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Latest results on rare and very rare decays at LHCb(*)

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Summary. — This contribution presents the most recent results related to rare and very rare decays at the LHCb experiment. These results encompass the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decays, using data obtained from proton-proton collisions at a centre-of-mass energy of 13 TeV during the LHC Run 2 data-taking, corresponding to a total integrated luminosity of 5.4 fb^{-1}. Additionally, this contribution includes the measurement of the branching fraction ratio $\mathcal{B}(\phi \to \mu^+\mu^-)/\mathcal{B}(\phi \to \mathrm{e}^+\mathrm{e}^-)$ with charm meson decays and a comprehensive analysis of local and nonlocal amplitudes in the $B^0 \to K^{*0}\mu^+\mu^-$ decay.

1. – Introduction

Despite its remarkable accomplishments, the Standard Model (SM) continues to be an incomplete framework, leaving various unanswered questions in its wake. Many of its problems can be studied by exploring the flavour sector, delving into the properties and interactions of different particle flavours and the mixing between them. The Large Hadron Collider beauty (LHCb) experiment at CERN has proven to be an ideal setting for investigating flavour physics.

The LHCb detector [1, 2] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. Within LHCb, the rare and very rare decays search programs continue to push the understanding of particle physics by shedding light on the most elusive and intriguing processes involving hadrons.

In the next sections, new LHCb results on the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decays are presented, following the measurement of the branching fraction ratio $\mathcal{B}(\phi \to \mu^+\mu^-)/\mathcal{B}(\phi \to \mathrm{e}^+\mathrm{e}^-)$ with charm meson decays and a comprehensive analysis of local and nonlocal amplitudes in the $B^0 \to K^{*0}\mu^+\mu^-$ decay. The inclusion of charge-conjugated processes is implied throughout this contribution.

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2. – Observation of the rare decay $J/\psi \to \mu^+\mu^-\mu^+\mu^-$

The observation of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay with significance greatly exceeding the discovery threshold is reported by the LHCb experiment. The following results are obtained using proton-proton (pp) collision data collected at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1} [3]. A first observation of this decay was presented by the CMS collaboration [4].

The branching fraction is measured and the $J/\psi \to \mu^+\mu^-$ decay is chosen as normalisation mode. The analysis is performed on a prompt sample([1]), including J/ψ mesons coming from the primary pp interaction, and a secondary sample, composed of J/ψ mesons from the b-hadrons decays. The fit to the invariant-mass distribution of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ candidates is shown in fig. 1 (top), where the signal is observed in both samples with a significance $\gg 5\sigma$. The absolute branching fraction is found to be

$$\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = (11.3 \pm 1.0 \pm 0.5 \pm 0.1) \times 10^{-7}, \tag{1}$$

where the first uncertainty is statistical, the second is systematic, and the third is due to the uncertainty on $\mathcal{B}(J/\psi \to \mu^+\mu^-)$.

The result is consistent with the SM within 1.4σ and it is the most precise measurement to date. The dimuon mass distributions are shown in fig. 1 (bottom). They are found to be in agreement with the QED predictions but differ significantly from the phase-space model [5].

3. – Search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay

The first search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay with full final state reconstruction and the first search for this decay at low $q^2 = m_{\mu\mu}^2$ are presented by the LHCb experiment, using pp collisions collected at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1} [6]. A first upper limit was measured by the LHCb collaboration to be $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2 \times 10^{-9}$ at 95% C.L. with the process being a partially reconstructed background of the $B_s^0 \to \mu^+\mu^-$ decay [7].

The analysis is performed in three dimuon mass bins, as defined in table I, and the results are obtained with and without a veto around the $\phi(1020)$ mass. The $B_s^0 \to J/\psi(\to \mu^+\mu^-)\eta(\to \gamma\gamma)$ decay is chosen as normalisation channel while the $B_s^0 \to \phi(\to K^+K^-)\gamma$ decay is exploited as control mode.

A fit to the signal regions in the q^2 bins is performed and no significant signal is found. Upper limits on the lowest q^2 bin are set with and without the ϕ veto at

$$\begin{aligned} &\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.9(3.4) \times 10^{-8} (90 - 95\% C.L.), \\ &\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.5(2.8) \times 10^{-8} (90 - 95\% C.L.). \end{aligned} \tag{2}$$

The LHCb results and the theoretical predictions are shown in fig. 2

([1]) This category contains candidates whose decay-length significance (DLS) with respect to the primary vertex (PV) does not exceed three standard deviations.

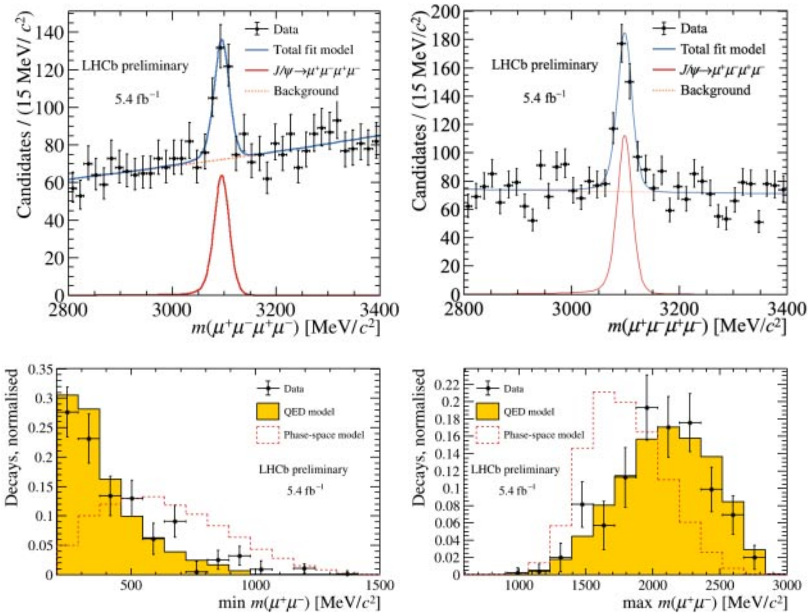

Fig. 1. – (Top) Invariant mass distributions for (left) prompt $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ candidates and (right) secondary $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ candidates. The results of the fit are overlaid. (Bottom) Dimuon mass distributions compared to the phase-space and QED models.

Table I. – *Mass range definition, predicted branching fraction and the expected fraction of signal yield in the different q^2 bins as calculated in* [8].

q^2 bin	I	II	III
q^2 [GeV^2/c^2]	[$4m_\mu^2$, 2.89]	[2.89, 8.29]	[15.37, $m_{B_s}^2$]
$m(\mu^+,\mu^-)$ [GeV/ c^2]	[$2m_\mu$, 1.70]	[1.70, 2.88]	[3.92, m_{B_s}]
$10^{10} \times \mathcal{B}(B_s \to \mu^+\mu^-\gamma)$	82 ± 15	2.54 ± 0.34	9.1 ± 1.1
Fraction of $B_s \to \mu^+\mu^-\gamma$	87%	2.7%	9.8%

4. – Measurement of the branching fraction ratio $\mathcal{B}(\phi \to \mu^+\mu^-)/\mathcal{B}(\phi \to \mathrm{e}^+\mathrm{e}^-)$ with charm meson decays

The branching fraction ratio $\mathcal{B}(\phi \to \mu^+\mu^-)/\mathcal{B}(\phi \to \mathrm{e}^+\mathrm{e}^-)$ is measured with $D^+ \to \pi^+\phi$ and $D_s^+ \to \pi^+\phi$ decays by the LHCb experiment, using pp collisions recorded at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1} [9]. The ratio is defined as

$$R_{\phi\pi}^{(s)} = \frac{\mathcal{B}\left(D_{(s)}^+ \to \pi^+\phi\,(\mu^+\mu^-)\right)}{\mathcal{B}\left(D_{(s)}^+ \to \pi^+\phi\,(e^+e^-)\right)} \Big/ \frac{\mathcal{B}\,(B^+ \to K^+ J/\psi\,(\to \mu^+\mu^-))}{\mathcal{B}\,(B^+ \to K^+ J/\psi\,(\to e^+e^-))}, \tag{3}$$

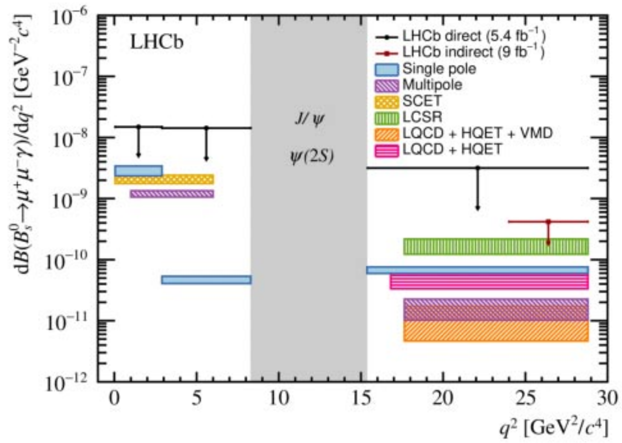

Fig. 2. – Upper limits on the branching fraction for the $B_s^0 \to \mu^+\mu^-\gamma$ decay and theoretical predictions.

normalised by the $B^+ \to K^+ J/\psi(\to \ell^+\ell^-)$ decay. The branching fraction ratio involving $D^+_{(s)}$ and the one with B^+ decays are expected to be unity, given that the $\phi(1020) \to \ell^+\ell^-$ and $J/\psi \to \ell^+\ell^-$ processes are dominated by the electromagnetic interaction.

The fit to the signal region in the muon and electron channels is shown in fig. 3.

The branching fraction ratio for the D^+ and D_s^+ decays and the combined result yields respectively

$$
\begin{aligned}
R^d_{\phi\pi} &= 1.026 \pm 0.020 \pm 0.056,\\
R^s_{\phi\pi} &= 1.017 \pm 0.013 \pm 0.051,\\
R_{\phi\pi} &= 1.022 \pm 0.012 \pm 0.048,
\end{aligned}
\tag{4}
$$

where the first uncertainty is statistical and the second is systematic.

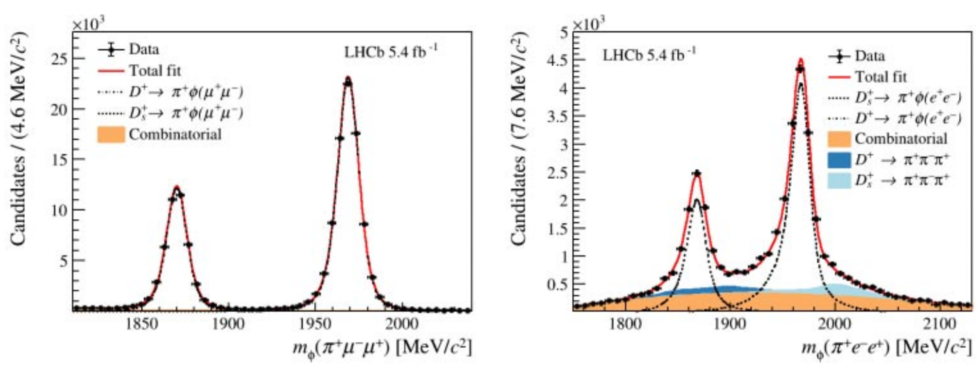

Fig. 3. – Fit to the signal region in the muon (left) and electron (right) channels.

This latter result is combined with the $\phi \to e^+e^-$ branching fraction, taken from the PDG [10], to measure the $\phi \to \mu^+\mu^-$ branching fraction

$$\mathcal{B}(\phi \to \mu^+\mu^-) = (3.045 \pm 0.049 \pm 0.148) \times 10^{-4}, \tag{5}$$

This is the most precise measurement of this branching fraction to date. The estimated ratios are compatible with the SM and LFU and are used to validate the correction strategies for the $B \to X\ell\ell$ rare decays, validating the correction and efficiencies at a q^2 value below the region of interest.

5. – Comprehensive analysis of local and nonlocal amplitudes in the $B^0 \to K^{*0}\mu^+\mu^-$ decay

LHCb performed a comprehensive study of the local and nonlocal amplitudes contributing to the $B^0 \to K^{*0}\mu^+\mu^-$ decay. The analysis is based on pp collision data recorded during the Run 1 and Run 2 periods, corresponding to an integrated luminosity of 8.4 fb^{-1} [11]. Previous LHCb measurements have investigated $B^0 \to K^{*0}\mu^+\mu^-$ decays with binned and unbinned methodologies using a dataset corresponding to an integrated luminosity of 4.7 fb^{-1} [12, 13].

The decay rate of the $B^0 \to K^{*0}\mu^+\mu^-$ P-wave process is described by transversity amplitudes that depend on the Wilson Coefficients (WCs) and $B \to K*$ form factors. The nonlocal model includes all vector resonances that couple to muons and contributions from $D^{(*)}\bar{D}^{(*)}$ and $\tau^+\tau^-$ loops [14]

$$\mathcal{C}_9^{\mathrm{eff},\lambda}\left(q^2\right) = \mathcal{C}_9^{\mu} + Y_{c\bar{c}}^{(0),\lambda} + Y_{c\bar{c}}^{1P,\lambda}\left(q^2\right) + Y_{\mathrm{light}}^{1P,\lambda}\left(q^2\right) + Y_{c\bar{c}}^{2P,\lambda}\left(q^2\right) + Y_{\tau\bar{\tau}}\left(q^2\right). \tag{6}$$

An angular analysis is performed using three decay angles $\Omega = (\cos\theta_K, \cos\theta_\ell, \phi)$ and q^2. The fit to the data leads to the following WCs

$$\begin{aligned} \mathcal{C}_9 &= 3.56 \pm 0.28 \pm 0.18 \\ \mathcal{C}_{10} &= -4.02 \pm 0.18 \pm 0.16 \\ \mathcal{C}_9' &= 0.28 \pm 0.41 \pm 0.12 \\ \mathcal{C}_{10}' &= -0.09 \pm 0.21 \pm 0.06 \\ \mathcal{C}_{9\tau} &= -(1.0 \pm 2.6 \pm 1.0) \times 10^2 \end{aligned} \tag{7}$$

The WC $\mathcal{C}_9$ exhibits a 2.1σ deviation from the SM expectation while $\mathcal{C}_{10}$, $\mathcal{C}_9'$ and $\mathcal{C}_{10}'$ are all in better agreement with the SM, with a global significance at the level of 1.5σ. The resulting angular observable P_5' is shown in fig. 4. The result indicate that the nonlocal contribution, if embedded in the decay amplitude model accounting for different sources as in eq. (6), is not sufficient to explain the deviations in the measured value of $\mathcal{C}_9$.

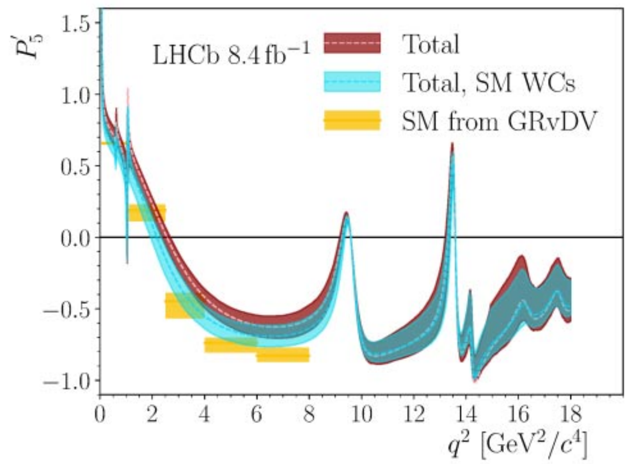

Fig. 4. – The P_5' angular observable as a function of q^2 obtained from the fit to data (red), compared to SM model predictions (yellow) and the fit result with the WC set to the SM values (cyan).

6. – Conclusions

In summary, recent results on rare and very rare decays at LHCb are reported. The observation of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay and the search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay are illustrated. Additionally, the measurement of the branching fraction ratio $\mathcal{B}(\phi \to \mu^+\mu^-)/\mathcal{B}(\phi \to e^+e^-)$ with charm meson decays and a comprehensive analysis of local and nonlocal amplitudes in the $B^0 \to K^{*0}\mu^+\mu^-$ decay are presented.

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