PROCEEDINGS OF SCIENCE

Experimental mini-review on $R(D)$ and $R(D^*)$ measurements at LHCb

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The large cross section for the production of b quark pairs at the LHC and the large boost of the resulting b-hadrons, combined to the excellent vertexing capabilities of the LHCb detector, enable precise measurements of semi-tauonic decays in an hadronic environment. By using a data sample of pp collisions, corresponding to $3 fb^{-1}$ integrated luminosity, LHCb has measured the ratio $R(D^*)$ of branching fractions for the $B^0 \to D^{*-}\tau^+\nu_\tau$ and $B^0 \to D^{*-}\mu^+\nu_\mu$ decays. The result $R(D^*) = 0.336 \pm 0.027 \pm 0.030$ is in tension with the Standard Model prediction at the 2σ level and, when combined with other measurements from the B Factories on decays with D and D^* mesons in the final states, increases the discrepancy with the Standard Model at the 4σ level. In this review, the LHCb measurement is described and an outlook on other possible studies in the domain of semitauonic decays of b-hadrons is given.

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1. Introduction

In the Standard Model (SM), semi-tauonic decays of b-hadrons are mediated by a single W boson. Given that the charged electroweak coupling does not depend on the lepton family, any difference between semileptonic decay rates with different lepton species is due in the SM to phase space only. A test of lepton universality in semileptonic decays of b-hadrons is therefore a very good probe of SM extensions with mass-dependent couplings, *e.g.* models with an enlarged Higgs sector or leptoquarks.

In semitauonic decays of b-hadrons, measurements of branching fractions relative to decays with lighter lepton families are particularly clean, given that many theoretical and experimental uncertainties cancel in the ratio. Indeed, SM calculations for decays involving D and D^* mesons have reached a precision at the percent level [1, 2], while experimental determinations range in the 5%-10% level of precision [3].

The interest in these decays has recently increased. The results from Babar and Belle, reviewed in [4], together with the LHCb measurement [5] described in Sec. 2, are consistently higher and average at about 4σ from the SM predictions. It is therefore mandatory to perform more measurements, by using other b-hadron decays but also other observables. The prospects for LHCb measurements in this area are reviewed in Sections 3 and 4.

The LHCb detector is a forward spectrometer that, due to its large acceptance ($2 < \eta < 5$), low trigger thresholds, precise vertexing and efficient particle identification, is optimised for heavy flavour physics at the LHC. The experiment runs at a constant luminosity of $4 \times 10^{32} cm^{-2} s^{-1}$, with an average number of collision per beam crossing $< \mu > \approx 1.7$, four times the design value. At the LHC, b-hadrons are produced in pairs mostly in the forward (or backward) direction and have a large boost which results in flight lenghts of the order of one centimeter. The large production cross section, about $300 mb$ at $\sqrt{s} = 7$ TeV and almost double at 13 TeV, and the excellent performance of the LHCb detector, allow to isolate large samples of b-hadron decays with a favourable signal-to-background ratio.

Semileptonic decays of b-hadrons at hadron colliders present several challenges. First of all, such decays are kinematically unconstrained, due to the presence of a neutrino in the final state, and up to three neutrinos in semi-tauonic decays. However, the large boost of b-hadrons at the LHC and the excellent vertex capabilities of LHCb allow to reconstruct the direction of the b-hadron and reconstruct its semileptonic decay with a reasonable accuracy on the kinematical variables of interest. Background contamination is mostly due to partially reconstructed B decays with additional (un)reconstructed charged and neutral particles originating from either the same or the accompanying b-hadron decay. The dominant contributions to this background result from feed-down in semileptonic decays involving excited charm hadrons mesons and decays with two charm mesons in the final state. In most cases, these background can be studied and suppressed by using data control samples and isolation techniques, where a veto can be built by looking at charged particles and/or neutral energy in the calorimeters close to the signal candidate.

2. Measurement of $R(D^*)$ with leptonic τ decays

A measurement of $R(D^*)$ by using the $\tau \to \mu \nu \bar{\nu}$ decay and the integrated luminosity collected in Run I was published by LHCb in 2015 [5]. In this measurement, the particles in the final state are the same for both the signal ($B \to D^{(*)}\tau\nu_\tau$) and normalization ($B \to D^{(*)}\mu\nu_\mu$) modes, thereby allowing the cancellation, up to second order effects, of systematic uncertainties due to *e.g.* charged particle tracking, particle identification, trigger acceptance. The branching fraction $\mathscr{B}(\tau \to \mu\nu\bar{\nu}) = (17.41 \pm 0.04)\%$ is large and well measured. Signal and normalization are best separated through the reconstruction of kinematical variables in the rest frame of the decaying B meson, such as the muon energy E^*_μ, the square of the invariant missing mass $m^2_{miss} = (p_B - p_{D^*\mu})^2$, with p_X being four-momenta, and the square of the invariant mass of the lepton pair $q^2 = (p_\nu + p_\mu)^2 = (p_B - p_{D^*})^2$. In principle, the well-measured B flight direction can be used to get the B momentum with a 2-fold ambiguity. This ambiguity is avoided by noticing that the boost of the B meson along the beam direction is much larger than the boost of the decay products in its rest frame. Therefore, the visible boost along the beam direction consitutes a good approximation for the B boost along the same direction and allows to obtain a 18% resolution on the B momentum, that is sufficient to preserve the differences between signal, normalization and backgrounds in the above variables.

Backgrounds from semileptonic decays into excited charm mesons and double charm decays are reduced by an isolation algorithm, that scans over every other reconstructed track in the event and assesses its compatibility with the $D^{*+}\mu^-$ vertex. Discriminating variables, obtained by adding this additional track in the computation, such as the vertex quality of primary (PV) and secondary (SV) vertices, the change in the displacement of the SV, the transverse momentum and the alignment of the track with the momentum of the $D^{*+}\mu^-$ system, are used to build a multivariate classifier that gives the probability of tracks to be “SV-like” or “PV-like”. Requiring that most SV-like tracks lie below a given classifier threshold selects a signal-enriched sample, where 70% of events with one additional pion are rejected. This cut can be reversed to get samples enriched in background: events where one or two identified additional pions are found are used to model backgrounds due to $B \to D^{**}\mu\nu$ decays, while events where an additional kaon is found are taken as proxy for the $B \to D^* H_c(\to \mu\nu X')X$ background. All major backgrounds, including combinatorial and muon mis-identification, are modelled using data control samples.

A three-dimensional template fit to the E^*_μ, m^2_{miss} and q^2 distribution on data is performed simultaneously on a sample where no additional particles are associated to the signal candidate, and three additional control samples defined by the isolation criteria described above. The projections of the fit model on the distribution of the three variables are shown in Fig. 1 for the sample without additional particles. The obtained signal yield corresponds to 16500 candidates. $R(D^*)$ is measured to be

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

where the first uncertainty is statistical, the second systematic. This result is in agreement with other measurements from Babar and Belle and 2.1σ higher than the SM prediction.

The total uncertainty at the 10% level is almost evenly split between the statistical and systematic contributions. The largest systematic uncertainties originate from the statistical error of the simulation and muon mis-identification. Both can be reduced by generating larger Monte Carlo samples and by improving the particle identification algorithms. The total uncertainty is expected to be halved with the addition of the $\tau \to 3\pi(\pi^0)$ decay mode and data to be taken in Run II, where the cross-section increases by a factor two due to the higher center-of-mass energy and an addi-

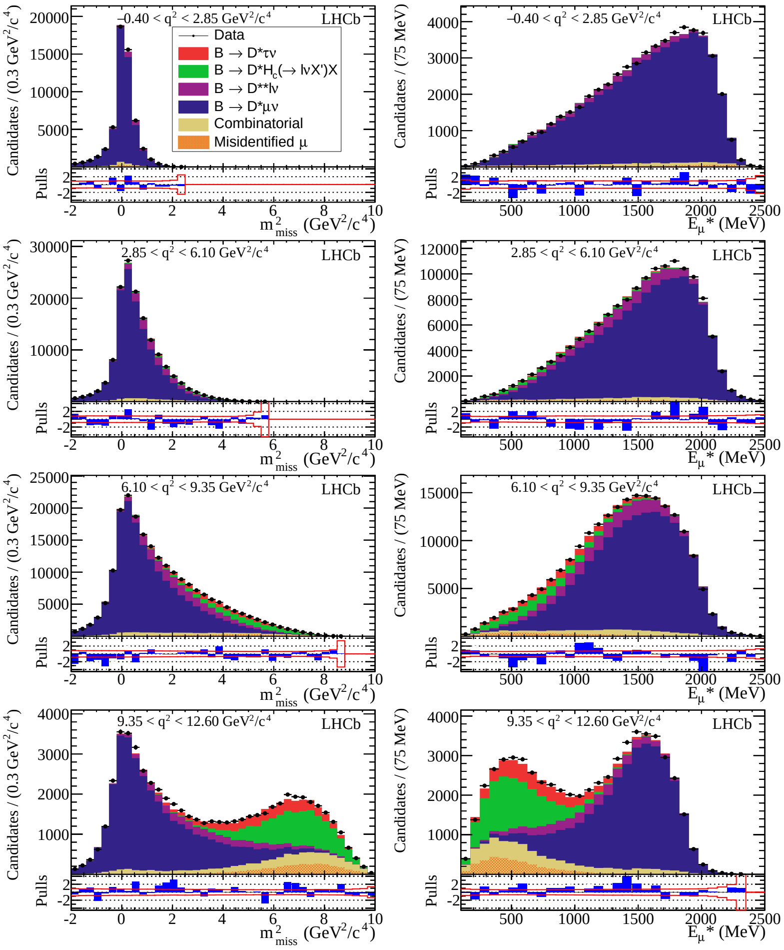

Figure 1: Distributions of m^2_{miss} (left) and E^*_μ (right) in four q2 bins of the signal data, overlaid with projections of the fit model. Below each panel differences between the data and fit are shown, normalized by the Poisson uncertainty in the data. The bands give the 1σ template uncertainties.

tional integrated luminosity of $5fb^{-1}$ is expected to be collected. Adding also Run III data to be taken with the upgraded LHCb detector would further decrease the uncertainty by a factor two.

3. Prospects for $R(D^*)$ with 3-prong τ decays

The $B \to D^{(*)}\tau\nu_\tau$ decay, with $\tau \to 3\pi(\pi^0)\nu_\tau$, results in two pions and a kaon from the D^* decay chain, and additional 3π system, a fairly common final state in b-hadron decays. The branching fraction for $B \to D^*3\pi(X)$ is indeed about two orders of magnitude larger than the SM prediction for $\mathscr{B}(B \to D^*\tau\nu_\tau; \tau \to 3\pi(\pi^0)\nu_\tau)$. This background can be suppressed by exploiting the *inverted vertex topology* of signal decays, for which the 3π system is “transported away” from the B vertex with a measurable decay length. As an example, requiring that the 3π vertex lies downstream of the D^0 decay vertex with a 5σ significance reduces the $D^*3\pi(X)$ background by more than four orders of magnitude. After applying such a requirement, the remaining background is due to b-hadron decays in a D^* and another charmed meson, and the 3π system originates from the decay of a D_s, D^+ or D^0. This background, about one order of magnitude larger than the expected SM signal, can be suppressed by using partial reconstruction techniques (by assuming either the signal or background hypotheses), by exploiting the Dalitz structure of the 3π system, by applying isolation criteria for charged tracks and neutral energy in a cone around the signal candidate. The expected precision of a $R(D^*)$ measurement with 3-prong τ decays is comparable to the one obtained with muonic τ decays.

4. Other decay channels and observables

The measurements of $R(D^*)$ described in the previous sections constitute a proof-of-concept ofr the feasibility of studies of semi-tauonic decays in an hadron collider enviroment, in a channel with simple and well known feed-down structure. There are in fact no limitations, due to *e.g.* signal purity or reconstruction technique, to study other decay channels.

A measurement of $R(D^0)$ would require the statistical separation of the feed-down from D^* decays; up to a factor five more events are expected with respect to the D^{*+} sample. LHCb can also efficiently isolate samples of semileptonic decays into narrow p-wave D mesons; samples of about $10^4 - 10^5$ events are expected, that would allow measurements of e.g. $R(D_1)$ and $R(D_2^*)$.

Moreover, LHCb has unique access to the production of B_s, B_c mesons and b-baryons, and therefore measurements of the corresponding ratios for semitauonic decays of these particles could be performed. The measurement of $R(D_s)$ through the $B_s \to D_s \tau \nu_\tau$ is challenging, due to a complicated feed-down structure where many excited states emit unreconstructed neutral particles. The $B_c \to J/\psi \tau \nu_\tau$ decay would give a spectacular signal with three muons in the final state for the muonic τ decay, thereby enabling a measurement of $R(J/\psi)$; moreover, the $J/\psi \to \mu\mu$ branching fraction is relatively high compared with the ones for other charm mesons, thus partially compensating for the lower B_c production rate.

The corresponding decays in the baryonic domain, e.g. $\Lambda_b \to \Lambda_c^{(*)} \tau \nu_\tau$ present a different spin structure with respect to their mesonic counterparts. Therefore, measurements of $R(\Lambda_c^{(*)})$ would be sensitive to different new physics models and would help discriminate tensor contributions.

As a further possibility, the increase in the integrated luminosity expected in Run III would give unprecedented samples of charmless semi-tauonic decays such as $B \to p\bar{p}\tau\nu_\tau$ or $\Lambda_b \to p\tau\nu_\tau$.

It should be also noted that several other observables, such as angular distributions, asymmetries, polarizations and form factors, have been proposed [6, 7] in addition to the ratios of branching fractions discussed so far. The measurements of these observables relies mainly on the unbiased determination of angular variables and the precise understanding of detector acceptance effects.

5. Conclusion

In summary, LHCb has provided the first measurement of a semi-tauonic b-hadron decay at a hadron collider, by exploiting the distinct features of the production of b-hadrons at the LHC and the excellent capabilities of the LHCb detector. The measurement of $R(D^*)$ with muonic τ decays represents the beginning of a vast exploration that will involve several decay channels and two τ decay modes. The addition of data that will be collected in Run II and Run III will eventually lead to samples of about $10^5 - 10^6$ events, that will be used to measure not only the ratios of branching fractions, but also other observables sensitive to physics beyond the SM, and to start the study of charmless semi-tauonic decays.

Figure 2 shows the current results and average in the $R(D), R(D^*)$ plane. The expected LHCb accuracy at the end of Run III will be competitive with the one of the final Belle-II measurements [4].

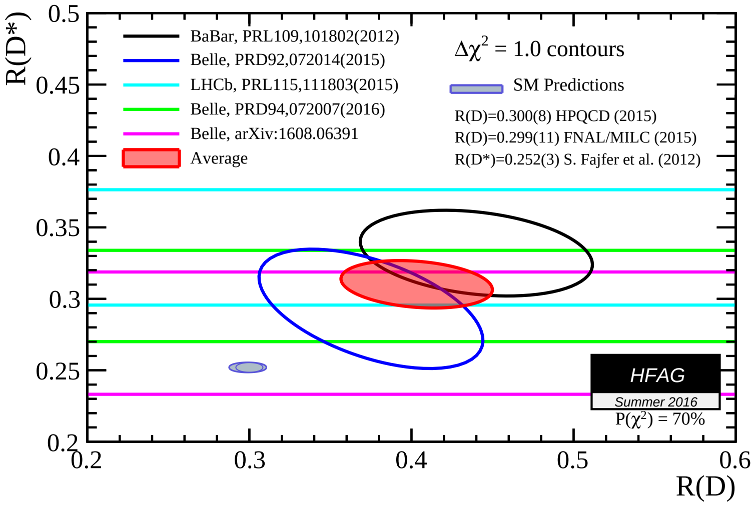

Figure 2: Measurements of $R(D), R(D^*)$, and their average, taken from [3]. The cyan band is the LHCb measurement, the black and blue ellipses represent BaBar and Belle measurements, respectively. The green and magenta bands represent new measurements presented by Belle in 2016. The red ellipse is the average of all measurements, to be compared with the SM prediction in blue-gray.

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