# Semester Report

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Ph.D. Thesis title: `Exploring Lepton Flavor Universality in Semitauonic` $\Lambda_b^0$ `Decays via Three-Pion` $\tau$`-Lepton Channels at LHCb`

# Introduction

In the Standard Model (SM), the electroweak couplings of the three lepton generations are identical, a property known as Lepton Flavour Universality (LFU). In recent years, several measurements in semileptonic $b$-hadron decays have shown tensions with this expectation, motivating precise tests of LFU using ratios of branching fractions involving $\tau$ leptons. In the charged-current sector, these tests are commonly expressed through

$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell^- \overline{\nu}_\ell)}, \quad \ell \in \{e^-, \mu^-\}, \tag{1}$$

which is expected to be unity up to lepton-mass effects.

While most measurements of $\mathcal{R}(H_c)$ have been performed in the mesonic sector, LHCb has recently provided the first determination of $\mathcal{R}(\Lambda_c^+)$ using the Run 1 dataset corresponding to an integrated luminosity of 3 $\text{fb}^{-1}$. Measurements in the baryonic sector offer complementary sensitivity to potential new physics effects due to their different spin structure and form-factor dependence, and model-independent relations exist linking baryonic and mesonic observables. With the availability of larger datasets, further exploration of this sector is therefore well motivated.

At LHCb, the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$ can be studied using the hadronic $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ final state. In this channel, the decay $\Lambda_b^0 \to \Lambda_c^+ 3\pi$ serves as the control and normalisation mode, analogous to the role of $\overline{B}^0 \to D^{*+}3\pi$ in mesonic analyses.

# Research work carried out in the current semester

In my 1st semester of PhD program I have mostly worked on upgrading the measurement of branching fraction of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$ with the complete Run 1+2 LHCb data where $\overline{B}^0 \to D^{*+}3\pi$ is considered as the normal mode. The $\Lambda_b^0 \to \Lambda_c^+ 3\pi$ decay was previously studied at LHCb with only 31 $\text{pb}^{-1}$ of data [1] with a signal yield of $174 \pm 18$. $\overline{B}^0 \to D^{*+}3\pi$ was specifically stuided with 1 $\text{fb}^{-1}$ Run 1 data [2] with an yield of $7228 \pm 93$. The present analysis reconstructs about $4 \times 10^5$ signal candidates, representing an increase in signal statistics by more than two orders of magnitude, similarly for $\overline{B}^0 \to D^{*+}3\pi$ it is more than 50 times of previous signal yields.

The analysis is performed using the full Run 1 and Run 2 LHCb dataset collected between 2011 and 2018, corresponding to an integrated luminosity of approximately 9 $\text{fb}^{-1}$. The data were processed using standard LHCb offline reconstruction and stripping campaigns corresponding to each data-taking period. The decay modes $\Lambda_b^0 \to \Lambda_c^+ 3\pi$ and $\overline{B}^0 \to D^{*+}3\pi$ are selected from the `BHADRONCOMPLETEEVENT` stream, with the intermediate states reconstructed via $\Lambda_c^+ \to pK^-\pi^+$ and $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, respectively, using dedicated stripping lines designed for semitauonic analyses.

Events are selected using a combination of hardware (L0) and software (HLT1 and HLT2) trigger requirements. At the hardware level, both trigger-on-signal (TOS) and trigger-independent-of-signal (TIS) categories are employed to maximise signal efficiency while ensuring orthogonality between samples. Different configuration of triggers(L0) and conditions of data-taking between Run 1 and Run 2 are accounted for by treating TIS and TOS samples, as well as different data-taking years, as independent sub-samples, resulting in 8 sub-dataset for each decay. These categories are probed separately throughout the analysis and will be combined at the final stage.

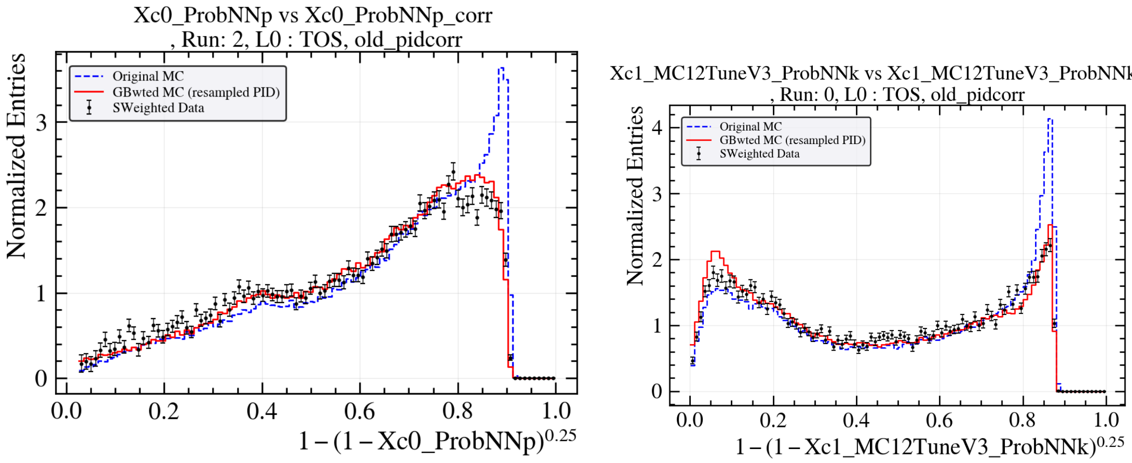


Figure 1: Comparison of particle-identification (PID) probability distributions in data and simulation for a representative Run 2 TOS subsample. **Left:** proton PID probability for $p$ from the $\Lambda_c^+ \to pK^-\pi^+$ decay in $\Lambda_b^0 \to \Lambda_c^+ 3\pi$ candidates. **Right:** kaon PID probability for the $K$ from the $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decay in $\overline{B}^0 \to D^{*+} 3\pi$ candidates. The original simulated distributions are shown before(blue) and after(red) gradient-boosted reweighting, together with the sWeighted data(**black error bars**) distribution. The PID variables are displayed using a monotonic transformation to enhance the visualisation of differences in the high-probability region.

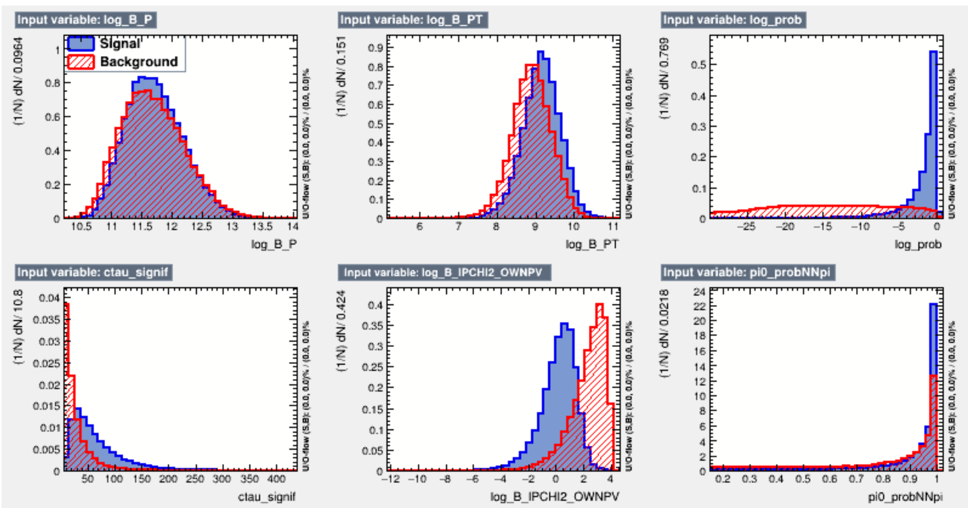


Figure 2: Signal and background separation for 6 training variabls used for BDT optimization

Simulation-to-data agreement is improved using gradient-boosted (GB) reweighting techniques applied to kinematic and event-level variables. The effect of the reweighting is shown in figure 1 by comparing the distributions of selected observables before and after correction, demonstrating a significantly improved agreement between simulated signal and data across the full phase space. Similar levels of agreement are observed in all of the 8 subsample of each decay.

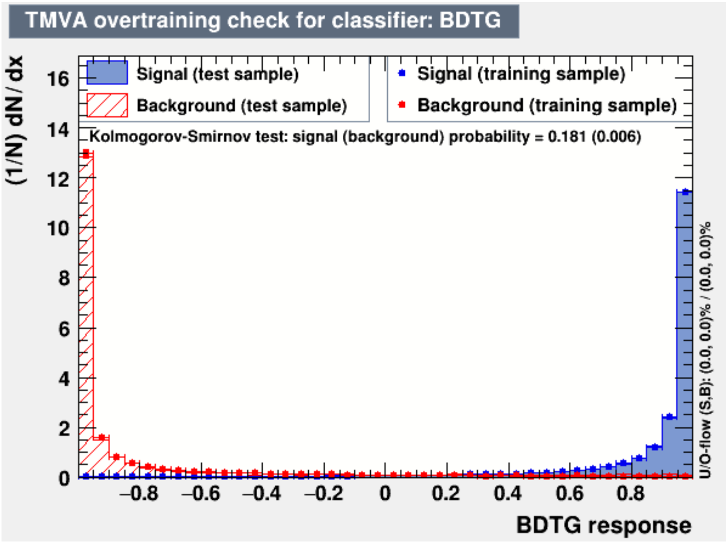


Figure 3: KS test result for BDT. These plots belong from the 2018 TOS dataset of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$ decay

Background is suppressed using a BDT trained on simulated signal and data sidebands. Exploiting kinematic, topological, and vertex variables. Some of these trainig variables are shown in figure 2 The model demonstrates strong separation and no overtraining, as validated by Kolmogorov–Smirnov tests shown figure 3. A point which needs to mentioned again is that such BDTs were performed for each of the 8 dataset of both $\Lambda_b^0$ and $B^0$ decay.

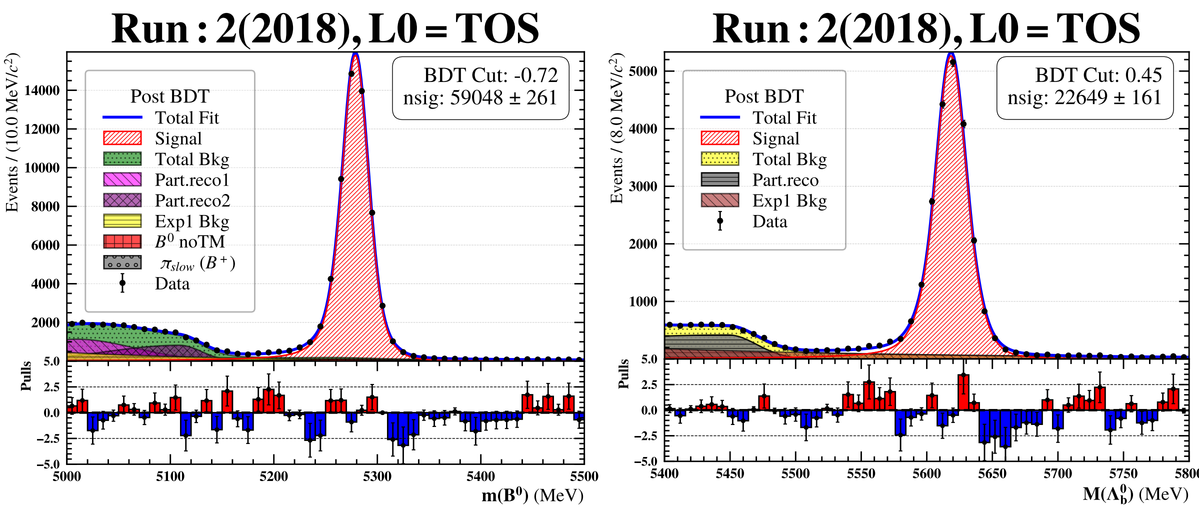


Figure 4: Post BDT optimization, mass fits for $B^0$ and $\Lambda_b^0$ peak in wide mass window for 2018 data with TOS subsets

After BDT, invariant-mass fits were performed to extract signal yields. figure 4 shows a representative fit with distinct signal peaks and well-described backgrounds. Consistent fit quality and yields across all eight datasets provide a robust foundation for subsequent efficiency corrections and branching fraction measurements. Intermediate steps such as veto optimisation, particle-identification corrections, pre-BDT fits, and validation studies are not shown here for brevity, but are fully implemented in the analysis workflow.

# Publications

- Analysis *"Measurement of the branching fraction of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$ for Run 1+2 data"* has reached an advanced stage within the LHCb collaboration and is expected to lead to a publication in 2026.

# Studies in the current semester

- Data mining and machine learning – FIZ/3/084
- Selected chapters in experimental high energy physics – FIZ/2/117

# Conferences and seminars

- LHCb Starter Kit (01–05/12/2025), **CERN**, on-site participation.

# Other activities

- **Mentoring at CERN**: Volunteer support during hands-on sessions of the "Python + ROOT" lectures at the LHCb Starter Kit, assisting students with exercises, software.
- **CERN Service work**: Shadow shift at CERN as LHCb Data Manager, gaining experience with operational procedures and data processing workflows.

# References

[1] R. Aaij et al. Measurements of the branching fractions for $B^0_{(s)} \to D_{(s)}\pi\pi\pi$ and $\Lambda_b^0 \to \Lambda_c^+\pi\pi\pi$. *Phys. Rev.*, D84:092001, 2011.

[2] R. Aaij et al. Study of $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ and $B^0 \to D^{*-}K^+\pi^-\pi^+$ decays. *Phys. Rev.*, D87:092001, 2013.