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$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ at LHCb

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LHCb has performed the first measurement at a hadron collider of a b-hadron decay into a final state with τ leptons. The analysis uses a sample of proton-proton collision data corresponding to 3 fb^{-1} of integrated luminosity recorded by LHCb at $\sqrt{s} = 7$ and $\sqrt{s} = 8$ TeV. The branching fraction of $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ decays, where the muonic decay $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ is considered, is measured relative to the branching fraction for $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ decays. The ratio is measured to be $R(D^*) \equiv \frac{\mathscr{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathscr{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)} = 0.336 \pm 0.027(\text{stat.}) \pm 0.030(\text{syst.})$ in good agreement with previous measurements and 2.1 standard deviations larger than the SM expectation, which assumes lepton universality.

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The flavour sector of the Standard Model (SM) and the CKM mechanism have been extensively tested in the past years with good agreement between experimental results and theory predictions. The lepton flavour universality, enforced in the SM by construction, has also been well tested so far. However, recent hints of lepton non-universality [1] and longstanding tensions among $|V_{ub}|$ ($|V_{cb}|$) parameters measured with exclusive or inclusive semileptonics decays of B mesons [2] raise great interest for new measurements of semileptonic decays. Charged lepton universality in the SM implies that branching fractions for B decays to final states with electrons, muons and taus differ only by phase space and helicity-suppressed contributions. Any violation of lepton universality would be a clear sign of physics beyond the SM. A quantity that is sensitive to contributions beyond the SM is the branching fraction of the $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ decay. It is particularly sensitive to contributions from non-Standard-Model particles that preferentially couple to the third generation of fermions, in particular Higgs-like charged scalars. The ratio

$$R(D^*) \equiv \frac{\mathscr{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathscr{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

is calculated with good precision in the SM as $R(D^*)^{SM} = 0.252 \pm 0.003$ [5]. The high precision can be partly attributed to the cancellations in the ratio of most uncertainties on the form factors. The BaBar and Belle Collaborations measured a value slightly above the SM expectation and found a similar excess in the $B^- \to D^0\tau^-\overline{\nu}_\tau$ decay [3, 4].

A precise measurement of a B decay involving τ leptons is a challenge at an hadron collider, and was never performed before LHCb, the reason being related to the lack of a kinematic constraint on the B energy, that is available at B Factories, and to the presence of large backgrounds.

In this measurement [6] of $R(D^*)$ the muonic decay $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ is considered, so that the signal and the normalization modes have the same visible final state particles and a large and well measured τ decay branching fraction is involved. The D^{*+} meson is reconstructed in the $D^{*+} \to D^0(K^-\pi^+)\pi^+$ decay mode. The analysis uses a sample of proton-proton collision data corresponding to 3 fb^{-1} of integrated luminosity recorded by LHCb at $\sqrt{s}$ = 7 and $\sqrt{s}$ = 8 TeV. The selection of the signal and normalization decays exploits the excellent capabilities of the LHCb detector concerning momentum and impact parameter resolution, and particle identification [7]. In order to preserve as much as possible the different kinematic properties of the two channels, the hardware trigger selection does not include requirements on the muon transverse momentum. The software trigger selection requires a D^0 meson signature. The efficiency ratio, after full selection, is found to be $\varepsilon_\tau/\varepsilon_\mu = (77.6 \pm 1.4)\%$. The τ mode is less efficiently selected primarily beacuse of the lower p_T of the secondary muon and the poorer vertex quality in the signal decay.

A good separation between the signal and the normalization channel is achieved by considering three key kinematic variables, computed in the B rest frame: the muon energy (E^*_μ), the missing mass squared calculated as $m^2_{miss} = (p^\mu_B - p^\mu_{D^*} - p^\mu_\mu)^2$, and the squared four-momentum transfer to the lepton system $q^2 = (p^\mu_B - p^\mu_{D^*})^2$, where p^μ_B, $p^\mu_{D^*}$ and p^μ_μ are the four-momenta of the B^0 meson, the D^{*+} meson and the muon. The determination of the B rest frame requires the knowledge of the B momentum in the laboratory frame. The momentum spectra of B mesons produced in hadronic collisions is wide and the exact determination of the B momentum in the laboratory frame from the reconstructed final state particles is not possible when one or more neutrinos are present in the decay. However the momentum direction is well determined from the unit vector to the B decay vertex from the associated primary vertex (pp collision vertex). In this analysis the B momentum component along the beam axis (z) is approximated using the relation $p_z(B^0) = \frac{m_{B^0}}{m_{D^*\mu}} p_z(D^*\mu)$ where m_{B^0} is the known B^0 mass and $m_{D^*\mu}$ and $p_{D^*\mu}$ are the mass and momentum of the reconstructed particles. Using this approximation the rest-frame variables are calculated with a resolution of approximately 15-20 % which is sufficient to preserve the differences among the two decay modes, as shown in Fig. 1.

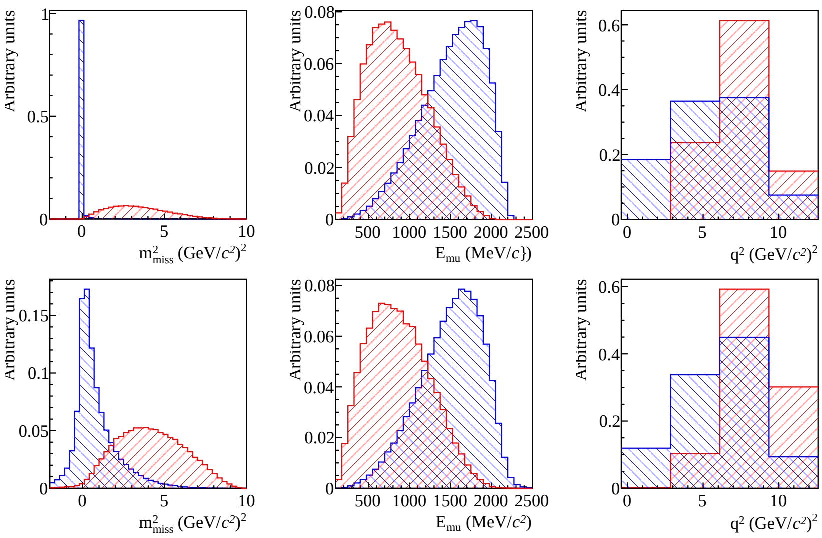

Figure 1: Distributions of (left) m^2_{miss}, (middle) E^*_μ and (right) q^2 for simulated (red) $\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$ and (blue) $\overline{B}^0 \rightarrow D^{*+}\mu^-\overline{\nu}_\mu$ decays using (top) Monte Carlo truth information and (bottom) reconstructed quantities.

The main background sources to the decays under study consist of partially reconstructed B decays. To suppress these decays an algorithm has been developed which determines the compatibility with the B decay vertex of any other track in the event. By requiring zero additional tracks at the B vertex the selected data sample is enriched in $\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$ and $\overline{B}^0 \rightarrow D^{*+}\mu^-\overline{\nu}_\mu$ decays. Alternative requirements allow to select three data control samples that are used to study the shape of the remaining background. In particular, the requirement that one or two additional tracks originate from the B vertex selects samples enriched in $\overline{B}^0 \rightarrow D^{*+}\mu^-\pi^-X$ and $\overline{B}^0 \rightarrow D^{*+}\mu^-\pi^+\pi^-X$ decays, respectively. If at least one selected track satisfies kaon identification requirements a sample enriched in $\overline{B}^0 \rightarrow D^{*+}\mu^-K^{\pm}X$ decays is selected.

The binned m^2_{miss}, E^*_μ and q^2 distributions in data are fit using a maximum likelihood method with three dimensional templates representing the signal, the normalization and the background sources. 40, 30 and 4 bins are defined, respectively, over the kinematic regions $-2 < m^2_{miss} < 10$ $(\text{GeV}/c^2)^2$, $100 < E^*_\mu < 2500$ MeV/c and $-4 < q^2 < 12.6$ $(\text{GeV}/c^2)^2$. Simulated and data events are used to derive the templates, which are validated with separate fits on the aforementioned control samples.

In the simulation, the hadronic transition-matrix elements for $\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$ and $\overline{B}^0 \rightarrow D^{*+}\mu^-\overline{\nu}_\mu$ form factors are described using form factors derived from the heavy quark effective theory [8] with parameters floated in the fit and their recent world average values included as external constraints. Uncertainties due to the finite number of simulated events are incorporated in the likelihood using the Beeston-Barlow "light" procedure [9] while shape uncertainties are included via interpolation between nominal and alternative histograms.

A large background contribution arises from semileptonic decays of excited charm states that are collectively named "D^{**}". Separate templates are defined for each of the established narrow resonances decaying into D^{*+}mesons $D_1(2420)$, $D_2^*(2460)$, $D_1'(2430)$ with form factors taken from Ref. [10]. Charm states with higher masses are also present, but since their properties are less well measured, they are modeled in the fit as a single component. The parametrization in Ref [11] is used and the derived q^2 distribution is tuned on data using the "$D^{*+}\mu^-\pi^+\pi^-$" control sample. A similar parametrization is used also for the semitauonic decay to high mass charm states. The total contribution of the semileptonic background amount to about 12% of the normalization mode.

A second important background, which represents 6-8% of the normalization mode is made of semileptonic decays of the charmed hadron H_c in $\overline{B} \to D^{*+}H_cX$, $H_c \to \mu^-\overline{\nu}_\mu X'$ decays. The template for this contribution is constructed from simulated samples of B^0 and B^+ decays, with an approximate mixture of final states. Empirical corrections are derived from a fit to the "$D^{*+}\mu^-K^\pm$" control sample. Similar simulated samples are used to represent contributions of tertiary muon decays due to $D_s^- \to \tau^-\nu_\tau$ decays.

Other background contributions arise from hadrons misidentified as muons and random combinations of a μ^- and a true D^{*+}or of a true μ^- and a fake D^{*+}. Templates for all these contributions are also modeled from data using several control samples, including combinations of D^{*-} mesons and muons of the same charge.

The maximum likelihood fit determines a total of 363 000 ± 3 600 events in the normalization mode and fraction of signal with respect to the normalization $N(D^{*+}\tau^-)/N(D^{*+}\mu^-) = (4.54 \pm 0.45)$ %, where the error is due to the data and Monte Carlo statistics and to the variation of the form factors. The smallness of the signal fraction is in agreement with the expectations from the τ branching fraction and the phase space suppression. In Fig. 2 the distributions of E_μ^* and m_{miss}^2 are shown, separated in the four q^2 bins, together with the fit function. From the calculated efficiency and the known τ branching fraction the value $R(D^*) = 0.336$ is derived.

Several sources of possible systematic uncertainties related to the modeling of the templates and to the normalization are considered. The largest contributions are due to the limited size of the simulated sample currently available and to the uncertainty in the shape of the template describing the component of hadron misidentified as muons. The latter uncertainty is determined by comparing the results of two different methods used to extract the shape form data. Uncertainties related to the modeling of the other background components are also considered. Uncertainties related to the normalization are small because they affect in a similar manner the $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ and $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ branching fraction and cancel out in their ratio. The list of all systematic uncertainties is reported in Table 1 and sum to an absolute 3%. It should be noted that most uncertainties depend on the available size the data control samples used for their determination, hence they are expected to decrease in the future with more data collected at LHCb.

In conclusion, LHCb has measured the ratio of branching fractions

$$R(D^*) = 0.336 \pm 0.027(\text{stat.}) \pm 0.030(\text{syst.})$$

in good agreement with previous measurements and 2.1 standard deviations larger than the SM

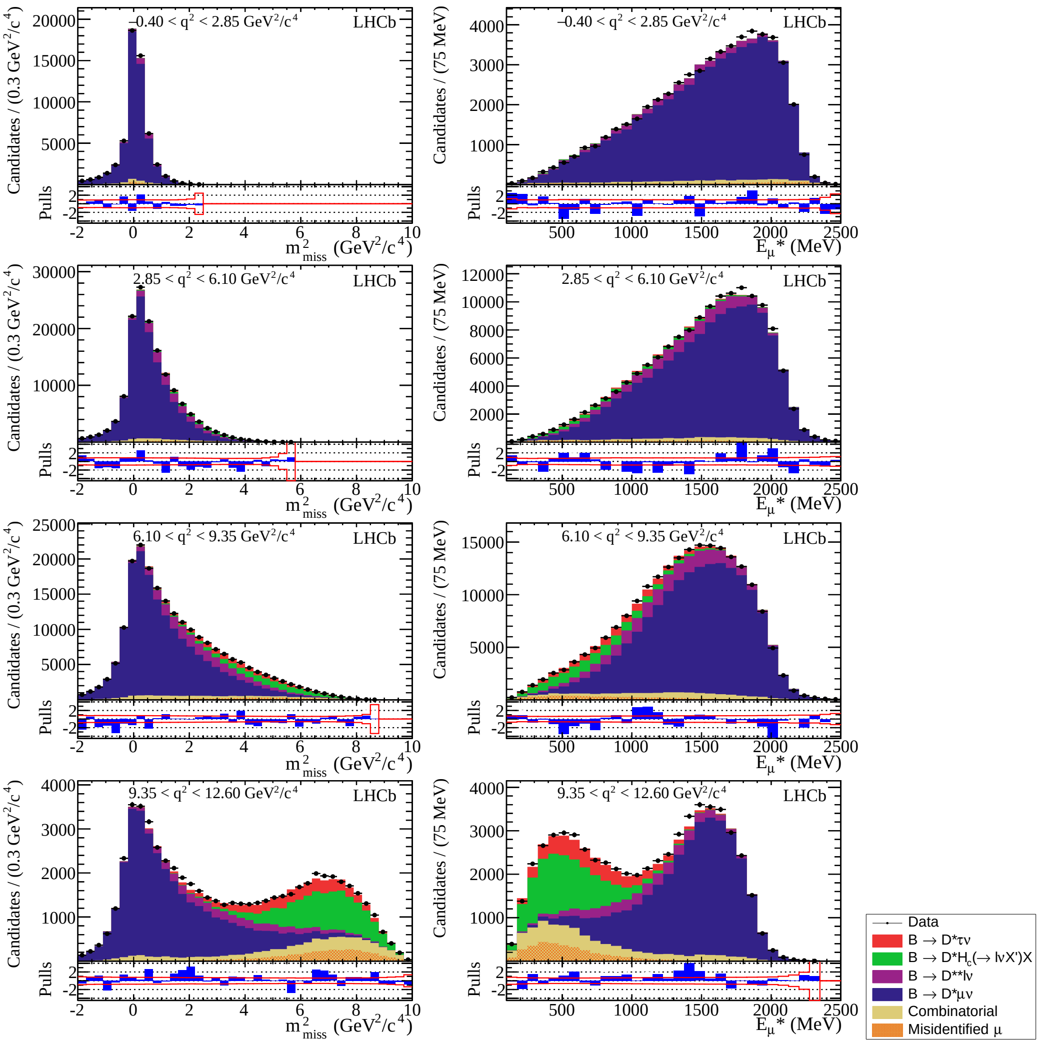

Figure 2: Distributions of (left) m^2_{miss} and (right) E^*_μ in four q^2 bins for signal data (points), overlaid with (histogarms) projections of the fit model with all normalization and shape parameters at their best-fit values. Below each panel differences between the data and fit are shown, normalized by the Poisson uncertainty in the data. The bands give the 1σ template uncertainties.

expectation, which assumes lepton universality. This is the first measurement of a decay of a b-hadron into a final state with τ leptons at a hadron collider.

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Table 1: Systematic uncertainty on $R(\mathrm{D}^*)$.

Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\mu^-\overline{\nu}_\mu$ form factors	0.6
$\overline{\mathrm{B}} \to \mathrm{D}^{*+}H_cX$ shape corrections	0.5
$\mathscr{B}(\overline{\mathrm{B}} \to \mathrm{D}^{**}\tau^-\overline{\nu}_\tau)/\mathscr{B}(\overline{\mathrm{B}} \to \mathrm{D}^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{\mathrm{B}} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{\mathrm{B}} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{\mathrm{B}} \to D^{*+}(D_s \to \tau\nu_\tau \mathrm{X}$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathscr{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

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