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Study of the measurement of the ratio $\mathcal{R}(D_s^*)$ at LHCb

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Summary. — The semileptonic b hadron decays with a heavy lepton are sensitive to non Standard Model couplings between quarks and leptons. The B-Factories and LHCb have previously performed various measurements of the observable $\mathcal{R}(D^{(*)})$. A global average of these measurements shows a discrepancy with the Standard Model expectations, which is above 3 sigma. The status of the analysis of $\mathcal{R}(D_s^*)$, exploiting the large amount of B_s^0 mesons collected by LHCb, is presented. The study of B_s^0 mesons provides a crucial cross-check of the existing measures, mostly based on B^+ and B^0. The treatment of some of the most important systematics to these decays will be discussed in detail.

1. – Introduction

In the mathematical formulation of the Standard Model of Particle Physics (SM), it is assumed that the weak coupling strengths of leptons are independent of their flavour. Any deviation from this should be only due to the mass difference between the three particles [1]. This is an interesting property to put under stringent test: Lepton Flavour Universality (LFU) violation would be a clear indication of New Physics (NP) processes at play. Several LFU testing observables have been measured, most notably ratios of branching fractions $\mathcal{R}(H_c) = \mathcal{B}(H_b \to H_c \ell \nu_\ell)/\mathcal{B}(H_b \to H_c \ell^{'} \nu_{\ell'})$. These compare the decay rates of a b hadron H_b into a c hadron H_c and two lepton-neutrino pairs of different flavour $\ell^{(')}\nu_{\ell^{(')}}$. At the moment, there is a standing discrepancy between the combined average of the measured values of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ and the corresponding SM prediction, at around 3.3 standard deviations [2]. Two measurements involving B hadrons other than the $B^{0/+}$, $\mathcal{R}(J/\psi)$ [3] and $\mathcal{R}(\Lambda_c)$ [4] show a less significant deviation. The overall experimental picture is still not clear, as more data and an enriched set of observables are needed to fully understand the nature of this statistical tension.

In this article, the ongoing study of the ratio $\mathcal{R}(D_s^*)$ by LHCb will be introduced. It is defined as $\mathcal{R}(D_s^*) = \mathcal{B}(B_s^0 \to D_s^{*-}\tau^+\nu_\tau)/\mathcal{B}(B_s^0 \to D_s^{*-}\mu^+\nu_\mu)$, where the tauonic mode is referred to as the signal mode, and the muonic mode is the normalisation mode; it has never been measured before. The motivations for this study, the experimental methods employed and the expected results will be discussed.

2. – Motivations for study

Though produced at a lower rate than their non-strange counterparts, which is about a quarter of the B^0 rate [5] for a center-of-mass energy of 13 TeV at LHCb, there are several advantages in studying the decays of B_s^0 mesons; these advantages are both on the theoretical and experimental side. Firstly, when modelling the behaviour of the bound state of two quarks composing the B meson, the numerical methods used to compute the theoretical values for the $\mathcal{R}$ ratios, generally benefit from the heavier s quark.

From the experimental point of view, the main advantage over non-strange B mesons decays comes from the spectroscopical properties of the D_s excited states, which will be generally referred to as D_s^{**}. The majority of the excited states of the D_s will decay strongly to the final states $D^{(*)}K$, and thus leading to a smaller contamination to the signal D_s^{*+} due to D_s^{**} feed-down. Overall, the physical background due to higher excitations is expected to be less intense than in its non-strange counterpart, and this makes a strong experimental argument for the study of semi-leptonic decays of strange B mesons in the context of LFU.

3. – Methods

3·1. *Choice of channels and selection strategy.* – The relevant channels for this study are the signal channel $B_s^0 \to D_s^{*-}\tau^+\nu_\tau$, and the normalisation channel $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ (charge-conjugated processes are implicit throughout this article). The τ is reconstructed in its leptonic decay $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$, which leads to the same visible final state in the detector for both channels, $D_s^{*-}\mu^+$. This works as an advantage to the analysis, as many reconstruction effects and systematic uncertainties are effectively cancelled out when measuring the ratio of branching fractions $\mathcal{R}(D_s^*)$.

The excited D_s meson reconstruction follows from the selection strategy reported in ref. [6]; a summary of it follows. The signal decay chain is $D_s^{*+} \to D_s^+\gamma$, with $D_s^+ \to K^-K^+\pi^+$. To reduce the combinatorial background for the selected $K^-K^+\pi^+$ candidates, cuts are applied in the D_s^+ Dalitz plane, namely that either the invariant mass $m(K^-K^+)$ lies in a narrow window around the ϕ resonant state, or that $m(K^-\pi^+)$ lies near the K^{*0} resonance. Then, to obtain a D_s^{*+} candidate, the selection strategy looks for a soft photon that lies in a Lorentz-invariant cone around the D_s^+ flight direction: for a photon to be compatible, its difference in pseudo-rapidity $\Delta\eta$ and azimuthal angle $\Delta\phi$ with the candidate meson must satisfy the relation $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$. If more than one photon is found to be compatible, the one with the highest transverse momentum is selected.

The muon candidate has only minimum requirements, as not to bias the selected sample towards tauonic or muonic decays. The candidate track is required to be originating from a secondary vertex compatible with the decay vertex of the excited D_s meson.

3·2. *Background contamination.* – A number of additional backgrounds will pass the aforementioned selection strategy. Firstly, one must consider the feed-down decays of higher D_s excited states; only two states are below the $D^{(*)}K$ mass threshold, the $D_{s0}^{*+}(2317)$ and $D_{s1}^{+}(2460)$ [7]. Additionally, doubly-charmed decays of B hadrons can pass the selection. These are decays of type $H_b \to D_s^{*-}H_c$, where the signal D_s^* meson is accompanied by another charmed hadron which then decays semileptonically $H_c \to \ell\nu_\ell X$. Requiring an isolated muon track, *i.e.*, that it only shares a decay vertex with the D_s^- candidate, can help in reducing this kind of background. Finally, because the PID per-

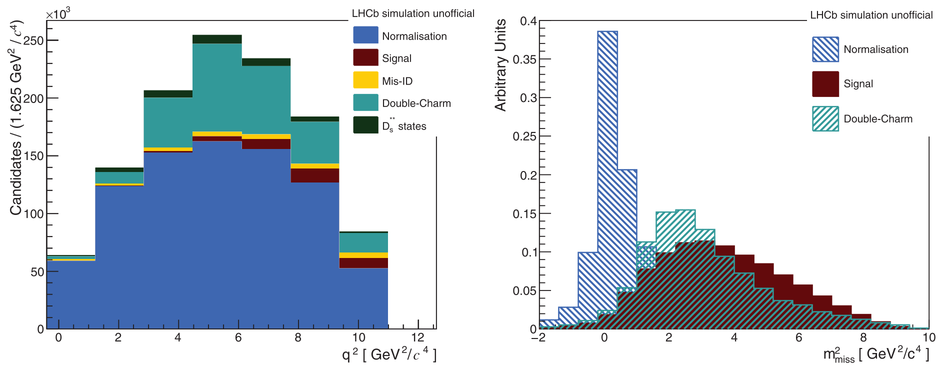

Fig. 1. – Left: expected q^2 distributions of signal, normalisation, and background components, for $6\,\text{fb}^{-1}$ of LHCb data collected at $\sqrt{s} = 13\,\text{TeV}$. The legend reports them in order of appearance. Right: expected m^2_{miss} distribution of signal, normalisation and the background due to double-charmed decays of B hadrons.

formance of LHCb is not 100% efficient, it is possible for other long-lived particles, such as pions and kaons, to be mis-identified as a candidate muon. This allows decays of type $H_b \to D_s^{*-}h^+X$ to pass the selection, where h is any long-lived particle other than a muon.

The signal, normalisation, and background components are separated in a three-dimensional fit to the following variables: the muon's energy in the B_s^0 rest-frame, E^*_μ; the missing invariant mass squared, *i.e.*, the neutrinos' invariant mass, m^2_{miss}; the squared four-momentum transferred to the lepton pair $\mu\nu$, q^2. These are reconstructed approximating the B_s^0 momentum along the beam axis with $(p_B)_z = (m_B/m_{visible})(p_{visible})_z$, where m_B is the known B meson mass, and $m_{visible}$ and $p_{visible}$ are the mass and momentum of the visible final state $D_s^{*-}\mu^+$, respectively. Figure 1 shows the separation between the signal, normalisation, and the largest expected background, in m^2_{miss}.

4. – Prospects and discussion

The selected sample is expected to be dominated by the normalisation channel. The signal channel will be reduced in statistics because of both the $\tau \to \mu\nu_\mu\nu_\tau$ branching fraction (which gives a factor of around 0.174 [7]) and the expected relative fraction to the muonic mode $\mathcal{R}(D_s^*) \approx 0.249$; overall, the signal is expected to have a yield of approximately 4% relative to the normalisation channel. The dominant background component will be the doubly-charmed decays, which are expected to add up to a yield of 38% relative to the normalisation. Figure 1 shows the expected q^2 distributions of all components for $6\,\text{fb}^{-1}$ of LHCb data, and table I reports the corresponding yields.

Using the $6\,\text{fb}^{-1}$ of data collected in the 2016–2018 period by LHCb, the absolute statistical error on $\mathcal{R}(D_s^*)$ is expected to be around 0.02. When compared with the expected error on $\mathcal{R}(D^*)$ of 0.013, using the same dataset, some factors have to be taken into consideration: first, the reduced B_s^0 production rate; then, while the D^* decay chain contains only charged particles, the more challenging photon reconstruction from $D_s^{*+} \to D_s^+\gamma$ lowers the overall signal efficiency.

In the most recent measurement of $\mathcal{R}(D^*)$ performed by LHCb [8], the two sources of systematic uncertainty were reported as most impactful: the limited simulated sample

Table I. – *Expected yields of the signal, normalisation, and various background components.*

Component	Signal	Normalisation	Mis-ID	Double-Charm	D_s^{**} States
Exp. yield	36200	831500	22800	244000	32200

size, accounting for an uncertainty of 0.02; the modelling of the mis-identified hadron background component, with an uncertainty of 0.016. Improvements have been brought forward to tackle these sources and possibly reduce their relative contribution to the total uncertainty.

New fast-simulation techniques have been developed in recent years, most notably ReDecay [9]. This approach results in increases in sample simulation speeds by an order of magnitude, thus allowing for simulated samples with much higher statistics without having to increase computing power. It is expected that the systematic uncertainty on $\mathcal{R}(D_s^*)$ due to Monte Carlo sample sizes will be reduced to around 0.008, thus becoming a sub-dominant source.

The mis-identification (mis-ID) probability of long-lived hadrons into muons is modelled in LHCb with data-driven methods, using specific control samples [10]. For pions and kaons, which are expected to be the biggest contributors, the control decay channel is $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$. In this specific case, however, there is an added contamination in the control samples due to decays-in-flight $\pi, K \to \mu\nu_\mu$. A new model for the distribution of the reconstructed D^0 mass was developed to better account for this, and this should in turn give a more accurate yield estimate for the mis-ID background. It will be possible to constrain the mis-ID background yield in the final fit, and thus reduce its contribution to the uncertainty on $\mathcal{R}(D_s^*)$; however, at this stage, it is not clear what the effect of the new method employed will be on the systematic uncertainty of this source. Nonetheless, this source is still expected to be a major contributor to uncertainty.

The analysis of $\mathcal{R}(D_s^*)$ outlined here is promising and LHCb is expected to release a measurement using the full dataset collected in the 2011-2018 period. This will be the first measurement using the B_s^0 mesons, and will be affected by different sources of backgrounds and systematics, providing a new environment in which to test Lepton Flavour Universality. The results will add crucial input in understanding the current experimental landscape, expanding on the existing measurements of other LFU testing observables.

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