PROCEEDINGS OF SCIENCE

Higgs Physics at LHCb

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LHCb functions as a spectrometer targeting the forward region of proton-proton collisions, focusing on the pseudo-rapidity (η) range $2 < \eta < 5$. Due to the scarcity of background events in the high mass region, along with its precise reconstruction capabilities and a trigger system featuring low energy thresholds, LHCb offers an optimal environment for probing (exotic) Higgs decays, complementing the efforts of other experiments such as ATLAS and CMS. This paper will delve into the latest investigations into Higgs physics conducted at the LHCb experiment, along with outlining the potential avenues for future data collection periods at the High Luminosity phase of LHC. Particularly, the search for $H \to b\bar{b}$ and $H \to c\bar{c}$ decays will be presented, with a focus on the latest results obtained using the full Run 2 dataset. Finally, prospects on the Standard Model Higgs searches are presented, with an eye toward the future LHCb experiment upgrades.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

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PoS(ICHEP2024)058

1. The LHCb Experiment

The LHCb experiment [1], initially focused on the exploration of b- and c-hadron physics, has evolved into a versatile, general-purpose forward detector. Optimized for detecting particles produced at small angles relative to the beamline, LHCb is uniquely positioned to study rare decays, CP violation, and precision measurements of heavy-flavor hadrons and electroweak processes, offering sensitive tests of the Standard Model (SM) and potential probes for physics beyond the SM.

A key feature of LHCb is its high-momentum resolution system, achieving remarkable precision in tracking particle momentum. This allows for accurate reconstruction of complex decay chains, particularly in events containing b- and c-quarks. Additionally, muon and electron identification capabilities enhance the experiment's ability to study decays involving leptons, making it well-suited to investigate electroweak processes and rare decays. Combined with specialized vertex reconstruction techniques, LHCb achieves efficient identification of secondary vertices, critical for tagging b- and c-jets. LHCb serves as a complementary experiment to ATLAS and CMS, with a unique forward acceptance range ($2 < \eta < 5$) that enables it to investigate both rare decays and processes at lower transverse momenta, as well as regions populated by heavy-flavor hadrons. This allows the LHCb experiment to test Quantum Chromodynamics (QCD) and electroweak theory predictions in a forward phase space largely unexplored by the ATLAS and CMS experiments, which focus primarily on central collisions. This is also shown in Fig. 1. By probing this unique phase space, LHCb enhances our understanding of parton distribution functions (PDFs) and the internal structure of the proton in kinematic regions that are inaccessible to general-purpose detectors.

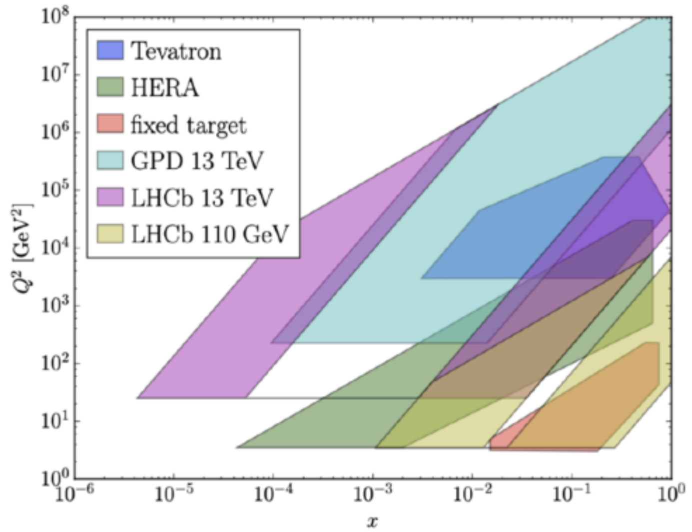

Figure 1: $x - Q^2$ plot [2] showing the LHCb coverage (violet) with respect to ATLAS and CMS (light-blue), Tevatron (blue), HERA (green contour) and fixed target (orange) experiments.

2. Search for Higgs Boson in Association with Vector Bosons

The LHCb experiment has expanded its research program to include searches for the Higgs boson produced in association with vector bosons, such as W or Z bosons, which are commonly denoted as

WH and ZH production modes [4]. These associated production modes offer unique opportunities to observe Higgs decays, particularly in the forward region where LHCb operates. The primary channels studied at LHCb include the decays of the Higgs boson in $b\bar{b}$ and $c\bar{c}$ jets pairs, focusing on final states containing jets tagged as originating from b- or c-quarks.

In this analysis [4], data from Run I are used, accounting for a total integrated luminosity of 2 fb^{-1}, targeting events with a vector boson and a Higgs boson that subsequently decays to a pair of b- or c-quarks. This analysis also involved identifying leptonic decays from the accompanying vector boson, providing a distinct experimental signature with low background contributions. Efficiently tagging jets originating from b-, c-, and lighter quarks is crucial, as this enables discrimination between signal and background events, as shown in Fig. 2.

Jet tagging for these analyses utilized Boosted Decision Trees (BDTs), which provided a strong separation between signal and background jets based on their distinct kinematic and structural features. Despite the advanced techniques employed, no significant signals were observed in the data, and as a result, upper limits on the Yukawa couplings of the Higgs to b- and c-quarks were established for the first time. The couplings denoted y_b and y_c, were constrained to values below approximately 7 times the Standard Model prediction for y_b and 80 times for y_c, respectively.

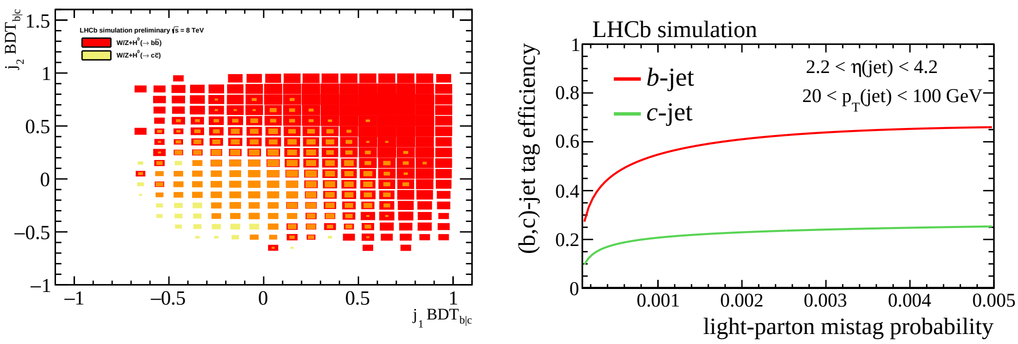

Figure 2: Outputs of the two BDTs employed to separate b- and c-jets (left). b- and c-jet tagging efficiency as a function of the light jet mis-identification probability (right) [4].

3. Measurement of Differential Cross Sections for $b\bar{b}$ and $c\bar{c}$ Jets

To perform an inclusive search of $h \to b\bar{b}$ and $h \to c\bar{c}$, the main background coming from di-jets produced by QCD processes has to be carefully considered. This analysis [3] aims at measuring the differential cross sections for di-jets originating from b- and c-quarks, as a function of several kinematic variables.

In this study, data from Run 2016 are used, at a center-of-mass energy of 13 TeV, accounting for a total integrated luminosity of 1.6 fb^{-1}. Two Multi-Variate Analysis (MVA) discriminators are combined from two BDT outputs to provide the flavor composition of di-jets. This approach enables a measurement of differential cross-section and cross-section ratios $R = \sigma_{b\bar{b}}/\sigma_{c\bar{c}}$, as functions of kinematic variables. Results from this study align well with theoretical expectations, marking the first measurement of the $c\bar{c}$ di-jet differential cross section at a hadron collider, and allowing a better understanding of such processes for further searches.

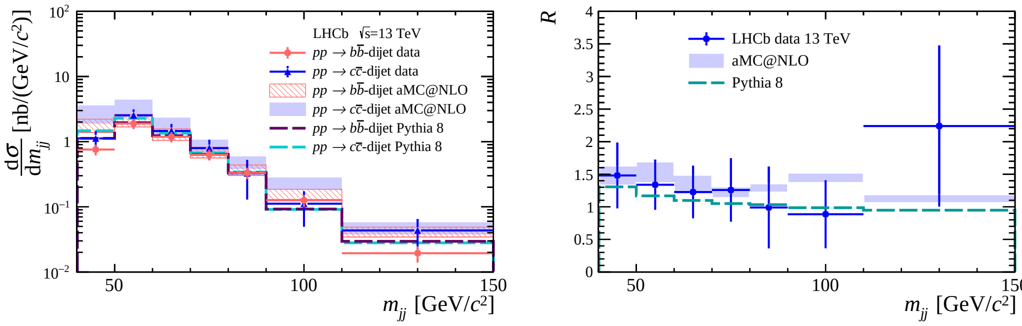

Figure 3: Differential cross section measurements for $b\bar{b}$ and $c\bar{c}$ di-jets as a function of the di-jets invariant mass m_{jj} (left). Ratio R as a function of the di-jets invariant mass m_{jj} (right). [3]

4. Towards inclusive Higgs searches in di-jets final states

The LHCb experiment is advancing towards fully inclusive Higgs searches, specifically targeting $h \to b\bar{b}$ and $h \to c\bar{c}$ decays. This new approach targets the analysis of the full Run 2 dataset, and it uses a model-independent method that imposes no restrictions on the Higgs production mechanism by simply requiring the presence of two tagged jets in the final state. With respect to the past analyses, this study relies on multiple improvements [5]. The first improvement relies on the usage of a new reconstruction tool to better reconstruct the di-jets invariant mass. This is rather important, as the search for Higgs' decays is performed by fitting the invariant mass spectrum of di-jets. To achieve a better reconstruction performance, the jet energy correction is based on a Gradient Boosted Regressor (GBR), which takes as input several variables coming from the jet substructure. As shown in Fig. 4, the invariant mass resolution improves by almost 50% with respect to the standard tools used in previous analyses.

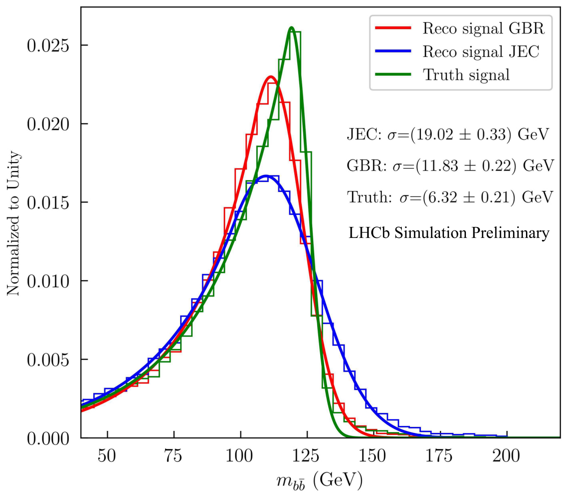

Figure 4: Invariant mass of di-jets pairs originated from the decay of a Higgs boson. The result of the new reconstruction tool based on GBR is shown in red, to be compared with the standard jet energy correction (JEC) procedure, shown in blue [5].

The second improvement comes from the tagging procedure. A Deep Neural Network (DNN) is used for jet tagging, which uses over 400 observables related to jet kinematics and substructure to accurately tag b- and c-jets. The structure of the DNN is heavily inspired by the CMS DeepJet algorithm. While in the previous analysis, the tagging of jets was performed by a Secondary Vertex Tagging (SVT) procedure, and afterward BDTs were used to further separate b- and c-jets, with this new approach the jet tagging does not rely anymore on the presence of a secondary vertex inside the jet, therefore improving the overall efficiency of the algorithms and increasing the statistics for those measurements relying on this tool. Figure 5 shows the jet tagging performance using a DNN model compared to the traditional SVT method for b- and c-jets, where the light jet mis-identification probability is forced to be the same for the two algorithms. The new DNN algorithm is showing a relevant improvement when compared to the standard SVT method, particularly for the c-jet tagging, where a 20% improvement is found.

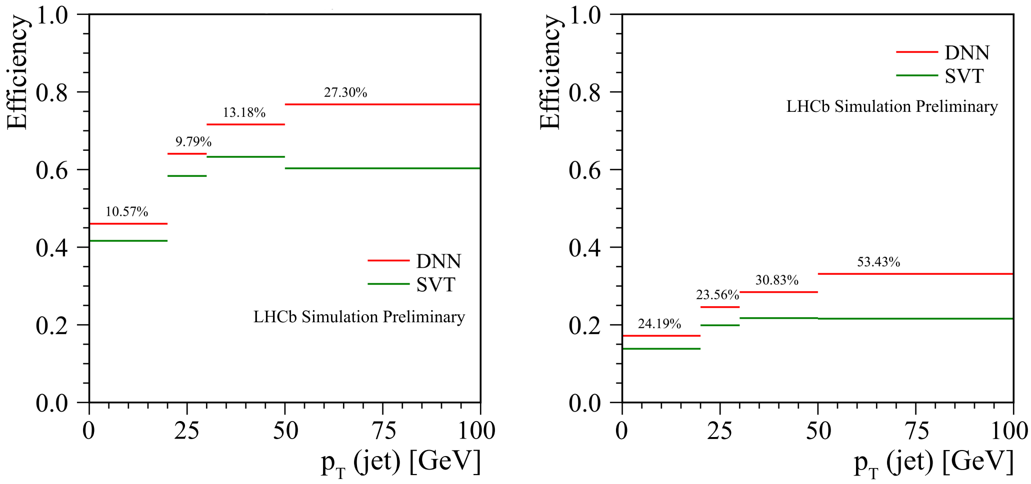

Figure 5: Jet tagging performance using a DNN model compared to the traditional SVT method, for b- (left) and c-jets, as a function of jet transverse momentum [5].

5. Prospects for Future LHCb Upgrades in Higgs Studies

Looking ahead, LHCb aims to extend its program of Higgs searches to higher integrated luminosities, projected to reach up to 300 fb^{-1} by the end of Run 5 [6]. Enhanced c-tagging efficiency, potentially exceeding 30% in the whole momentum range, will allow the improvement in sensitivity in measuring the Yukawa coupling for charm quarks, y_c, aiming for limits near twice the Standard Model prediction. Future studies will build on recent analysis developments, incorporating state-of-the-art machine learning techniques and detector upgrades that further optimize b- and c-tagging. This will improve the quality of LHCb's Higgs program in measuring the interactions of the Higgs boson with charm quarks, contributing to our understanding of Yukawa couplings and advancing the search for new physics phenomena.

6. Conclusion

The LHCb experiment has become a general-purpose forward detector that is able to investigate both QCD and electroweak physics in the forward region. In recent years, emphasis has been put to study searches for the decay of the Higgs boson in pairs of jets. With ongoing upgrades and novel analysis methods, LHCb is well-positioned to contribute critical insights into Higgs couplings to heavy quarks, advancing our understanding of the Standard Model and potential new physics.

References

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