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1 # Rare decays of flavoured mesons at the LHC

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In absence of strong, direct signs of New Physics at the LHC, rare decays of heavy flavoured hadrons constitute an ideal laboratory for indirectly exploring energies beyond those of the LHC in order to look for deviations from the Standard Model. The main results regarding flavour changing neutral current transitions obtained at the LHC are presented here, with particular emphasis put on $b \to s$ transitions, in which tensions with the Standard Model have been observed.

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1. Introduction

Quarks and leptons in the Standard Model (SM) of particle physics are organized in *flavours*. Changes between flavours can only occur through the charged current weak interaction—that is, mediated by a W boson—and transitions between same-charge fermions must occur through second order, loop processes [1]. Since the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [2, 3], which governs transitions between flavours, is found to be approximately diagonal, generation-changing processes are suppressed. As a consequence, processes involving *flavour changing neutral currents* (FCNC) are predicted to be rare within the SM.

Observables related to these decays—branching fractions, CP asymmetries, kinematic distributions, among others—can be predicted in the SM with low theoretical uncertainty. Many models of New Physics (NP) predict noticeable differences in the measured quantities, making the study of rare decays of flavoured hadrons an ideal laboratory for studying physics Beyond the Standard Model. In particular, loop-mediated processes allow indirect access to quantum corrections from degrees of freedom at larger scales and provide excellent complementarity to direct searches of new phenomena.

FCNC transitions with $|\Delta B| = |\Delta S| = 1$ are described by a low energy effective field theory in the form of an Operator Product Expansion [4–6]:

$$\mathscr{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \frac{\alpha}{4\pi} \sum_i \left\{ C_i O_i + C_i' O_i' \right\}, \tag{1.1}$$

where G_F is the Fermi constant, V_{ij} are CKM matrix elements and α_e is the fine structure constant. The $O_i^{(\prime)}$ local operators take into account all possible left(right)-handed Lorentz structures and come with their corresponding Wilson coefficients $C_i^{(\prime)}$. The fact that the charged current interaction is left-handed implies that the Wilson coefficients corresponding to the right-handed O_i' operators are suppressed by $\mathscr{O}(m_s/m_b)$.

The most important operators for the study of rare $b \to s\gamma$, $b \to s\ell^+\ell^-$ and $b \to \ell^+\ell^-$ decays[1] are

$$\begin{aligned}
O_7^{(\prime)} &= \frac{m_b}{e} \bar{s}\sigma^{\mu\nu} P_{R(L)} b F_{\mu\nu}, \\
O_9^{(\prime)} &= \bar{s}\gamma_\mu P_{R(L)} b \bar{\ell}\gamma^\mu \ell, \\
O_{10}^{(\prime)} &= \bar{s}\gamma_\mu P_{R(L)} b \bar{\ell}\gamma^\mu \gamma_5 \ell, \\
O_S^{(\prime)} &= \bar{s} P_{R(L)} b \bar{\ell}\ell, \\
O_P^{(\prime)} &= \bar{s} P_{R(L)} b \bar{\ell}\gamma_5 \ell,
\end{aligned} \tag{1.2}$$

where $P_{L(R)}$ denotes the left(right)-handed chiral projector and $F_{\mu\nu}$ the electromagnetic field strength tensor. Radiative $b \to s\gamma$ transitions are controlled by the *photon penguin* operator $O_7^{(\prime)}$; semileptonic $b \to s\ell^+\ell^-$ processes receive contributions from $O_7^{(\prime)}$ and the *electroweak penguin* operators $O_9^{(\prime)}$ and $O_{10}^{(\prime)}$; and the fully leptonic $b \to \ell^+\ell^-$ decays are ruled by $O_{9,10}^{(\prime)}$ and the *scalar* and *pseudoscalar penguin* operators $O_S^{(\prime)}$ and $O_P^{(\prime)}$.

[1] $b \to d\gamma$ and $b \to d\ell^+\ell^-$ transitions are treated analogously, but are more suppressed due to the replacement of $V_{tb}V_{ts}^*$ by $V_{tb}V_{td}^*$ in Eq. 1.1.

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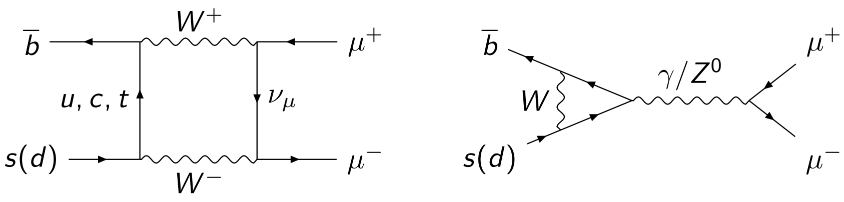

Figure 1: Feynman diagrams of the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays.

Effects from NP can be easily incorporated in Eq. 1.1 by adding an extra term for each operator

$$\mathscr{H}_{\text{eff}}^{\text{NP}} = \sum_i \frac{C_i^{\text{NP}}}{\Lambda_{\text{NP}}^2} O_i^{\text{NP}}, \tag{1.3}$$

where Λ_{NP} is the NP scale.

Measurements of different observables and decay modes can then be combined in *global fits* of Wilson coefficients and used to constrain NP contributions in FCNC. Hence, the strategy in the indirect searches for NP in rare decays is to perform many measurements, study their discrepancies and agreements with the SM through global fits, and try to solve the puzzle: how do we explain all these results in a single model, *i.e.*, which is the structure of the model beyond the SM?

The current situation in terms of rare decay results and the constraints they impose on NP are discussed in the next sections.

2. Fully leptonic $b \to \ell^+\ell^-$ decays

The dileptonic $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays are suppressed due to their loop only diagrams, the involved CKM matrix elements and the particular helicity structure of a pseudoscalar decaying into a pair of leptons (Fig. 1), and thus are very rare in the SM. More precisely, the time-integrated branching fractions are predicted to be [7]

$$\begin{aligned} \mathscr{B}(B_s^0 \to \mu^+\mu^-) &= (3.66 \pm 0.23) \times 10^{-9}, \\ \mathscr{B}(B^0 \to \mu^+\mu^-) &= (1.06 \pm 0.09) \times 10^{-10}, \end{aligned} \tag{2.1}$$

where the main uncertainties come from the knowledge of the decay constants and the CKM matrix elements. Several NP models including sizeable scalar or pseudoscalar operators can enhance the branching fractions of one or both the B_s^0 and the B^0 modes [8], as shown in Fig. 2.

Culminating a story started more than thirty years ago by the CLEO collaboration [9], the LHCb and CMS collaborations performed a combined analysis of the data collected during Run I, and reported the first observation of $B_s^0 \to \mu^+\mu^-$ with a significance of 6.2σ and an evidence for $B^0 \to \mu^+\mu^-$ at 3σ. The measured branching fractions [10]

$$\begin{aligned} \mathscr{B}(B_s^0 \to \mu^+\mu^-) &= (2.8^{+0.7}_{-0.6}) \times 10^{-9}, \\ \mathscr{B}(B^0 \to \mu^+\mu^-) &= (3.9^{+1.6}_{-1.4}) \times 10^{-10}, \end{aligned} \tag{2.2}$$

are compatible with the SM at 1.2σ and 2.2σ, respectively, as shown in Fig. 3. Despite this fact, these results are very important as they put strong constraints on NP scenarios [11].

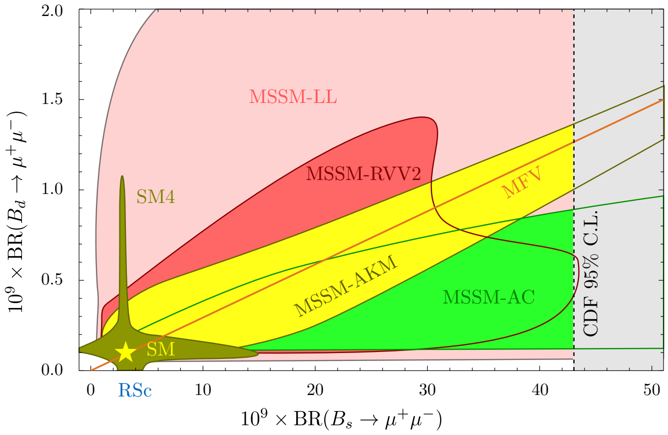

Figure 2: Correlation between the branching fractions of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ in several NP models [8]. The grey area was the one excluded experimentally before the LHC.

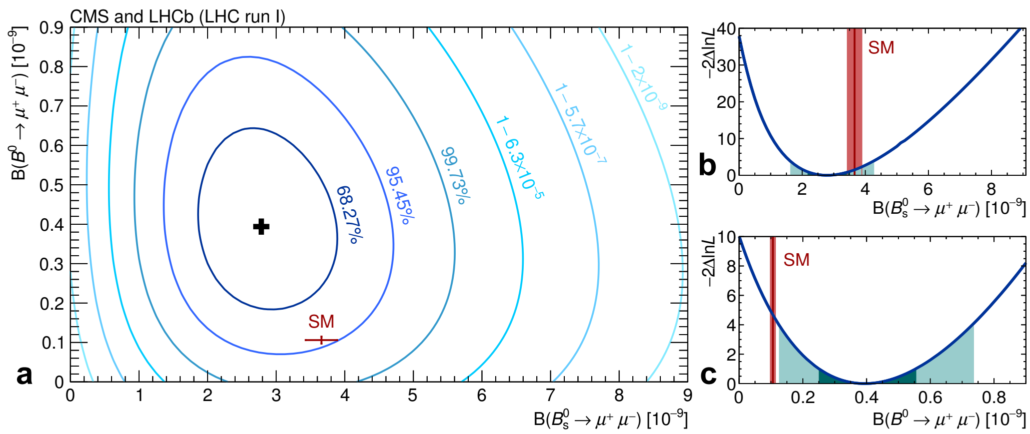

Figure 3: Likelihood contours in the $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ vs $\mathscr{B}(B^0 \to \mu^+\mu^-)$ plane (a), with variations of the $-2\Delta\ln\mathscr{L}$ test statistic for each of the modes shown in (b) and (c) [10].

The ATLAS collaboration has also found compatible results with CMS and LHCb [12]:

$$\begin{aligned} &\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}, \\ &\mathscr{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ at 95\% C.L..} \end{aligned} \tag{2.3}$$

3. Semileptonic $b \to s(d)\ell^+\ell^-$ decays

Semileptonic $b \to s(d)\ell^+\ell^-$ decays have been extensively studied at the LHC, where the signal yields of many modes are large enough for precision measurements. Results on differential branching fractions and angular distributions, as well as ratios between muonic and electronic decays, have provided many constraints on NP and have yielded interesting tensions with the SM, and will be discussed in the following.

Differential branching fractions The LHC measurements of the branching fractions of $B \to K\mu^+\mu^-$ [13], $B \to K^*\mu^+\mu^-$ [13–16], $B_s^0 \to \phi\mu^+\mu^-$ [17] and $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [18], performed in

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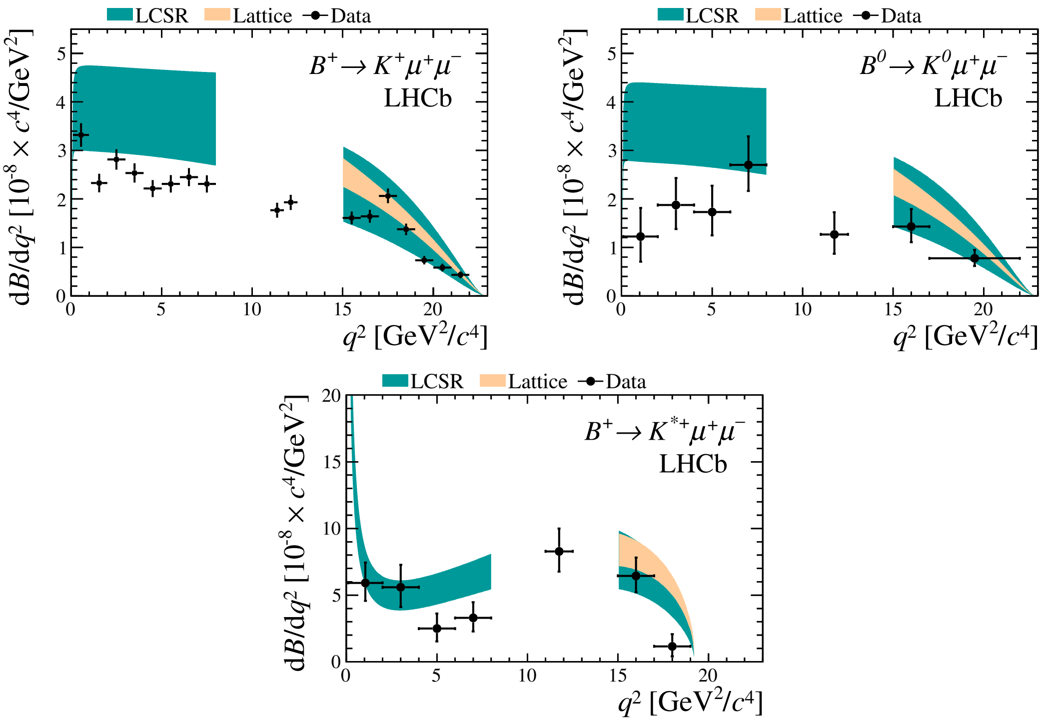

Figure 4: Differential branching fraction in bins of q^2 of the $B^+ \to K^+\mu^+\mu^-$ (top left), $B^0 \to K^0\mu^+\mu^-$ (top right) and $B^+ \to K^{*+}\mu^+\mu^-$ (bottom) decays as measured by LHCb [13]. Theoretical predictions obtained with LCSR [19] and lattice QCD [20, 21] calculations are shown for comparison.

bins of the dilepton mass squared (q^2), are much more precise than the corresponding theoretical predictions, sensitive to hadronic uncertainties in the form factors. These theoretical uncertainties, typically of the order of 30%, limit the sensitivity to NP, but are expected to improve in the future with progress from lattice QCD.

While some precision results from the large datasets collected by LHCb point towards lower values than the SM prediction in some cases, as shown in Figs. 4 and 5, the measurements are in general compatible with the SM prediction. The branching fractions of the $B^0 \to K^{*0}\mu^+\mu^-$, measured both by CMS [15, 16] and LHCb [14], and the $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decays, affected by large form factor uncertainties, don't show any deviations from the SM prediction, as shown in Figs. 6 and 7. The latest LHCb result on $B^0 \to K^{*0}\mu^+\mu^-$ [14] is the first one to include a measurement of the S-wave component in the $K^+\pi^-$ system, in contrast with previous studies, which considered it small and treated it as a systematic uncertainty. As the theory predictions are made for purely resonant P-wave, an accurate assessment of the S-wave fraction is critical, and, as can be seen on the left plot in Fig. 7, agreement between the measurement and the SM prediction from lattice QCD is good.

As a complement to the measurement of $b \to s\ell^+\ell^-$ transitions, $b \to d\ell^+\ell^-$ decays, suppressed by $|V_{td}/V_{ts}|^2$, allow to test whether NP—if any—is minimally flavour violating (MFV). The LHCb collaboration has the $B^+ \to \pi^+\mu^+\mu^-$ [26] and has found good compatibility with the SM predictions, as can be seen in Fig. 8, with the uncertainty in the result still dominated by statistics. Further improvements in this study, as well as observations of more $b \to d\ell^+\ell^-$ modes, are expected in the

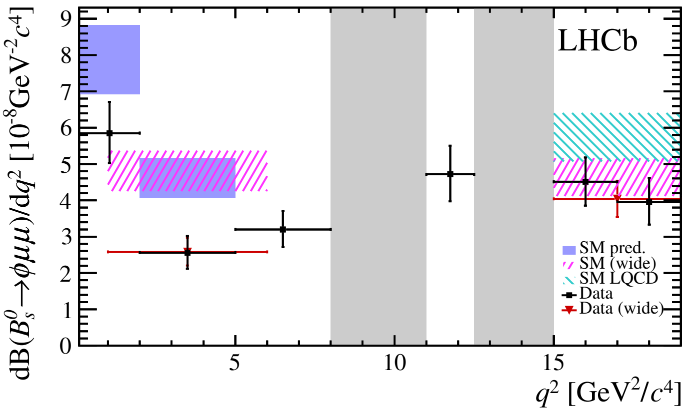

Figure 5: Differential branching fraction in bins of q^2 of the $B_s^0 \to \phi\mu^+\mu^-$ decay as measured by LHCb [17]. The SM prediction with LCSR [22, 23] is overlaid in purple and magenta for different q^2 binning schemes, while the LQCD prediction for high-q^2 is showed in cyan [21].

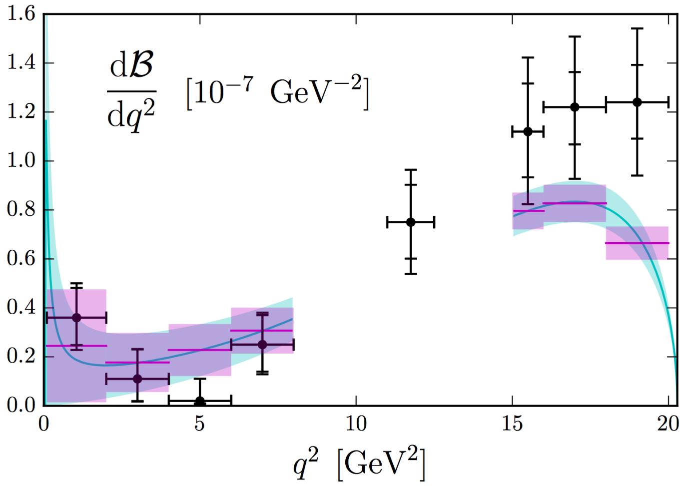

Figure 6: Differential branching fraction in bins of q^2 of the $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decay as measured by LHCb [18]. The plot, obtained from Ref. [24], shows an updated SM prediction from lattice QCD with respect to that included in Ref. [18].

coming years.

Angular distributions The angular distributions of $b \to s\ell^+\ell^-$ decays provide a large number of observables with different sensitivities to different types of NP. In particular, each of the observables arising from the angular distributions—or combinations thereof—has a different dependence on the Wilson coefficients—mainly $C_7^{(\prime)}$, $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$—and form factors.

The $B^0 \to K^{*0}\mu^+\mu^-$ angular distribution depends on three angles: the direction of the μ^+ (μ^-) with respect to the B^0 ($\bar{B}^0$) in the dimuon rest frame (θ_l), the direction of the kaon with respect to the B in the $K\pi$ system rest frame (θ_K), and the angle between the dimuon plane and the $K\pi$ system

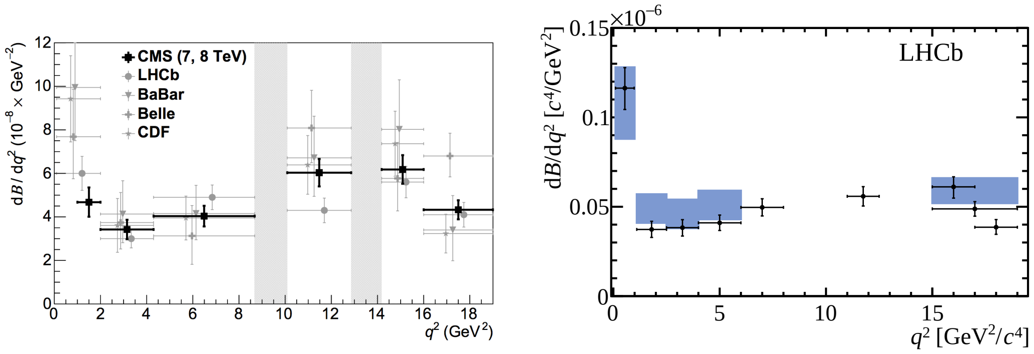

Figure 7: On the left, differential branching fraction in bins of q^2 of the $B^0 \to K^{*0}\mu^+\mu^-$ as measured by CMS, LHCb, the B factories and CDF, taken from Ref. [16]. On the right, latest differential branching fraction LHCb result in bins of q^2 of the purely resonant $B^0 \to K^{*0}\mu^+\mu^-$ decay, after measuring the S-wave component [14]; the overlaid theory prediction is from Refs. [23, 25].

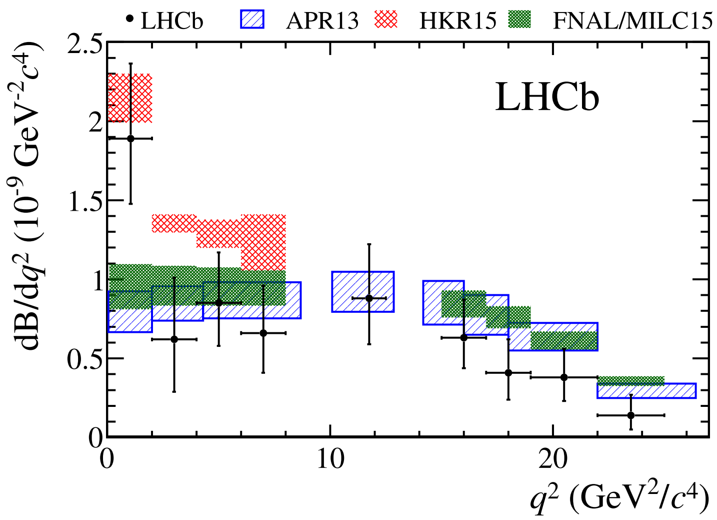

Figure 8: Differential branching fraction in bins of q^2 of the $B^+ \to \pi^+\mu^+\mu^-$ decay as measured by LHCb [26], compared with the APR13 [27], HKR15 [28] and lattice QCD FNAL/MILC15 [29] SM predictions.

plane (ϕ). The *CP* averaged differential decay rate in terms of these angles and q^2 can be written as:

$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K \\
&+\tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\
&-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\varphi \\
&+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\varphi + S_5\sin 2\theta_K\sin\theta_\ell\cos\varphi \\
&+\tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\varphi \\
&+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\varphi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\varphi\Big],
\end{aligned} \tag{3.1}
$$

where S_i, F_L (fraction of longitudinal polarization of the K^{*0}) and A_FB (forward-backward asymmetry

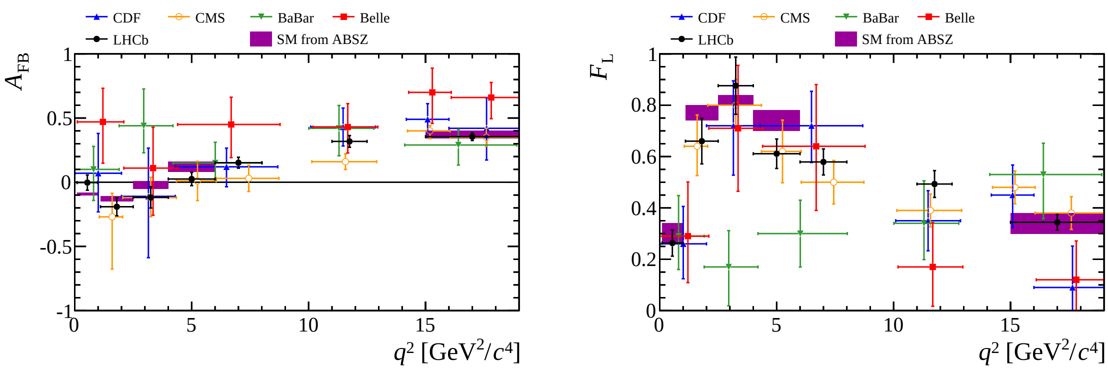

Figure 9: Forward-backward asymmetry of the dimuon system, A_{FB}, (left) and fraction of longitudinal polarization of the K^{*0} mesons, F_{L}, (right) in $B^0 \to K^{*0}\mu^+\mu^-$ decays in bins of q^2 as measured by the CDF, BaBar, Belle, CMS and LHCb collaborations, taken from Ref. [34]. The SM prediction is obtained from Ref. [23].

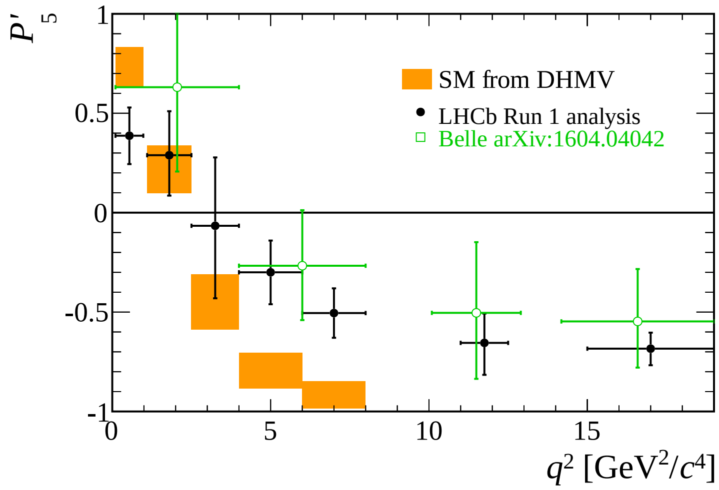

Figure 10: The optimized angular observable P'_5 in bins of q^2 as measured by LHCb and Belle, overlaid with the SM prediction from Ref. [36].

of the dilepton system) are the observables to be measured. It is possible to build theoretically cleaner observables by combining helicity amplitudes to exploit cancellations. In particular, the P'_i set of observables [30], such as

$$P'_5 = \frac{S_5}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}, \tag{3.2}$$

focuses on reducing the dependence on form factors, thus reducing the theoretical uncertainty.

While the measurements of the standard $B^0 \to K^{*0}\mu^+\mu^-$ angular observables performed by CDF [31], BaBar [32], Belle [33], CMS [16] and LHCb [34] have been found to be compatible with the SM (see Fig. 9), the optimized P'_5 observable, measured by LHCb and Belle [35], presents a large local discrepancy between data and the SM prediction, shown in Fig. 10, at the level of 3.7σ.

Measurements of simplified angular distributions in bins of q^2 carried out by LHCb in the $B^0_s \to \phi\mu^+\mu^-$ [17] and $\Lambda^0_b \to \Lambda\mu^+\mu^-$ [18] decays don't show large deviations from the SM, and

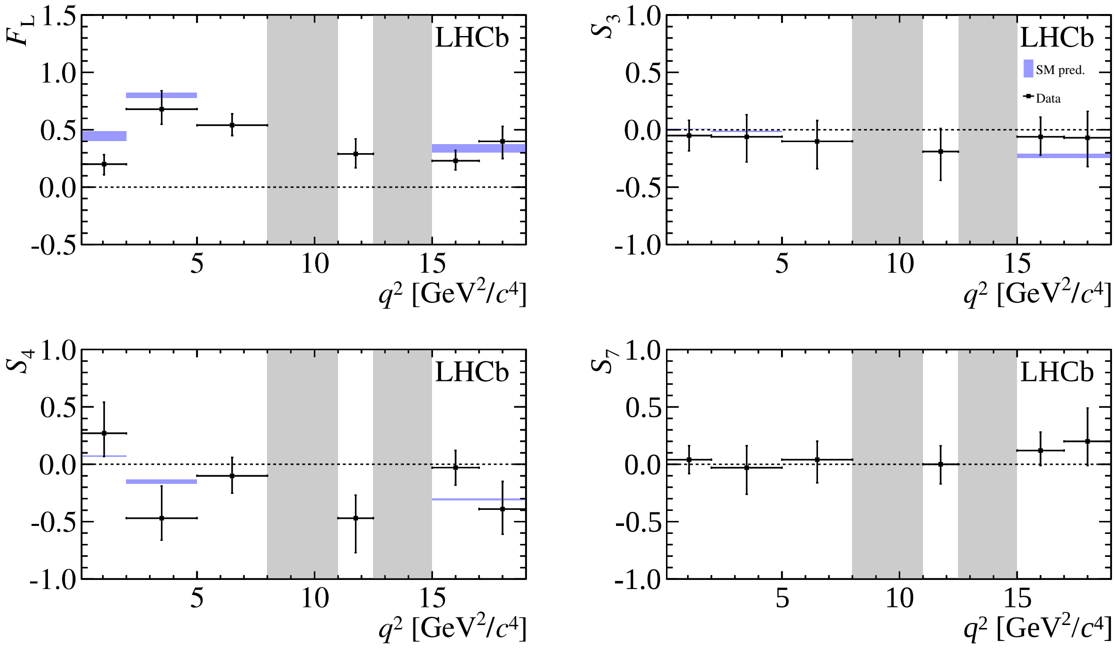

Figure 11: Fraction of longitudinal polarization of the K^{*0} mesons, F_L, S_3, S_4 and S_9 distributions in $B_s^0 \to \phi\mu^+\mu^-$ decays in bins of q^2 as measured by LHCb [17]. The SM prediction is obtained from Refs. [22, 23].

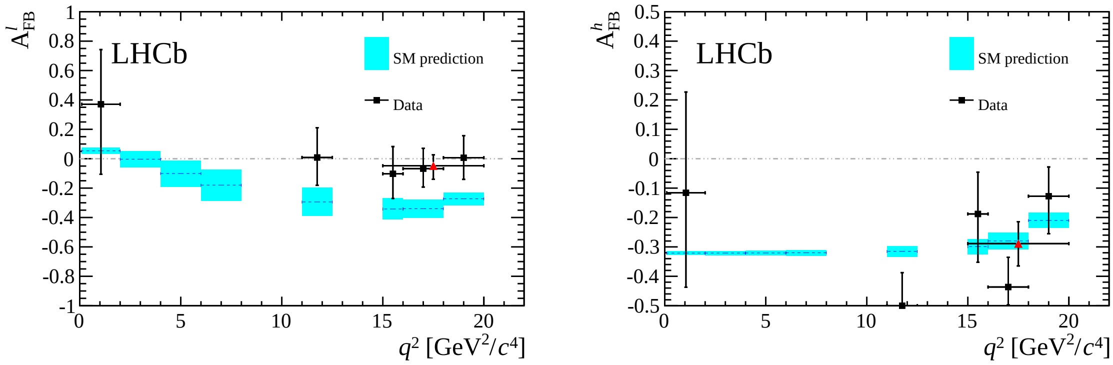

Figure 12: Forward-backward asymmetry of the dimuon system, A^l_{FB}, (left) and forward-backward asymmetry of the hadron system, A^h_{FB}, (right) in $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decays in bins of q^2 as measured by LHCb [18]. The SM prediction is obtained from Ref. [37].

can be seen in Figs. 11 and 12, respectively.

Additionally, the LHCb collaboration has studied the angular distribution of the $B^0 \to K^{*0}e^+e^-$ decay in the low-q^2 region [38], performing some angular transformations to reduce the number of angular observables on account for the limited signal yield. The obtained results,

$$\begin{aligned} F_{\mathrm{L}} &= \quad 0.16 \pm 0.06 \pm 0.03, \\ A_T^{\mathrm{Re}} &= \quad 0.10 \pm 0.18 \pm 0.05, \\ A_T^{(2)} &= -0.23 \pm 0.23 \pm 0.05, \\ A_T^{\mathrm{Im}} &= \quad 0.14 \pm 0.22 \pm 0.05, \end{aligned} \tag{3.3}$$

are compatible with the SM predictions [39,40] and help constrain the $C_7^{(\prime)}$ Wilson coefficient thanks to the low lepton mass.

Global fits With the wealth of measurements produced at the LHC, including some tensions with the SM predictions, it becomes possible to gain insight on possible NP contributions to the Wilson coefficients through the combination of these measurements, *i.e.*, performing global fits of $b \to s$ observables. Taking into account more than eighty observables from $b \to \ell^+\ell^-$, $b \to s(d)\ell^+\ell^-$ and $b \to s\gamma$ transitions, measured by six experiments, most global fits [41–44] prefer a negative NP contribution $C_9 \sim -1$, with other NP parameters consistent with zero, as shown in Fig. 13. While this destructive contribution would better accommodate the data by reducing the branching fraction of $b \to s(d)\mu^+\mu^-$ decays and modifing the angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$ to be more consistent with the P_5' measurements, it is worth noting that these fits are still compatible with the SM prediction at $3-4.6\sigma$.

Further measurements $b \to s\ell^+\ell^-$ transitions, in particular of angular observables, with the LHC Run II dataset, will be crucial in the clarification of the real nature of this tension—currently one of the most significant in flavour physics.

Lepton flavour universality Another interesting tension with the SM, complementary to those described above, arises from the studies of lepton flavour universality. In the SM, with the exception of the Higgs boson, particles couple equally to different lepton flavours. As a consequence, ratios of decay rates such as

$$R_K = \frac{\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{\mathscr{B}(B^+ \to K^+e^+e^-)}, \tag{3.4}$$

are expected to be very close to unity, save from very small Higgs penguin contributions and difference in phase space due to the lepton mass. The LHCb collaboration has measured R_K in the $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ range to be $0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$ [45], 2.6σ away from the SM prediction of $R_K = 1.0003 \pm 0.0001$ [46]. While the significance of this discrepancy is not enough to be considered even as evidence, the combined 4.0σ enhancement, shown in Fig. 14, of τ with respect to μ in tree-level $B^+ \to D^{(*)}\ell^+\nu_\ell$ decays observed by BaBar, Belle and LHCb [47], has prompted great theoretical interest in these types of measurements.

Interpretation While the results discussed so far are basically compatible with the SM picture, a pattern of NP seems to start emerging in flavour physics, with two different sets of anomalies in $b \to s$ transitions: angular distributions of $b \to s\ell^+\ell^-$ decays and lepton flavour universality violation. These point to a preference for sizable NP in vector leptonic couples and lepton non-universality, leaving room for the contribution of non-SM right-handed currents and, thus, a non-MFV flavour sector.

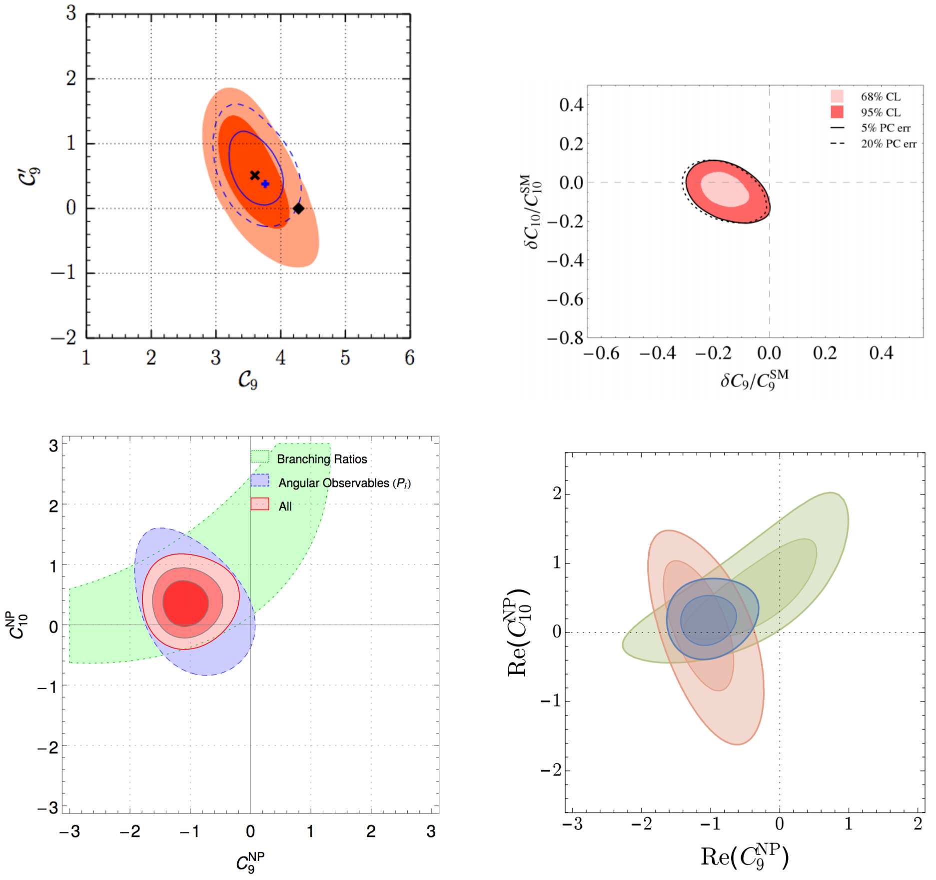

Figure 13: Results from the global fits to $b \to s$ observables: the top left plot, from Ref. [41], shows the $C_9 - C_9'$ plane, including NP contributions, with the SM prediction represented as a black dot; on the top right, taken from Ref. [42] one can see the one- and two-sigma contours of the relative NP contributions in C_9 and C_{10}, with the SM being at $(0,0)$; the bottom left plot, from Ref. [43], shows, in red, directly the contours of the value of the NP contributions in C_9 and C_{10}, highlighting as well the contributions coming only from angular observables (blue) and branching fractions (green); the bottom right plot, taken from Ref. [44], shows, in blue, the contours of the real values of the NP contributions in C_9 and C_{10}, also highlighting the contributions coming only from angular observables (red) and branching fractions (green).

Several types of models have been built to explain these hints of anomalies, including the existence Z' bosons [54, 55] or leptoquarks [56, 57], as well as the gauged $L_\tau - L_\mu$ SM extension [58, 59]. There exists, however, concern in the theory community about to which extent the long-distance contributions from $c\bar{c}$ resonances pollute the observables and how factorisation holds in this case [60]; it is hard to answer those concerns from first principles, so it is necessary to use models to try to measure the size of the $c\bar{c}$ pollution. While this could affect the uncertainty of the SM prediction in the case of angular observables, reducing the significance of the anomalies, measurements such as R_K are mostly free of this type of hadronic uncertainties.

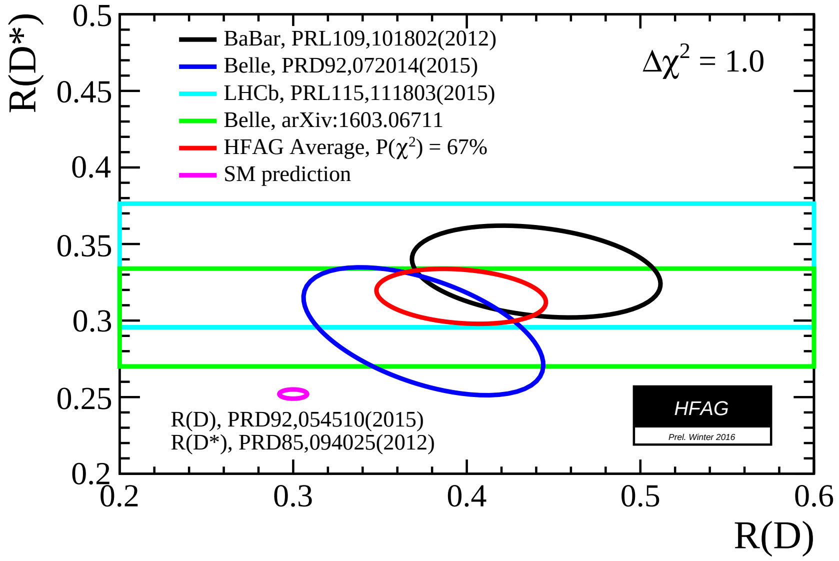

Figure 14: One sigma contour (red) of the combination of the BaBar (black) [48], Belle (green and dark blue) [49, 50] and LHCb (cyan) [51] results of the ratio of tauonic and muonic channels in $B^+ \to D\ell^+\nu_\ell$ and $B^+ \to D^*\ell^+\nu_\ell$ decays, taken from Ref. [47], with the SM prediction from Refs. [52, 53] overlaid in magenta.

4. Other rare decays

Rare charm decays The short-distance contributions to rare $c \to u$ transitions are very small due to the stronger GIM suppression ($m_b << m_t$), so rare charm decays are dominated by long-distance contributions.

While the current state of measurements, shown in Fig. 15, is still not close to the SM predictions, typically of $< \mathscr{O}(10^{-9})$, large improvements on the limits have been achieved at the LHC. In particular, LHCb has significantly improved the limits in the searches for the FCNC $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [61], $D^0 \to \mu^+\mu^-$ [62] and $D^+_{(s)} \to \pi^+\mu^+\mu^-$ [63] decays, and the LFV $D^0 \to e^\pm\mu^\mp$ decay [64]. Additionally, it has performed the first observation of the $D^0 \to K^-\pi^+\mu^+\mu^-$ decay in the ρ-ω region in $\mu^+\mu^-$ mass [65], necessary to understand the long-distance, tree-level contributions of vector resonances to the rare $D \to X\mu^+\mu^-$ mode.

Great improvements are expected in the Run II of the LHC thanks to the improved trigger strategy at LHCb—increasing the sample size by more than proportionally to the luminosity—with the potential for reaching even more interesting regions in the LHCb upgrade.

Rare strange decays While the LHC is not the main player in rare kaon physics, a very competitive result in the search for the $K^0_\mathrm{S} \to \mu^+\mu^-$ decay was published by the LHCb collaboration using data from 2011 [66]. The limit on the branching fraction of this decay,

$$\mathscr{B}(K^0_\mathrm{S} \to \mu^+\mu^-) < 9 \times 10^{-9} \text{ at 90\% C.L.,} \tag{4.1}$$

is still far from the SM prediction of $\mathscr{B}(K^0_\mathrm{S} \to \mu^+\mu^-) = (5.1 \pm 1.5) \times 10^{-12}$ [67], but the LHC has the potential of reaching the most interesting region of study, in which it will be possible to assess possible NP short-distance effects in the $K^0_\mathrm{L} \to \mu^+\mu^-$ decay.

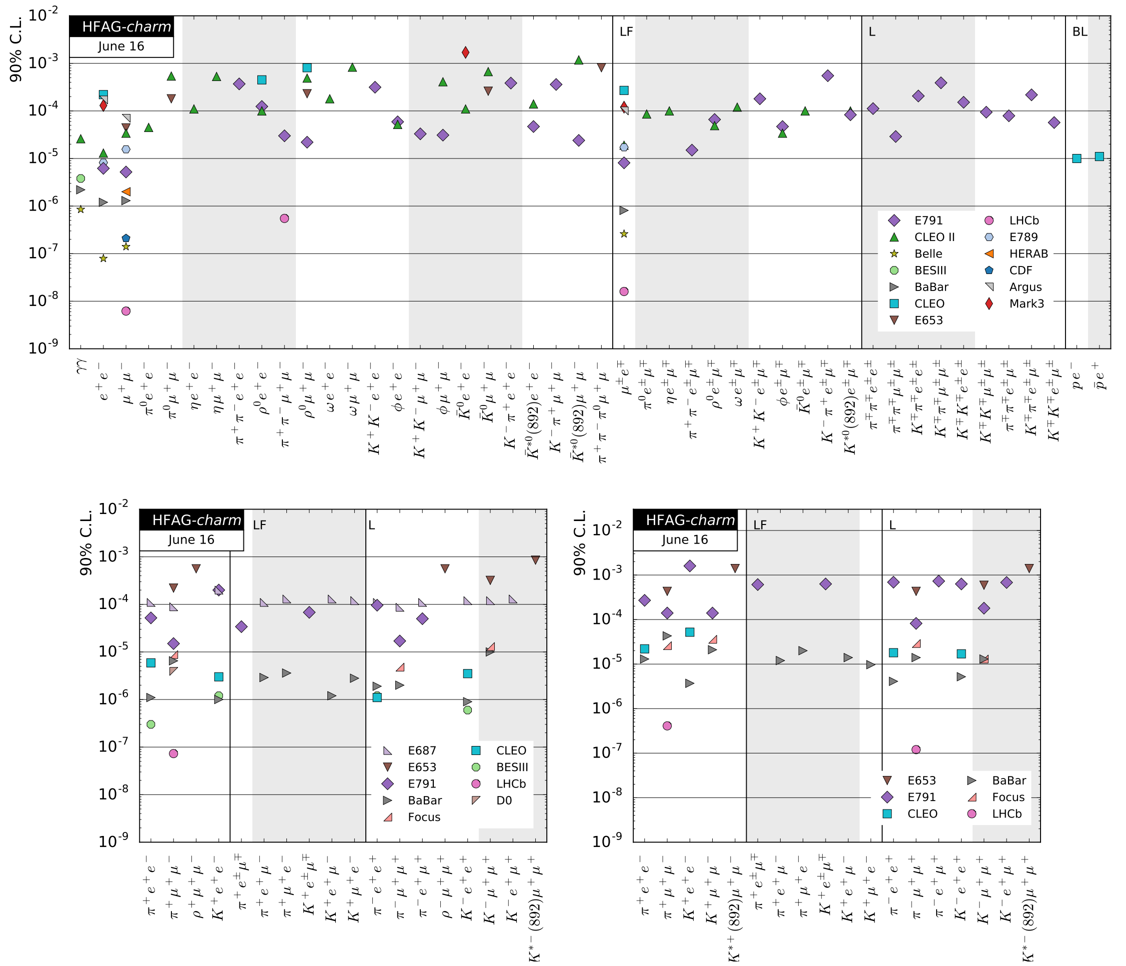

Figure 15: Status of rare charm searches for D^0 (top), D^+ (bottom left) and D_s^+ (bottom right) mesons [47].

The limit $K_S^0 \to \mu^+\mu^-$ on shows, nonetheless, the potential of LHCb to produce significant results in the following years—especially in its Upgrade phase—such as the study of the $\Sigma^+ \to p\mu^+\mu^-$ decay to assess the HyperCP anomaly [68], the update of the limit $K_S^0 \to \mu^+\mu^-$ with the full Run I dataset, and the exploration of further modes, including those with electrons in their final state. These all will contribute to the exciting prospects from non-LHC experiments: NA62 took its first data in 2015 and is currently getting ready for its 2016 run, while KOTO is expecting to reach SM sensitivity in the search for the $K_L^0 \to \pi^0\nu\nu$ decay by 2018.

Hidden sector The $b \to s$ penguin decay is also an excellent place to search for low-mass hidden sector particles, which can mix with the Higgs boson and then decay in SM final states. The LHCb collaboration has performed a search for hidden-sector bosons in $B^0 \to K^{*0}\chi(\to \mu^+\mu^-)$ decays allowing—but not requiring—non zero lifetime of the $\mu^+\mu^-$ system [69]. The search at different lifetimes, covering prompt and displaced $\mu^+\mu^-$ vertices and shown in Fig.16, found no significant signal and allowed both to set model-independent limits and to constrain specific models, such as the ones described in Refs. [70–73].

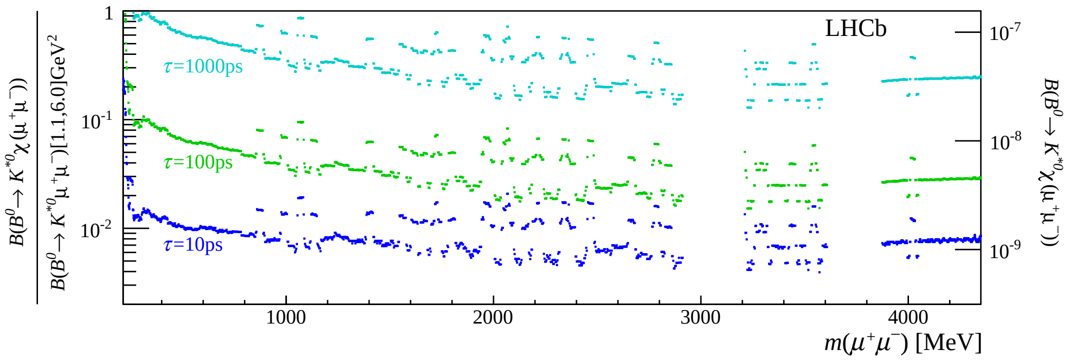

Figure 16: Upper limit at 95% C.L. for the $B^0 \to K^{*0}\chi(\to \mu^+\mu^-)$ decay as a function of the $\mu^+\mu^-$ mass, obtained at different lifetimes of the $\mu^+\mu^-$ system [69].

5. Conclusions

Rare flavoured decay observables place strong constraints on many NP models, allowing to probe higher energies than direct searches due to the fact that they are forbidden at tree-level in the SM. A large number of analyses performed using data collected during Run I of the LHC have lead to substantial improvement in the precision of several key observables. Results like the observation of the $B_s^0 \to \mu^+\mu^-$ decay or the study of angular observables in $B^0 \to K^{*0}\mu^+\mu^-$, while largely consistent with the SM, have given rise to interesting tensions with the SM expectations.

While there is not significant NP evidence from a single measurement, global fits to rare decays observables point to a pattern that favours the existence of NP. In this situation, it is necessary to continue improving the precision and to add measurements, both of new, more sensitive observables, and of new decay modes. An effort in the theory side, especially in the reduction of uncertainties due to hadronic effects, will also be needed.

In a nutshell, the main goal in the next few years will be to try to confirm these tensions of the SM, find the first evidences of NP and then study their features to determine which models are favoured by the data.

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