Measurement of $R(D^*)$ with hadronic $\tau$ decays

B G Siddi$^{1,2}$ on behalf of the LHCb collaboration

$^1$Università degli studi di Ferrara, Dipartimento di fisica, Via Saragat 1, 44122, Ferrara
$^2$CERN, CH-1211 Geneva 23, Switzerland
E-mail: bsiddi@cern.ch, siddi@fe.infn.it

Abstract. Lepton universality, described in the Standard Model (SM), predicts equal coupling between gauge bosons and the three lepton families. SM extensions give additional interactions, implying in some cases a stronger coupling with the third generation of leptons. Semileptonic decays of $b$-hadrons provide a sensitive probe to such New Physics effects. The presence of additional charged Higgs bosons, required by such SM extensions, can have significant effect on the semileptonic decay rate of $B^0 \to D^* \tau \nu$. A probe of new physics effects is the measurement of the quantities:

$$R(D^*) = \frac{B(\bar{B}^0 \to D^* \tau \nu)}{B(\bar{B}^0 \to D^* \mu \nu)},$$

and

$$R(D) = \frac{B(\bar{B}^0 \to D \tau \nu)}{B(\bar{B}^0 \to D \mu \nu)},$$

The combination of experimental measurements performed by BaBar, Belle and LHCb observing the channel where the $\tau$ decays in leptons, gives a deviation from the SM prediction of about 4$\sigma$. It is therefore important to perform additional measurements in this sector in order to improve the precision and confirm or disprove this deviation. Another possibility is to perform this measurement using the channel where the semileptonic $\tau$ decays in 3 pions. This in LHCb allows to have a better reconstruction of vertices and other kinematic variables. Results obtained by LHCb on $B^0 \to D^* \tau \nu$ decays, where the $\tau$ decays hadronically, are reported.

1. The LHCb Detector

The LHCb detector [1] (see Fig. 1) is a single arm spectrometer covering the rapidity region $2 < \eta < 5$. It is optimized to study hadron decays containing $b$ and $c$ quarks. These are important to analyze CP violation, rare decays, and heavy quark production. It has an excellent vertex resolution for $B$ and $D$ hadrons, a good momentum and invariant mass resolution. The detector provides good Particle Identification (PID) capabilities; the kaon identification efficiency is 88% and the pion mis-identification is 3%. LHCb during Run 1, collected about 1.0$fb^{-1}$ of data at $\sqrt{s} = 7$ TeV and about 2.0 $fb^{-1}$ at $\sqrt{s} = 8$ TeV.

2. B hadron semileptonic decays with $\tau$ leptons in final states

Semileptonic decays of $b$ hadrons are successfully studied in B-factories with high purity and high statistics $D^{(*)} \tau \nu$ samples; despite the hadronic environment LHCb is also able to study such kind of decays and extend to other $b$ hadrons thanks to their high boost and excellent vertexing of the detector. However there are some analysis challenges in an hadronic enviroment, e.g., it needs to find the correct kinematic variables in order to distinguish between signal and background, suppress the background due to additional charged and/or neutral particles, and find the best normalization channel. These challenges have different levels of importance and difficulty, and different solution between analyses, especially between muonic and hadronic $\tau$ decays.
3. $\tau$ leptons with hadronic final state
A way to measure $R(D^*)$ is to reconstruct the $\tau^-$ in the hadronic $\pi^-\pi^+\pi^-\nu_\tau$ decay channel. This is a semileptonic decay without charged leptons in the final states. In this case what is measured is:

$$K(D^*) = \frac{B(B^0 \to D^*\tau\nu)}{B(B^0 \to D^*\pi\pi)}$$

(1)

The two decay modes shares the same final state and in this case most of the systematic uncertainties will cancel. To compute $R(D^*)$ a second equation will be needed:

$$R(D^*) = K(D^*) \times \frac{B(B^0 \to D^*3\pi)}{B(B^0 \to D^*\mu\nu)}$$

(2)

The quantities multiplied by $K(D^*)$ are then taken as external inputs.

4. Background
4.1. Vertex inversion
The most abundant background source is due to hadronic $B$ decays into $D^*3\pi X$. Such background has a branching fraction that is about 100 times the signal one.

$$\frac{B(B^0 \to D^*3\pi X)}{B(B^0 \to D^*\tau\nu)}_{SM} \sim 100$$

(3)

In Fig. 2 a schematic view of the $B^0 \to D^*3\pi X$ decay is presented.

Thanks to the good precision on the $\tau$ vertex reconstruction, it is possible to apply the so called vertex inversion cut. This consists on the requirement that the $\tau$ vertex is downstream with respect to the $B^0$ one with a significance of at least 4$\sigma$. A schematic view of this requirement is shown in Fig. 3. In this way the background coming from these decays is suppressed by about 3 orders of magnitude.

The distribution of the quantity $\Delta z/\sigma$ for different background sources is presented in Fig. 4. The $D^*3\pi$ contribution (grey) is basically suppressed, after a value of $\Delta z/\sigma = 4$.
Figure 2. Schematic view of the $B^0 \to D^{*}3\pi X$ decay.

Figure 3. Schematic view of the vertex cut requirement.

Figure 4. Distribution of the vertex significance ($\Delta z/\sigma$) for different background sources. The black line represents the applied cut.
4.2. Double charm decays
The remaining background consists of $B^0$ decays where the 3π vertex is transported away from the $B^0$ one by a charm carrier, such as $D^0$, $D^+$ and $D_s$. This background has a yield that is about 10 times the signal:

$$\frac{B(B^0 \to D^+ D^{(s)}_\pi, D^{(s)}_\pi \to 3\pi + X)}{B(B^0 \to D^+ \tau \nu)} \sim 10$$

(4)

To limit these background sources, LHCb has three very good tools: the 3π dynamics; the isolation criteria against charged tracks and neutral energy deposits; partial reconstruction techniques in the signal and background hypotheses. All these variables are used to train a Boosted Decision Tree (BDT) in order to discriminate double charm decays from the signal.

4.3. $D_s$ decay model
The $D_s$ decay model has been determined directly from data, using a sample obtained using a BDT output that is enriched in such decays (high purity is reached). In order to retrieve the sub-decays relative fractions, a simultaneous fit in the minimum and maximum of the opposite sign $2\pi$ mass, in the same sign pions ($\pi^+\pi^+$) mass and $3\pi$ mass has been performed. The result of the fit is shown in Fig. 5. The total PDF of the fit contains:

- $D_s$ decays where at least 1 pion is from $\eta$ or $\eta'$: $\eta\pi$, $\eta\rho$, $\eta'\pi$ and $\eta'\rho$;
- $D_s$ decays where at least 1 pion is from an IS (Intermediate Resonance) other than $\eta$, $\eta'$: IS$\pi$, IS$\rho$ (IS could be $\omega$, $\phi$);
- $D_s$ decays where none of the 3 pions comes from an IS, subdivided in: $K^0 3\pi$, $\eta 3\pi$, $\eta' 3\pi$, $\omega 3\pi$, $\phi 3\pi$, $3\pi$ non resonant final state.

The weights obtained by the fit are then used to construct the $D_s$ template utilized in the final fit.

5. Normalization
The normalization channel has to be as similar as possible to the signal channel in order to cancel all systematics linked to trigger selection, particle identification and selection cuts. Due
to this, in this analysis what is measured is the ratio:

$$K(D^*) = \frac{B(B^0 \rightarrow D^*\tau\nu)}{B(B^0 \rightarrow D^*\pi\pi\pi)}$$  \hspace{1cm} (5)

The two decays differ by the presence of a softer pion and $D^*$ in the signal decay due to the two extra neutrinos, and the kinematics of the $3\pi$ system. This will give a residual effect on the efficiency ratio.

6. Signal extraction

6.1. Signal reconstruction

The presence of the neutrino in the final state of the signal decay can be inferred, up to a two-fold ambiguity, by exploiting the flight direction of the $\tau$. In this way it is possible to compute the $\tau$ momentum with the following equation:

$$|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\vec{p}_{3\pi}| \cos \theta \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2 \sin^2 \theta}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2 \cos^2 \theta)}$$  \hspace{1cm} (6)

where $\theta$ is the angle between $\tau$ and $3\pi$ direction as shown in Fig. 6.

The ambiguity can be resolved by choosing the maximum value for the opening angle between the three charged pions system and the direction of the $\tau$ lepton, as in the following equation:

$$\theta_{max} = \arcsin \left( \frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau|\vec{p}_{3\pi}|} \right)$$  \hspace{1cm} (7)

This will introduce a negligible bias in the signal reconstruction.

6.2. Fit

An extended maximum likelihood 3-dimensional fit, using templates has been performed. The fitted variables are:

- $q^2$, the squared momentum transferred to the $\tau - \nu$ system;
- $\tau$ decay time;
- The output of the BDT extracted from simulated and data-driven control samples.

The fit model used to extract the signal yield consists of 5 main categories:

- Signal described by the sum of two $\tau$ decays, $\tau \rightarrow \pi\pi\pi\nu$ and $\tau \rightarrow \pi\pi\pi\pi^0\nu$;
• $B^0 \rightarrow D^{**}\tau\nu$ decays;
• Double charm components;
• $B^0 \rightarrow D^*3\pi X$ decays;
• Combinatorial background.

7. Systematic uncertainties
The main systematic uncertainty is due to the size of samples used for the construction of the fitted templates. Another source of main systematics is the external branching ratio of the $B^0 \rightarrow D^*3\pi$ decay. This value was known in the particle data group 2014 with a 11% precision. Thanks to the last BaBar measurement of this decay, this systematics has been reduced to 4.3% [2]. In the uncertainty computation, another contribution is given by the knowledge of the $B \rightarrow D^*(D_s, D^0, D^+)X$ and $B^0 \rightarrow D^*3\pi X$ background shapes. The size the total systematics is above the statistical precision but there is room for improvements, i.e., with more data and simulated samples, and a better knowledge of the external branching fractions using also results from other experiments.

8. Conclusion
Semitauonic $B$ decays are a great tool to discover new physics. There are several measurement of $R$ in LHCb, e.g. $R(D^*)$, $R(D)$, $R(J/\psi)$, $R(\Lambda_c)$ and more modes are possible. Thanks to the LHCb excellent performances, it is possible to reconstruct hadronic $\tau$ decays with a good precision. This allowed to extract the signal for hadronic $R(D^*)$ with a 7% of precision using just the Run1 data. This measurement is competitive with the LHCb one in which the muonic $\tau$ decay has been used, and with the world average [3]. However, it is possible to use such decays to study not only $R$ but also other quantities such as angles, polarizations, form factors.

References
[1] Aaij R et al 2014 LHCb Detector Performance CERN-LHCB-DP-2014-002
[2] Lees J P et al. 2016 Measurement of the $B^0 \rightarrow D^* \pi^+\pi^-\pi^+$ branching fraction Phys.Rev. D94 091101
[3] Heavy Flavor Averaging Group (HFLAV) Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of summer 2016 arXiv:1612.07233