LHCb, while purpose built for $b$-physics, also functions as a general purpose forward detector, covering the pseudo-rapidity range 2.0 to 5.0. LHCb has performed several measurements including jets, which concern, e.g., QCD, top and Higgs physics. A selection of LHCb results in this area will be presented, focusing on the most recent ones.
1 Introduction

LHCb is one of the four largest detectors of the Large Hadron Collider (LHC) project at CERN (Geneva, Switzerland). It is a single-arm forward spectrometer with a fully instrumented detector with a unique coverage in terms of pseudo-rapidity: $2 < \eta < 5$ [1]. While originally designed to study the production and decay of $b$ and $c$ hadrons, LHCb has extended its physics programme to also include other areas such as physics with jets.

The results presented in these proceedings correspond to proton-proton collision data taken by LHCb during Runs 1 and Run 2 of the LHC, recorded at centre of mass energies of $\sqrt{s} = 8$ TeV (during the year 2012) and 13 TeV (during the year 2016). LHCb recorded 2 fb$^{-1}$ of data in 2012 and 1.7 fb$^{-1}$ of data in 2016.

Measurements of jets at LHCb address several interesting areas, such as:

- QCD: to set important constraints on proton PDFs, to probe hard QCD in a unique kinematic range or to look into jet properties.
- Higgs physics: in direct searches for the Higgs boson decaying to $b\bar{b}$ and $c\bar{c}$ final states.
- Direct searches of long-lived beyond the SM particles decaying to jets.

In these proceedings, the first two groups of topics will be covered, while examples of the third can be found elsewhere [2].

2 Jet reconstruction at LHCb

Jets are reconstructed at LHCb using a particle flow algorithm [3] and clustered using the anti-$k_T$ algorithm [4] with $R = 0.5$. The calibration of the jet reconstruction is performed in data using $Z \rightarrow \mu^+\mu^-$ events containing a jet reconstructed back-to-back with respect to the $Z$. The efficiency for reconstructing and identifying jets is around 90% for jets with a transversal momentum, $p_T$, above 20 GeV/$c$.

Furthermore, LHCb has developed [5] a method to tag jets and determine whether they correspond to a $b$ or $c$ hadron or to a lighter particle. Jets are tagged whenever a secondary vertex (SV) is reconstructed close enough to the jet in terms of $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$. This provides a light jet mistag rate below 1%, with an efficiency on $b$ ($c$) jets of $\sim 65\%$ ($\sim 25\%$). Moreover, using the SV and jet properties, two BDTs [6] have been developed: one to separate heavy from light jets (BDT($bc|udsg$)) and one to separate $b$ from $c$ jets (BDT($b|c$)). Figure 1 shows the two-dimensional distribution of BDT($b|c$) vs. BDT($bc|udsg$) for MC $b$ and $c$ SV-tagged jets, together with the BDT($b|c$) distribution in a $c$-enriched data sample. Fitting the BDT($b|c$) distribution allows separating the different components in data.

![Figure 1: Two-dimensional distribution of BDT($b|c$) vs. BDT($bc|udsg$) for MC $b$ (left) and $c$ (center) jets. BDT($b|c$) distribution in a $c$-enriched data sample. More details about the method can be found in [5].](image)
3 Measurements with EW bosons and jets

3.1 Z and W + jets production

LHCb has measured the production of Z and W bosons associated with jets using the data collected at $\sqrt{s} = 8$ TeV \cite{7}. Jets are reconstructed as explained above, while Z and W bosons are reconstructed using the muonic final states. The production of W boson plus jets is discriminated from misidentified background processes arising in QCD using a muon isolation variable, which is built as the ratio between the $p_T$ of the jet containing the muon and the $p_T$ of the muon alone. Figure 3.1 (left) shows the distribution of this variable, with genuine muons from the W boson peaking at 1.

The absolute and differential cross sections, as well as ratios of these and charge asymmetry have been measured in this analysis and compared to different theoretical predictions. The agreement found is good in general. A graphical example can be found in Fig. 2 (right picture).

3.2 W + b\bar{b}, W + c\bar{c} and t\bar{t}

LHCb has measured the $W^+ + b\bar{b}$, $W^+ + c\bar{c}$, $W^- + b\bar{b}$, $W^- + c\bar{c}$ and $t\bar{t}$ production cross sections using a sample of pp collisions taken at $\sqrt{s} = 8$ TeV with a high-$p_T$ isolated lepton (electron or muon) and two heavy flavour ($b$ or $c$) tagged jets in the final state. The channel $W + c\bar{c}$ is studied for the first time.

In this analysis, jets are reconstructed as already described and those coming from heavy quarks tagged using the method explained above. In order to extract the different signal components, a simultaneous 4-D fit is performed to the $\mu^+$, $\mu^-$, $e^+$ and $e^-$ samples. The four variables used in the fit are the dijet mass, a MVA-response to discriminate $t\bar{t}$ from $W + b\bar{b}$ and $W + c\bar{c}$ events (referred to as uGB \cite{8}) and BDT($b|c$), used for both jets. As an example, Fig. 3 (left picture) shows the projections of this fit for the $\mu^+$ sample.

This analysis measures the production of $W^+ + b\bar{b}$, $W^+ + c\bar{c}$, $W^- + b\bar{b}$, $W^- + c\bar{c}$ and $t\bar{t}$ with statistical significances of 7.1σ, 4.7σ, 5.6σ, 2.5σ and 4.9σ respectively. The cross sections obtained in the LHCb fiducial region and the Next-to-Leading-Order (NLO) theory predictions can be found in Fig. 3 (right picture).

3.3 Search for associated production of the Higgs boson decaying to b\bar{b}

Using the same dataset as in Sect. 3.2, LHCb has performed search for the SM Higgs boson decaying to a pair of b\bar{b} quarks and produced in association with a W or Z boson \cite{10}. In this case, the cut on the $p_T$ of
Data LHCb, $s = 8$ TeV

As an example of the LHCb discrimination capabilities between $H \rightarrow b\bar{b}$, $H \rightarrow c\bar{c}$ and $t\bar{t}$ production cross sections the jets is tightened to reduce the $W + b\bar{b}$ background, and two uGB are created to discriminate signal from background: one to separate signal from $t\bar{t}$ and another to separate signal from $W + b\bar{b}$. Then, the expected background is fixed to the theory predictions and this is compared to data using the CL$_S$ method. The result obtained, showed in Fig. 4 is not competitive with ATLAS and CMS, but it is currently the best limit on Higgs boson production at LHCb, and shows the future potential in this channel.

At the same time, as part of this analysis, a search for $H^0 \rightarrow c\bar{c}$ was performed too. Although the final result was not significant, a search could be performed if a High Luminosity LHCb upgrade takes place. As an example of the LHCb discrimination capabilities between $H^0 \rightarrow b\bar{b}$ and $H^0 \rightarrow c\bar{c}$, Fig. 4 shows the BDT$(b|c)$ distribution for both jets in both decays, normalized to their relative SM branching fractions.

Figure 3: Left: Example of the fit used to extract the production cross sections in [9]. Projections of the simultaneous 4D-fit results are shown for the $\mu^+$ sample corresponding to: a) the dijet mass; b) the uGB response; the BDT$(b|c)$ of the c) leading and d) sub-leading jets. Right: Graphical display of the measured $W + b\bar{b}$, $W + c\bar{c}$ and $t\bar{t}$ production cross sections and the corresponding NLO theoretical SM predictions.

Figure 4: Left, CL$_S$ vs. the product $B(H^0 \rightarrow b\bar{b}) \times \sigma(pp \rightarrow W/Z + H^0)$ normalized to the SM values. This plot was used to obtain a 95% CL upper limit on this ratio of $\sim 50$. Right, BDT$(b|c)$ distribution for both jets in $H^0 \rightarrow b\bar{b}$ (red) and $H^0 \rightarrow c\bar{c}$ (yellow) decays. The relative normalization corresponds to the SM branching fractions. More information can be found in [10].
4 $J/\psi$ production in jets

Measuring the production of $J/\psi$ within jets can be useful to study QCD phenomenology. In this regard, for instance, $J/\psi$ are expected to be isolated if they are produced directly in parton-parton scattering. To study this, $z(J/\psi)$ is defined as the ratio of the $p_T$ of the $J/\psi$ and the $p_T$ of the jet that contains the $J/\psi$ ($z(J/\psi) \equiv p_T(J/\psi)/p_T(jet)$). Therefore, $z(J/\psi)$ is a good proxy of the $J/\psi$ isolation.

LHCb has measured the distribution of $z(J/\psi)$ using 2016 data taken at $\sqrt{s} = 13$ TeV [11]. It should be highlighted that for this analysis the $J/\psi$ were selected directly at trigger level, which allowed a significant increase of statistics. After this, the jets are reconstructed offline, and the $J/\psi$ are separated if they are prompt or produced from a $b$ quark decay (detached). For this, a pseudo-lifetime is defined and a fit is performed to separate both components. Figure 5 shows this fit, together with an example of the dimuon invariant mass fits used to discriminate $J/\psi$ from the combinatorial background.

![Figure 5](image)

Figure 5: Examples of fits to subtract the $J/\psi$ yields [11]. Left, dimuon invariant mass. Right, pseudo-lifetime, which allows to differentiate prompt $J/\psi$ from those coming from a $b$ quark decay.

In order to measure the raw distribution of $z(J/\psi)$, the detector response has to be corrected. For this, an iterative 2D Bayesian unfolding is performed, which corrects for the $z(J/\psi)$ and $p_T(jet)$ resolution, which are at the level of $\sim 20-25\%$.

With all this, the $z(J/\psi)$ distribution is measured for prompt and detached $J/\psi$. The results are compared to the PYTHIA 8 predictions. The results can be found in Fig. 6. Although the detached $z(J/\psi)$ distribution is well described by PYTHIA 8 [12], this is not the case with the prompt one, even when Double Parton Scattering effects are taken into account. This result indicates that additional processes must be considered to explain $J/\psi$ production, either through directly considering higher order effects in the hard process, or through simulating $J/\psi$ production in the parton shower. In this regard, as a consequence of this result, alternative descriptions of the quarkonium production have already been suggested, providing a better qualitative description of the prompt $z(J/\psi)$ distribution [13].

5 Conclusions

Although it was initially designed for flavour physics, LHCb can now be considered a general purpose detector in the forward direction. Several examples of this have been shown through results involving jets. The Run 2 of the LHC will extend even more the capabilities of LHCb beyond flavour physics.
Figure 6: $z(J/\psi) \equiv p_T(J/\psi)/p_T(\text{jet})$ distribution for prompt $J/\psi$ (left) and $J/\psi$ coming from a $b$ quark decay (right) [11]. In both cases, the results are compared to the theory predictions.

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