in Run 3 is $196\,\mathrm{fb}^{-1}$ and is subject of ongoing analyses. The majority of data delivered by LHC is successfully recorded and certified for analyses. As an example, in 2024, the CMS recording efficiency is 92% of which about 96% of data is certified for physics.

2. Measurement of CP violation in $B_s \to J/\psi\phi$

The $B_s \to J/\psi\phi$ decay followed by $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ is a flagship channel for measurements of CP violation, which enters in the weak sector of the SM due to a single irreducible phase of the Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix. The $\bar{B}_s^0$–B_s^0 system can oscillate and thus should be described by a combined state $a(t)|B_s^0\rangle + b(t)|\bar{B}_s^0\rangle$ with time evolution given by the Wigner–Weisskopf formalism. Within that, the effective Hamiltonian $\mathcal{H} = M - \frac{i}{2}\Gamma$ can be expressed by two 2×2 Hermitian matrices with off-diagonal terms related to flavour-changing transitions (for a comprehensive review, see the Buras textbook [5]). The mass and lifetime eigenstates can be expressed as

$$|B_{s,\mathrm{L}}\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle\,, \qquad |B_{s,\mathrm{H}}\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$

(with $|p|^2 + |q|^2 = 1$), where L and H indices refer to light and heavy mass eigenstates (however note that the mass difference between two eigenstates is small compared to their masses). Taking into account CPT invariance and theoretical predictions indicating that the dominant contribution to mixing amplitudes is due to the exchange of top quark in box diagrams. Furthermore, using the well experimentally established approximation $\Gamma_{12} \ll M_{12}$, it can be shown that

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \approx \sqrt{\frac{M_{12}^*}{M_{12}}} \approx \frac{V_{ts}V_{tb}^*}{V_{ts}^*V_{tb}}\,,$$

where V_{ij} are elements of the CKM matrix. Within approximations one has $|\frac{q}{p}| = 1$ and $\Gamma(B_s \to \bar{B}_s) = \Gamma(\bar{B}_s \to B_s)$, thus there is no CP violation in mixing.

For the B_s meson, assuming that both B_s^0 and $\bar{B}_s^0$ can decay to the same CP eigenstate, $f_{\rm CP}$ with a single tree diagram governed by $b \to c + \bar{c}s$ transition, the ratio of amplitudes $A = A(B_s^0 \to f_{\rm CP})$ and $\bar{A} = A(\bar{B}_s^0 \to f_{\rm CP})$ is given by

$$\frac{\bar{A}}{A} = \eta_{\rm CP}\frac{V_{cs}^*V_{cb}}{V_{cs}V_{cb}^*}\,,$$

where $\eta_{\rm CP}$ is $f_{\rm CP}$ state CP-eigenvalue: ${\rm CP}|f_{\rm CP}\rangle = \eta_{\rm CP}|f_{\rm CP}\rangle$. In such a scenario, neglecting the oscillations $|\bar{A}/A| = 1$ and $\Gamma(B_s^0 \to f) = \Gamma(\bar{B}_s^0 \to \bar{f}\,)$, there is no CP violation in decays.

Taking into account direct $B_s \to f_{\rm CP}$ transitions and with $B_s \to \bar{B}_s \to f_{\rm CP}$ oscillations, one obtains interplay of two amplitudes, which may result in $\Gamma(B_s^0 \to f) \neq \Gamma(\bar{B}_s^0 \to \bar{f})$, so-called CP violation in interference. It is possible to measure the time-dependent asymmetry

$$a_{\rm CP} = \frac{\Gamma(\bar{B}_s^0(t) \to f_{\rm CP}) - \Gamma(B_s^0(t) \to f_{\rm CP})}{\Gamma(\bar{B}_s^0(t) \to f_{\rm CP}) + \Gamma\left(B_s^0(t) \to f_{\rm CP}\right)} \propto {\rm Im}\left(\frac{q}{p}\frac{\bar{A}}{A}\right)\sin\left(\Delta m_s t\right).$$

For the case of the $J/\psi\phi$ CP eigenstate,

$$\lambda = \frac{q}{p}\frac{\bar{A}}{A} = \eta_{\rm CP}\frac{V_{ts}V_{tb}^*}{V_{ts}^*V_{tb}}\frac{V_{cs}^*V_{cb}}{V_{cs}V_{cb}^*} = \eta_{\rm CP}\exp\left(-i\phi_s\right),$$

where $\phi_s = -2\beta_s$, $\beta_s = \arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$ — one of angles of the so-called "B_s unitary triangle" $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$.

The CMS $B_s \to J/\psi\phi(1020)$ analysis [6] is done with $95.6\,{\rm fb}^{-1}$ of 2017–2018 data and updates the previous study [7]. There are two triggers used in this analysis. The *muon tagging* (MT) trigger requires two muons from J/ψ decay and the additional muon intended to come from the associated b-quark decay. The second, *standard trigger* (ST), is a dimuon trigger with displaced J/ψ vertex compatible with the $\phi \to K^+K^-$ vertex. The additional offline selection requests a minimal proper time $ct > 60(100)\,\mu$m for

MT(ST) triggered events. The final signature can be reconstructed with high signal-to-background ratio, the example distribution of invariant mass ($\mu^+\mu^-K^+K^-$) and ct are shown in Fig. 1 (left and middle plot).

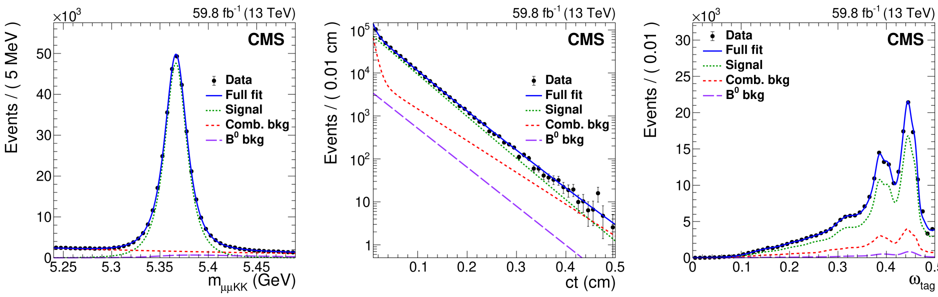

Fig. 1. 2018 data: invariant mass distribution for signal candidates (left), distribution of proper decay time ct (middle), and mistag probability for the ST trigger category (right).

For the CP measurements, it is necessary to establish the flavour of initially produced B_s^0 or $\bar{B}_s^0$ that evolves and later decays to the $J/\psi\phi$ state. That flavour cannot be established from the final state itself and a tagging is needed. For the purpose of the discussed analysis, the CMS has developed a novel flavour-tagging framework. It is composed of opposite-side or the same-side taggers. The opposite-side tagger takes advantage of the fact that in strong interactions, b–$\bar{b}$ pairs are produced and explores the decays not of the signal b quark that leads to $J/\psi\phi$ but of the other b quark. The opposite-side tagger can be a charge of muon, electron or jet from associated b quark. The same-side tagging explores the correlations of produced signal b flavour and particles produced during hadronization in its neighborhood. For tagged events, the mistag probability ω_{tag} (Fig. 1, right plot) is estimated per event basis using a dedicated deep neural network. This algorithm is developed using simulated data sample and calibrated using collected data.

Since the B_s is the spin-0 pseudoscalar which decays into spin-1 vector mesons J/ψ and $\phi(1020)$, the final state is a mixture of eigenstates. This causes additional experimental difficulties in separating CP-even and CP-odd amplitudes. To cope with that, the analysis is performed in the transversity basis [8] with the decay angles (θ_{T}, ψ_{T} and ϕ_{T}). The decay amplitude can be decomposed into polarization amplitudes, CP-even: A_0 — longitudinal, $A_{\parallel}$ — parallel, and CP-odd: $A_{\perp}$ — perpendicular, and the corresponding strong phases δ. The time-dependent and flavoured-tagged angular analysis allows us to disentangle CP final states. Furthermore, contributions from non-resonant $B_s \to \mu^+\mu^-K^+K^-$ and $B_s \to J/\psi f_0(980)$ decays are taken into account by introducing additional S-wave amplitude A_S.

As only the relative difference matters, taking into account the amplitudes normalization constraint, the event decay model depends on the following parameters: ϕ_s, $\Delta\Gamma_s$, Γ_s, Δm_s, $|\lambda|$, $|A_0|^2$, $|A_\perp|^2$, $\delta_\parallel, \delta_\perp, \delta_{\perp S}$. These parameters are extracted with a simultaneous unbinned multidimensional extended maximal likelihood fit using as input the following observables: $m_{\mu\mu KK}, ct, \sigma_{ct}, \cos\theta_\mathrm{T}, \cos\psi_\mathrm{T}, \phi_\mathrm{T}$, and ω_tag.

The CMS measurements are compatible with world-average results and, wherever available, theoretical predictions. The weak CP violating phase is measured to be $\phi_s = -73 \pm 23(\mathrm{stat.}) \pm 7(\mathrm{syst.})\,\mathrm{mrad}$, while $|\lambda| = 1.011 \pm 0.014 \pm 0.012$ is consistent with no direct CP violation ($|\lambda| = 1$). CMS measurements are similar in precision to those currently most precise obtained by the LHCb. The CMS Run 2 results combined with Run 1 $\sqrt{s} = 8$ TeV [9] result give $\phi_s = -74 \pm 23\,\mathrm{mrad}$ which is 3.2 standard deviations from 0, thus providing the first evidence for CP violation in this channel.

3. Search for CP violation in $D^0/\bar{D}^0$ decays

The CP violation in the D^0 sector is suppressed in the SM by the GIM mechanism and magnitude of CKM matrix elements. Thus, any significant CP violation measured therein may indicate a contribution from New Physics. The CMS experiment is measuring the CP violation by the time-integrated asymmetry in the $D^0/\bar{D}^0 \to K^0_\mathrm{S} K^0_\mathrm{S}$ channel [10] with $41.6\,\mathrm{fb}^{-1}$ of 2018 data. The asymmetry is defined as

$$A_\mathrm{CP}\left(K^0_\mathrm{S} K^0_\mathrm{S}\right) = \frac{\Gamma\left(D^0 \to K^0_\mathrm{S} K^0_\mathrm{S}\right) - \Gamma\left(\bar{D}^0 \to K^0_\mathrm{S} K^0_\mathrm{S}\right)}{\Gamma\left(D^0 \to K^0_\mathrm{S} K^0_\mathrm{S}\right) + \Gamma\left(\bar{D}^0 \to K^0_\mathrm{S} K^0_\mathrm{S}\right)} \,.$$

The theoretical predictions indicate similar amplitudes for the decay via the W-boson exchange and penguin diagrams, which may lead to a few percent CP violation in this channel.

There are several experimental difficulties. Since the final state is fully hadronic, it cannot be used to provide a trigger. Thus, collected events were triggered by a single-muon trigger with a transverse impact parameter intended to select $b \to c\mu X$ or $c \to s\mu X$ transitions. The flavour of $D^0/\bar{D}^0$ is established from the charge of pion from $D^{*\pm}$ decays ($D^{*+} \to D^0\pi^+$, $D^{*-} \to \bar{D}^0\pi^-$). Furthermore, the branching fraction in this channel is rather small, $(1.41 \pm 0.05) \times 10^{-4}$.

CMS does not measure the asymmetry directly but establishes it from the CP asymmetry difference ΔA_CP in the signal channel ($D^0 \to K^0_\mathrm{S} K^0_\mathrm{S}$) and reference non-CP-violating $D^0 \to K^0_\mathrm{S}\pi^+\pi^-$ channel, which is not CKM suppressed and where the asymmetry was measured previously to be consistent with zero. The reason is that in pp collisions, the D^{*+} and D^{*-} production cross sections may differ and some fake asymmetries may be induced by the detector geometry. Due to these effects, the target CP asymmetry may differ from the raw measurement: $A_{\rm CP} \approx A_{\rm CP}^{\rm raw} - A_{\rm CP}^{\rm prod} - A_{\rm CP}^{\rm det}$, where the initially measured "raw" asymmetry is an asymmetry between the number of reconstructed D^{*+} and D^{*-} events, $N(D^{*+} \to D^0\pi^+)$ and $(D^{*+} \to D^0\pi^+)$, for $D^0/\bar{D}^0$ reconstructed in the signal or reference channel. However, for both channels, the production and detector-induced asymmetries are the same, so $\Delta A_{\rm CP} = A_{\rm CP}(K_{\rm S}^0 K_{\rm S}^0) - A_{\rm CP}(K_{\rm S}^0\pi^+\pi^0) = A_{\rm CP}^{\rm raw}(K_{\rm S}^0 K_{\rm S}^0) - A_{\rm CP}^{\rm raw}(K_{\rm S}^0\pi^+\pi^0)$.

The event selection includes requirements that oppositely-charged pions form a common vertex. In the case of $K_{\rm S}^0 \to \pi^+\pi^-$, the invariant mass of two pions should be compatible with the mass of $K_{\rm S}^0$. Furthermore, for signal $K_{\rm S}^0$ $K_{\rm S}^0$ events and for the reference $K_{\rm S}^0\pi^+\pi^-$ channel, they should form a common vertex $(D^0/\bar{D}^0)$ and have an invariant mass compatible with D^0. The reconstructed D-meson with the flavour-tagging charged pion should form a common vertex (D^*) and point to the primary vertex. In Fig. 2, the invariant mass of $D^0\pi^+$ is shown (left plot) for the signal channel, $K_{\rm S}^0$ $K_{\rm S}^0$ mass for D^0 events (middle plot), and the invariant mass of $D^0\pi^+$ for the reference channel (right plot). Similar distributions are obtained for D^{*-} events. The measured by CMS raw asymmetries combined with the world average value of $A_{\rm CP}(K_{\rm S}^0\pi^+\pi^-)$ on the reference channel lead to the final CMS measurement of $A_{\rm CP}(K_{\rm S}^0 K_{\rm S}^0) = (6.2 \pm 3.0({\rm stat.}) \pm 0.2({\rm syst.}) \pm 0.8({\rm ref.}))\%$, where the last uncertainty is given by the reference channel. This is the first CP violation measurement by CMS in the charm sector.

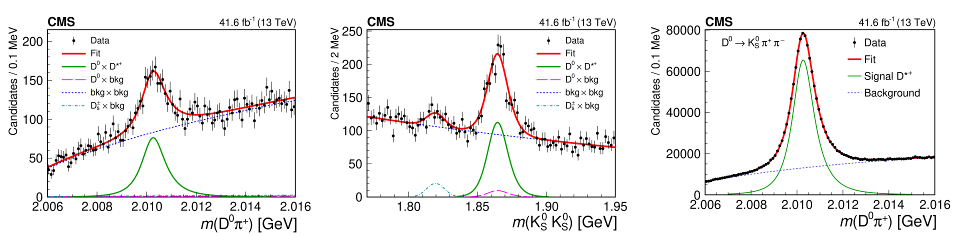

Fig. 2. Invariant mass distributions for D^{*+} events: $D^0\pi^+$ for the signal channel (left), $K_{\rm S}^0$ $K_{\rm S}^0$ for the signal channel (middle), and $D^0\pi^+$ for the reference channel (right).

4. Highlights on selection of other recent CMS measurements

4.1. Tests of LFU with $R_{J/\psi}$

The three leptons families have the same electroweak couplings in the SM, known as Lepton Flavour Universality. As there is no explanation by the underlying structure of the SM, this accidental symmetry is the subject of extensive tests. The universality is confirmed in leptonic decays of weak gauge bosons down to the per-mille level and is further tested in heavy-flavour decays, where some tensions with SM expectations are noticed. CMS provides a measurement of $R_{J/\psi} = \frac{\mathcal{B}(B^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B^+ \to J/\psi\mu^+\nu_\mu)}$, where $J/\psi \to \mu^+\mu^-$. The τ can be reconstructed using its muonic $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ decay [11] or its 3-prong $\tau^+ \to \pi^+\pi^-\pi^+(+\pi^0)\bar{\nu}_\tau$ decays [12]. The combined CMS result is $R_{J/\psi} = 0.49 \pm 0.25(\text{stat.}) \pm 0.09(\text{syst.})$, what is compatible with the SM prediction of 0.2582 ± 0.0038.

4.2. Effective $B_s \to J/\psi K^0_{\mathrm{S}}$ lifetime

The studies of CP violation with $B \to J/\psi K^0_{\mathrm{S}}$ provide precise measurements of the unitary triangle $\sin(2\beta)$ parameter. The understanding of small contributions from penguin diagrams becomes important. The study of d–s counterpart of $B \to J/\psi K^0_{\mathrm{S}}$, the $B_s \to J/\psi K^0_{\mathrm{S}}$ channel, where the penguin contribution is not suppressed, is a valuable test of the SM. Since B_s mesons evolve as mass eigenstates B_{H} or B_{L}, neglecting the small CP violation therein, the study of the decay time of flavour-untagged B_s decaying to $J/\psi(\to \mu^+\mu^-)K^0_{\mathrm{S}}(\to \pi^+\pi^-)$ provides information about the time evolution of B_{H}. The effective lifetime is determined by the measurement of the proper lifetime expectation value: $\tau(B_s \to J/\psi K^0_{\mathrm{S}}) = \frac{\int_0^\infty t\{\Gamma[B^0_s(t)\to J/\psi K^0_{\mathrm{S}}]+\Gamma[\bar{B}^0_s(t)\to J/\psi K^0_{\mathrm{S}}]\}\mathrm{d}t}{\int_0^\infty \{\Gamma[B^0_s(t)\to J/\psi K^0_{\mathrm{S}}]+\Gamma[\bar{B}^0_s(t)\to J/\psi K^0_{\mathrm{S}}]\}\mathrm{d}t}$, and is measured by CMS [13] to be $1.59 \pm 0.07(\text{stat.}) \pm 0.03(\text{syst.})\,\text{ps}$ which is the most precise measurement to date, in agreement with the SM prediction $1.62 \pm 0.02\,\text{ps}$.

4.3. Search for rare charm decays: $D^0 \to \mu^+\mu^-$

The $D^0 \to \mu^+\mu^-$ is an example of FCNC very rare decay, forbidden at tree level. The theoretical prediction for the branching fraction is about 3×10^{-13}. Due to the involvement of light quarks in the loop, the theoretical predictions are less precise for D than for B or K sector, but are still orders of magnitude below the current experimental sensitivity. Thus, any small effects related to the New Physics may lead to significant discrepancies with respect to the SM expectations. Although muons are easy to identify and can be measured precisely, the challenge for this analysis is to extract a signal in the bulk of background given by b, c semileptonic decays. To provide an additional constraint for event reconstruction, only the signal cascade $D^{*+} \to D^0\pi^+$ decays are considered. In the CMS analysis [14], an unbinned maximum likelihood method is used to extract the D^0 mass and mass difference between D^{*+} and D^0. The latter observable appears to be a powerful discriminator against combinatorial backgrounds. In order to gain maximal sensitivity, the analysis explores the latest soft low-mass dimuon triggers in Run 3 data. Based on $64.5\,\text{fb}^{-1}$, the upper limit is $\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.5 \times 10^{-9}$ at 95% C.L., which is the new strictest limit for this channel.

4.4. Rare $B/B_s \to \mu^+\mu^-$ decays

$B \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ are other rare decays that have been intensively studied by CMS [15–18]. These FCNC decays are further helicity and CKM suppressed, thus the channel is an ideal place to look for New Physics and to verify theoretical predictions. The measured [18] branching ratio $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = [3.83^{+0.38}_{-0.36}(\mathrm{stat.})^{+0.19}_{-0.16}(\mathrm{syst.})^{+0.14}_{-0.13}(f_s/f_u)] \times 10^{-9}$ and the limit $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-9}$ at 95% C.L. are consistent with recent theoretical predictions [19, 20].

5. Summary and perspectives

The multipurpose CMS experiment is well-suited to study heavy-flavour physics, resulting in many important measurements delivered by the CMS, including flagship analyses of $B_s \to J/\psi\phi(1020)$ and $B/B_s \to \mu^+\mu^-$. The presented measurements rely mostly on Run 2 data and their precision is usually dominated by statistical errors. The ongoing Run 3 is expected to end in the summer of 2026 and is projected to provide an additional 170 fb^{-1} of data on top of the already collected statistics, resulting in a total integrated luminosity of over 500 fb^{-1} delivered to CMS during the Phase-I LHC. This will improve the precision of the presented results and allow for further studies. The CMS is preparing for LHC Phase-II period, scheduled for the years 2030–2041. The upgrade of CMS data-taking system will allow to continue the heavy-flavour program. The perspectives are summarized in the CMS contribution to the European Particle Physics Strategy Update document [21].

This contribution was partially supported by the Ministry of Science and Higher Education, Poland, grant No. 2022/WK/14.

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