Search for $\Lambda_b^0 \rightarrow \Lambda^0 \gamma$ at LHCb

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Abstract

The $\Lambda_b^0 \rightarrow \Lambda^0 \gamma$ decay plays an important role in the determination of the photon polarization and the search of new physics. A search for this decay has been performed using the 3 fb$^{-1}$ data samples by the LHCb experiment at CERN during Run I (2011–2012). A background study has been carried out on the $\Lambda_b^0$ and $\Lambda^0$ mass sidebands and a multivariate analysis has been set to extract the signal yield. Though a reasonable large branching ratio is expected for this mode ($\mathcal{O}(10^{-5})$), the difficult configuration of its decay (a $\Lambda^0$ and $\gamma$ in the final state, no reconstructed $\Lambda_b^0$ vertex) as well as the lack of dedicated HLT2 line, result in a very low efficiency and sensitivity. No signal event has been found in the data. The trigger efficiency is explained in details and an exclusive HLT2 trigger line, which requirements are based on this analysis, has been proposed for Run II. This should result in an increase of the trigger efficiency by one order of magnitude and allow us to observe for the first time the $\Lambda_b^0 \rightarrow \Lambda^0 \gamma$ decay.
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1 Introduction

The aim of this analysis is to search for $\Lambda^0_b \rightarrow \Lambda^0(\rightarrow p\pi^-)\gamma$ decay in the data samples taken in 2011 and 2012 by the LHCb experiment at CERN. The $\Lambda^0_b$ is a heavy baryon with quark content $udb$, it has a spin 1/2 and a mass of 5620.2 MeV/$c^2$ [1].

Flavor-changing neutral currents (FCNC) are forbidden at first order by the GIM mechanism [2] in the Standard Model (SM)\footnote{The GIM mechanism (Glashow-Iliopoulos-Maiani, 1970) states that there is mixing between the generations of quark, their amplitudes is given by the CKM matrix. However, there is no mixing between quark with the same electric charge.}. They can only appear with higher order processes, for example via a penguin diagram (Fig. 1). The $\Lambda^0_b \rightarrow \Lambda^0(X)\gamma$ decay, where $X$ is the mass of the $\Lambda^0$ baryon, occurs through the electromagnetic penguin process $b \rightarrow s\gamma$. The main motivation for studying this decay is to constrain new physics from the polarization of the emitted photon. The photon in this decay is expected to be mostly left-handed by the SM. However some new physics models predict a right-handed component for the polarization of the photon [3, 4]. The polarization of the photon is thus a promising tool to reveal physics beyond the SM [5].

This work will concentrate on the ground state $\Lambda(1115)^0$ that has a spin 1/2 and a mass of $(1115.683 \pm 0.0006)$ MeV/$c^2$. From now, if not stated explicitly, $\Lambda^0$ will state as the ground state $\Lambda(1115)^0$. The $\Lambda^0$ decays into one proton and one pion with a branching ratio of 64% [1], but heavier $\Lambda(X)$ baryons decay strongly, mostly into one proton and one kaon. The branching ratio of $\Lambda^0_b \rightarrow \Lambda^0\gamma$ is estimated in the framework of the SM [7] to be

$$B(\Lambda^0_b \rightarrow \Lambda^0\gamma) \simeq (3 - 10) \cdot 10^{-5}.$$  \hspace{1cm} (1)

This decay is difficult to observe because the presence of a photon in the final state combined with the long lifetime of the $\Lambda^0$ baryon ($c\tau = 7.89$ cm [1]) makes it impossible to reconstruct the decay vertex of the $\Lambda^0_b$ baryon (see Fig.2).

An upper limit of the branching ratio of the decay $\Lambda^0_b \rightarrow \Lambda^0\gamma$ has been established by the CDF collaboration in 2002 [8]. They used data produced in $p - \bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at Fermilab. They considered three different radiative $B$ hadrons including $\Lambda^0_b \rightarrow \Lambda^0(\rightarrow p\pi^-)\gamma$, for which two independent methods to identify the photons have been used. The first method is the
detection of the photon in the electromagnetic calorimeter. The second one is the identification of an $e^+e^-$ pair produced by the photon before the calorimeter. Combining both methods, they obtained an upper limit on the branching ratio of $\Lambda_0^b \rightarrow \Lambda^0\gamma$ as
\[
B(\Lambda_0^b \rightarrow \Lambda^0\gamma) < 1.9 \cdot 10^{-3},
\]
two orders of magnitude above the expected branching ratio (Eq. 1).

The $\Lambda_0^b \rightarrow \Lambda^0\gamma$ decay has never been searched in LHCb data but has been studied with simulation in the PhD thesis of Federica Legger [9] in 2006, where a signal yield of 750 events for the $\Lambda_0^b \rightarrow \Lambda^0\gamma$ decay was predicted for one year of data taking.

The photon polarization $\alpha_\gamma$ is defined as:
\[
\alpha_\gamma = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)},
\]
where $P(\gamma_{L/R})$ is the probability of production of a left/right-handed photon. The Hamiltonian of the electromagnetic penguin decay $b \rightarrow s\gamma$ can be estimated at the leading order (LO) by the Heavy Quark Effective Theory (HQET) [7]. The photon polarization is then estimated to be:
\[
\alpha_{\gamma}^{LO} = \frac{1 - |r|^2}{1 + |r|^2},
\]
where $r$ is given by the ratio of the masses of the $s$ and $b$ quarks, $r = \frac{m_s}{m_b}$, expected to be small. Therefore the photon emitted in the $b \rightarrow s$ transition is predominantly left-handed. However QCD corrections or $C\mathcal{P}$ violating effects can be included at higher order and modify the relation 4.

Photon polarization can be tested by measuring the following angular distributions:
\[
\frac{d\Gamma}{d\cos(\theta_\gamma)} \propto 1 - \alpha_\gamma P_{\Lambda_b} \cos(\theta_\gamma)
\]
\[
\frac{d\Gamma}{d\cos(\theta_p)} \propto 1 - \alpha_\gamma \alpha_{p,1/2} \cos(\theta_p),
\]
where
- $\theta_\gamma$ is the polar angle of the photon with respect to the spin of the $\Lambda_0^b$,
- $P_{\Lambda_b}$ is the polarization of the $\Lambda_0^b$,
- $\theta_p$ is the polar angle of the proton with respect to the $\Lambda^0$ momentum direction and
- $\alpha_{p,1/2}$ is the weak decay parameter.

The equation 5 is sensitive to the photon polarization only if the $\Lambda_0^b$ is polarized. The polarization of the $\Lambda_0^b$ baryon has been measured by the LHCb collaboration by performing an angular analysis on the $\Lambda_0^b \rightarrow J/\psi\Lambda$ decay using the 2011 data at $\sqrt{s} = 7$ TeV [10]. The HQET theory predicts that the transverse polarization of $\Lambda_0^b$ hadrons produced from highly energetic $b$ quarks preserves the polarization of the $b$ quarks while their longitudinal polarization is canceled due to parity conservation in strong interactions. This transverse production polarization has been measured to be small and compatible with zero: $0.06 \pm 0.07 \pm 0.02$.

As a consequence, the only way to measure the photon polarization is through equation 6. For spin 1/2 $\Lambda(X)$ resonances decaying into a proton and kaon, the proton angular distribution is
flat, the ground state $\Lambda(1115)$ resonance is the only $\Lambda^0$ baryon that can used to find the photon polarization. The weak parameter for $\Lambda(1115)^0$ has been measured to be $\alpha_{p,1/2} = 0.642 \pm 0.013$ [1].

2 LHCb experiment

The LHCb is one of the experiments located around the Large Hadron Collider (LHC) ring at CERN [11]. The LHC is a circular collider of 27 km circumference that produces mainly $p-p$ collisions. The collisions were achieved with a center-of-mass energy of $\sqrt{s} = 7$ TeV in 2011 and $\sqrt{s} = 8$ TeV in 2012. The LHC experiments aim to test the Standard Model and searches for new physics.

The LHCb experiment is dedicated to the high precision study of $CP$ violating processes in the quark sector and rare decays of beauty and charm hadrons. These fields are good probes for physics beyond the SM. LHCb collected data corresponding to an integrated luminosity of $1.1 \text{fb}^{-1}$ in 2011 and $2.08 \text{fb}^{-1}$ in 2012 (Fig. 4).

The instantaneous luminosity of the LHCb experiment at the interaction point is around $\mathcal{L} = 4 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$ [12], much lower than the LHC luminosity. This low luminosity allows to avoid multiple $p-p$ interactions in the same bunch crossing (the mean number is 1.8 [13]). If an event contains several PVs, it is difficult to distinguish them from secondary vertices, making the analyses more challenging. Other advantages of a low luminosity are less detector occupancy and less radiation damages. At the high energies of the LHC, the $b\bar{b}$ quarks are produced at very low angles, either both forward or both backward (Fig. 3). This fact motivated the choice of the peculiar geometry of the LHCb detector.

The LHCb detector is a single-arm spectrometer that covers 10 to 300 mrad in the bending plane and 250 in the non-bending plane. The main distinctive features of the LHCb detector are

\footnote{$\Lambda(1115) \to p\pi$ is parity violating, while the decay $\Lambda(X) \to pK$ conserves parity.}
a high resolution vertex detector, a precise particle identification system and a high performance trigger. The LHCb subdetectors can be classified into two main categories: the tracking system and the particle identification system.

2.1 Particle identification system

The particle identification system is composed of three elements:

- Two Ring Imaging Cherenkov detectors (RICH1 and RICH2) are designed to identify charged particles: kaons, protons, pions, muons and electrons. They distinguish particles using the Cherenkov effect; when a charged particle penetrates a medium with a speed greater than the speed of light, it emits photons in a cone which aperture depends on the momentum of the particle (Fig. 6).

- The calorimeter system identifies photons, electrons and hadrons, and measures their energy and their position. It is also used in the hardware stage of the trigger to select very quickly particles with high $E_T$. The subdetectors are made by alternating metal and scintillators planes to detect the particles and measure their energy. The scintillator planes are segmented in cells of various sizes. The calorimeter system is composed of:
  - The Scintillating Pad Detector (SPD) estimates the number of charged tracks. The total number of cells of the SPD which have a hit is used to evaluate the charged track multiplicity and to reject high occupancy events.
  - The PreShower detector (PS) identifies electromagnetic or hadronic showers and can

Figure 5: View of the LHCb detector in the non-bending plane [11]. The $z$ axis is along the beam pipe.

Figure 6: Reconstructed Cherenkov angle as a function of the track momentum in RICH1 [14].
thus disentangle neutral pions from photons \(^3\) by analyzing the longitudinal profile of the showers.

- The Electromagnetic Calorimeter (ECAL) measures the transverse energy of photons and electrons. It contains the full electromagnetic shower. It alternates scintillating tiles and lead plates.

- The Hadronic calorimeter (HCAL) is used mainly for trigger purposes and identification of the hadrons. The HCAL is not thick enough to contain the full hadronic shower; it only gives an estimation of the \(E_T\) of the hadrons. The scintillating tiles and iron plates of the HCAL are parallel to the beam axis.

- The muon system composed of five stations, each having four quadrants. The stations are located at the end of the LHCb detector because of the very long lifetime of muons \((c\tau \simeq 660 \text{ m})\) and their low interaction probability. The muon system is used to give fast information to the high-\(p_T\) L0 muon trigger and identification for the high level triggers.

### 2.2 Tracking system

The tracking system allows a high precision reconstruction of tracks of charged particles. It is composed of:

- The Vertex Locator (VELO) \([15]\) is a silicon microstrip detector providing accurate reconstruction of displaced vertices. In this purpose, it surrounds the interaction point and can be as close as 7 mm to the beams. The VELO best single hit resolution is 4 \(\mu\)m \([16]\). It is composed of two retractable detector halves with 21 tracking modules (Fig. 7). The two halves can be retracted up to 6 cm during the LHC beam injection. A module consists of one \(r\) and one \(\phi\) measuring silicon sensors, which are 300 \(\mu\)m thick half-disks with active inner and outer radii of 8 mm and 42 mm, respectively. The \(r\) module measures the radial distance while the \(\phi\) module the azimuthal angle of the hit. There are 16 modules between about \(-200\) and \(300\) mm, where the origin is defined as the interaction region, and the 5 remaining are arranged between 450 and 700 mm.

- The Turicensis Tracker (TT) is located in front of the magnet and is composed of four plates of silicon strip detector arranged in two half stations. It recovers low momentum tracks being bent by the magnet out of the acceptance of the tracking stations.

- The magnet has with a bending power of 4 Tm allows to measure the radius of curvature of charged particles trajectories. The magnetic field can be inverted to cope with left-right asymmetries in the detector.

- After the magnet, they are three tracking stations (T1, T2 and T3). Each of them is split in two parts, the inner and outer tracker, using different technologies. The Inner Tracker (IT) is a silicon strip detector situated around the beam pipe, where high density of events

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\(^3\) Neutral pions mostly decay into two photons and can easily be misidentified as photons; if the pions are highly boosted, they produce photons in a very low angle which can be reconstructed as one single cluster.
Figure 7: Illustration of the vertex locator at LHCb. Down left: Both halves of the VELO are fully closed with a small overlap, allowing the modules to be at 7 mm from the beams. Down right: Both halves of the VELO are retracted up to 3 cm each to allow the LHC beam injection.

is expected. The Outer Tracker (OT), composed of four layer of drift chambers, detects charged tracks with an angle higher than 15 mrad.

Track types

Depending of the number of hits in each part of the tracking system, different track types are defined [17]. Relevant track types for this work are (Fig. 8):

- **Long Tracks (L):**
  Tracks traversing the detector, having hits from the VELO (at least 3 \( r \) hits and 3 \( \phi \) hits) to the tracking stations (at least 1 hit in each station). These tracks have the most precise momentum reconstruction and are thus commonly used in physics analyses.

- **Downstream tracks (D):**
  Tracks with hits in the TT (at least one hit in each half station) and in the tracking stations. It occurs when very long lived particles decay after the VELO (the daughters of the \( \Lambda \) for example).

2.3 Relevant observables for the analysis

We define here the observables used for this analysis.

- **Track quality**
  The track \( \chi^2 \) indicates the quality of the track fit. A low track \( \chi^2 \) reduces the back-
2.3 Relevant observables for the analysis

Figure 9: Illustration of the $\Lambda^0$ observables $IP$ (impact parameter), $p_T$ (transverse momentum) and $FD$ (flight distance) in the decay $\Lambda^0_b \rightarrow \Lambda^0 \gamma$. (MTDOCA)

ground composed of ghost particles, which are reconstructed tracks produced by fake hits corresponding to no particle.

- **Transverse momentum**
  The transverse momentum of a particle is defined as its projection on the plane perpendicular to the beam axis, illustrated in Fig. 9.

- **Impact parameter**
  The impact parameter of a candidate is the perpendicular distance between its momentum direction and the PV as illustrated in Fig. 9. The PV of a candidate is chosen among the multiple PVs in an event as the one according to which the $\chi^2$ of impact parameter ($\chi^2_{IP}$) of the candidate is the smallest. The $\chi^2_{IP}$ measures the compatibility of the hypothesis that the particle comes from the primary vertex. To get the $\chi^2_{IP}$ of a candidate, a vertex is built from the tracks used to reconstruct the PV combined with the tracks used to reconstruct the $B$-candidate vertex. The $\chi^2$ of this new vertex is then computed and subtracted to the $\chi^2$ of the reconstructed $B$-candidate vertex, giving the $\chi^2_{IP}$. A cut on $IP(\Lambda^0)$ or $\chi^2_{IP}$ ($\Lambda^0$) reduces the background of candidates coming from the primary vertex (called *prompt* particles).

- **DOCA and vertex**
  The distance of closest approach (DOCA) of a candidate reconstructed with two tracks is the minimal distance between the two tracks. It gives an indication of the quality of the reconstructed vertex.

In order to provide an estimation of position of a decay vertex without reconstruction, the Mother-Trajectory distance-of-closest-approach (MTDOCA) has been introduced [18]. A ”mother trajectory” is constructed from the $\Lambda^0$ candidate closest PV along to the reconstructed $\Lambda^0$ momentum direction, where the $\Lambda^0_b$ momentum is obtained by combining the photon and the $\Lambda^0$ candidate momenta. The MTDOCA of $\Lambda^0_b$ is the DOCA between the $\Lambda^0$ candidate momentum and this ”mother trajectory”.

- **Vertex separation**
The vertex separation of a candidate, also called *flight distance*, is the distance between the PV and the decay vertex of a candidate. The vertex $\chi^2$ indicates the quality of the decay fit. The vertex separation $\chi^2 (\chi^2_{VS})$ is constructed by calculating the $\chi^2$ of the common vertex formed by candidate decay vertex and the PV.

### 2.4 Trigger system

The goal of the trigger system [19] is to reduce the interaction rate of 40 MHz to 5 kHz, the largest rate at which events can be stored. Among the total visible interaction rate only 1% is expected to contain $b\bar{b}$ quarks pairs, with 15% of them producing at least one $B$ hadron with all its daughter particles included in the acceptance of the LHCb detector. The typical $B$ mesons branching ratios used for CP violation studies are smaller than $10^{-3}$, hence the need for the offline selections to achieve to highest signal over background ratio possible. To do so, the trigger exploits the typical high mass and lifetime of $B$ hadrons to select the most relevant events for LHCb analyses.

The trigger system consists of a hardware trigger (L0), exploiting information from the muon and the calorimeter systems, and a software trigger (HLT), which reconstructs all charged particles with high $p_T (p_T > 300$ MeV/c for 2011 and $p_T > 500$ MeV/c for 2012), and neutral particles by analyzing energy deposits in the calorimeter.

#### Level-0 Trigger (L0)

The Level-0 trigger is the hardware stage of the LHCb trigger that aims to reduce the beam crossing rate to 1 MHz, corresponding to the maximum rate with which all the subdetectors can be read out. The two main subdetectors triggers used in L0 trigger are:

- **The L0 Calorimeter Trigger** reconstructs the highest $E_T$ hadron, photon and electron clusters in the ECAL and HCAL. To do so, first the clusters are formed by summing the $E_T$ of each 2x2 cells. The information of the calorimeter subdetectors is then used to identify the type of particle for each cluster:
  - The PS identifies L0 candidates as electromagnetic if the energy deposit exceeds a certain threshold, proof that an electromagnetic shower began in the lead wall.
2.4 Trigger system

- The SPD information is then used to recognize photons from electrons candidates. For hadrons candidates, the $E_T$ from the ECAL is added to the HCAL clusters.

Finally, the L0 candidate with the highest $E_T$ cluster for each type of particle is kept.

- **The L0 Muon Trigger** reconstructs the two highest $p_T$ muons from each quadrant of the muon detector.

**Level-1 Trigger**

The Level-1 Trigger (HLT1) uses only a partial reconstruction of the events in order to reduce the rate by a factor 20, allowing the Level-2 Trigger to use fully reconstructed events. Most HLT1 trigger lines are kept inclusive, which means that they can trigger various $B$-hadron decays. The most relevant HLT1 triggers for this work are the single track lines [20], which search for a single track with specific requirements to select for $B$-hadrons decays. The reconstruction of the tracks obeys the following stages:

1. **Global Events Cuts (GEC):** The events with too high occupancy in the VELO, IT and OT detectors are removed.

2. **VELO track selection:** Because of timing constraints, the strategy is to first reduce the events using only the VELO information. A minimum number of hits and a maximum number of missing hits in the VELO are required. The latter is computed by subtracting the expected number of hits, given the track direction and the first measured point, by the numbers of hits. Finally high impact parameter events are selected.

3. **Forward track reconstruction:** The VELO tracks are extrapolated to the tracking stations to estimate their momentum. Only events with high transverse momentum and momentum are reconstructed in order to save processing time.

4. **Forward track selection:** The events are reduced by selecting high $p$ and $p_T$ tracks, then the tracks are fitted and selected with small $\chi^2$ and large $\chi^2_{IP}$.

The $p_T$ requirement on the track is slightly relaxed in order to increase efficiency for radiative decays in the photon or electron track lines, as the L0 requirement of a high $E_T$ photon makes it less likely that a high $p_T$ track can also be found in the same decay.

**Level-2 Trigger**

The rate reduction obtained in the HLT1 trigger allows the Level-2 trigger (HLT2) [21] to use selections that are closer to those used in offline analyses, with the tracking only reconstructing long tracks with $p_T > 500$ MeV/c and $p > 5$ GeV/c. The HLT2 bandwidth is mostly dedicated to inclusive lines, but some exclusive ones are kept, at a lower rate, to select particular decays.

The most important inclusive HLT2 trigger lines for this work are the topological ones [22, 23]. They are designed to trigger any $B$-hadrons decay with at least two charged tracks, providing high background rejection and high signal efficiency for most $n$-body $B$-hadrons decays.
As not all the daughter particles of the $B$ hadrons are used to build the topological trigger candidates, a cut on the mass of the $B$-candidate is to be avoided to preserve inclusiveness. It is possible to use the corrected mass:

$$m_{\text{corr}} = \sqrt{m^2 + |p_{T,\text{miss}}|^2 + |p_{T,\text{miss}}|},$$

where $m$ is the reconstructed invariant mass of the $B$-candidate and $|p_{T,\text{miss}}|$ is the missing transverse momentum with respect to its flight direction as illustrated in Fig. 12.

The corrected mass allows to take into account the missing particles even without knowing their number or their identity. If there is one single massless missing particle, the corrected mass gives the exact mass of the $B$-candidate. In the case of the decay $\Lambda_0^0 \rightarrow \Lambda^0 \gamma$, although the missing particle is a photon, the correct mass will not actually recover the missing mass. It is due to the fact that because of the missing $\Lambda_0^0$ decay vertex, the $\Lambda^0$ vertex will be used instead to construct $|p_{T,\text{miss}}|$, therefore the momentum of the photon will not be completely recovered.

![Figure 12: Illustration of the construction of the variable $|p_{T,\text{miss}}|$ for the corrected mass computed in the HLT2 topological trigger. $Y_i$ are the daughters of the decay of the particle $X$. The decay of $X$ has been triggered without the daughter $Y_3$.](image)

To reduce background, the selection criteria of HLT2 topological lines concentrate on quantities that preserve the inclusiveness. Before building the $n$-body candidate, some upfront cuts on $\chi_{\text{IP}}^2$, track $\chi^2$, $p$ and $p_T$ are applied to reduce the data sample.

After these upfront cuts, a Bonsai Boosted Decision Tree (BBDT) method is applied [21]. The BBDT [24] is a statistical analysis tool which performs cut on a complex multi-dimensional binned variable instead of a series of simple cuts. The variables used as input of the BBDT are for the tracks the sum of $p_T$, the minimum $p_T$, the DOCA between them and their $\chi_{\text{IP}}^2$, and for the $B$-candidate the $\chi_{\text{VS}}^2$, the reconstructed mass and the corrected mass.

The radiative topological lines [22] have been designed to trigger on any $B$-hadron decay with at least two charged tracks and a photon of $E_T > 2.5$ GeV. They have been created to improve the efficiency in the regular topological lines for radiative $B$-hadron decays. In this purpose, they have a cut-based approach with looser selections on the tracks than the standard topological lines to take into account the photon.
TIS and TOS events

The TISTOS method makes it possible to compute the efficiency of trigger lines directly on data, and works on MC events too. Two types of (non-exclusive) trigger decisions are defined [25] :

- Trigger Independent of Signal (TIS): The event is triggered independently of the signal, that is the so-called ”rest of the event”, obtained by removing the signal and all detector responses corresponding to it, that generated a positive trigger decision. In the case of single $b\bar{b}$ pair, the other $b$ quark is responsible for the TIS trigger decision, which therefore has some small correlation with the signal through the $B$-hadron momentum.

- Trigger On Signal (TOS): Events that have been triggered on the signal, independently of the rest of the event.

Selection for the analysis

For this analysis, the lack of an exclusive HLT2 line and the particular topology of the signal decay mean that HLT2 efficiency is very low (see section 5), and therefore we will mostly have to rely on TIS. This situation can be be improved on Run II (see section 5.4), but for the selection design procedure we work on L0 and HLT1 selected simulation, concentrating on the background suppression before applying HLT2.

In L0, we will rely on the photon TOS, therefore the relevant L0 lines for TOS events are the electron and photon calorimeter trigger lines $L0\text{Photon}$ and $L0\text{Electron}$.

On the other hand, some HLT1 TIS lines are required to recover the maximum of efficiency. The used HLT1 decisions are the following:

- HLT1 TOS decisions: $Hlt1\text{TrackPhoton}$ or $Hlt1\text{TrackAllL0}$,
- HLT1 TIS decisions: $Hlt1\text{TrackPhoton}$, $Hlt1\text{TrackAllL0}$, $Hlt1\text{TrackMuon}$ or $Hlt1\text{SingleElectronNoIP}$.

3 Samples

Data in LHCb follow a particular procedure before being used for analyses. A selection of the data collected by detectors is made by the hardware trigger L0. Then the events rate is further reduced to allow a reconstruction and a storage of the events by the HLT triggers. Raw data are then reconstructed and a loose offline selection called stripping is applied in order to reduce the data samples for a specific analysis. In order to compare the background from data with known simulated signal events, Monte-Carlo (MC) simulations are produced.

3.1 Monte-Carlo sample

The MC sample used for this work simulates the data from 2012 with $\sqrt{s} = 8$ TeV, for the decay $\Lambda_0^0 \rightarrow \Lambda^0(\rightarrow p\pi^-)\gamma$ in which the $\Lambda^0$ is forced to decay in a $p\pi^-$ final state. In the simulation,
$p - p$ collisions are generated using Pythia [26] with a specific LHCb configuration [27]. Decays of hadronic particles are described by EvtGen [28], in which final-state radiation is generated using Photos [29]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [30, 31] as described in Ref. [32]. The MC events passed the stripping but not the trigger. However, the behavior of each trigger lines is simulated.

More than 6 million events have been generated within the LHCb acceptance (the daughters of the $\Lambda^0_b$ are in the acceptance but not necessarily the daughters of $\Lambda^0$). The generator level cut efficiency is

$$\epsilon_{gen} = 50.3 \pm 0.1 \%.$$  \hspace{1cm} (8)

To have a pure MC signal sample, we require the background category variable BKG_CAT to be zero, which means that the reconstructed candidate in MC is signal [33].

### 3.2 Data sample

The full datasets collected during the Run I of the LHC in 2011 at $\sqrt{s} = 7$ TeV and 2012 at $\sqrt{s} = 8$ TeV, corresponding respectively to 1.1 fb$^{-1}$ and 2.08 fb$^{-1}$ are studied. This is a blind analysis, which means that the signal region of the $\Lambda^0_b$ mass will not be looked at until the whole procedure is validated.

The behavior of the background will be studied with the data located in the mass sidebands of the $\Lambda^0_b$, defined outside the $5\sigma$ of the $\Lambda^0_b$ mass distribution from the data sample (Fig. 13). The sidebands limits have been estimated from a simple gaussian fit to the core of the $\Lambda^0_b$ mass distribution in the MC signal (after preselections):

$$\mu_{M(\Lambda_b)} = 5595.9 \pm 2.2 \text{ MeV}/c^2,$$

$$\sigma_{M_{\Lambda_b}} = 108.8 \pm 0.8 \text{ MeV}/c^2.$$  \hspace{1cm} (9)

However, a more accurate fit will be applied to the unblinded data in section 4.6.

After stripping, there are 34 million of events in the data sample, 16 million of them populating the $\Lambda^0_b$ mass sidebands. The selection will aim to reduce the events in the $\Lambda^0_b$ mass sidebands while keeping the maximum of signal events in the signal mass window.

### 3.3 Stripping

There are different stripping lines optimized for specific decays. The stripping line used for the analysis of the $\Lambda^0_b \to \Lambda^0 \gamma$ decay is the StrippingLb2L0Gamma line, summarized in Table 1.

In this work only the combinations of two long tracks (called LL $\Lambda^0$ candidates in this report) have been considered when building $\Lambda^0$ hadrons candidates (see Fig. 8). The LL $\Lambda^0$ candidates account for 43.5 $\%$ the $\Lambda^0_b$ mass sidebands (see Fig. 14) and 19.8 $\%$ of the MC signal events before trigger. However after applying the L0 and HLT1 triggers, the LL $\Lambda^0$ hadrons represent 39.8 $\%$ of the MC signal events.

Tracks are selected with a low $\chi^2$ to guarantee a good track quality, a track ghost probability smaller than 0.4 and a $\chi^2_{IP}$ greater than 16 to suppress prompt particles. The track ghost
3.3 Stripping

![Figure 13: Distributions of the $\Lambda^0_b$ invariant mass. The blue histogram contains events from the $\Lambda^0_b$ mass sidebands and the red one contains MC signal events. The green and yellow vertical lines show the signal mass window limits (5270.5 and 5922.3 MeV/c$^2$) inside which all the events are considered as signal, respectively the sidebands limits (5051.9 and 6139.9 MeV/c$^2$) beyond which all the events are considered as background.](image)

![Figure 14: Repartition of the track types in background (sidebands of $\Lambda^0_b$). No preselections has been yet applied, only the stripping and the L0 and HLT1 triggers.](image)

![Figure 15: Repartition of the track types in signal MC. No preselections has been yet applied, only the stripping and the L0 and HLT1 triggers.](image)
probability is computed via a neural network which combines general information about tracks (as track $\chi^2$ or the number of hits in the VELO) with specific pattern reconstruction algorithm variables [34].

Protons and pions candidates are selected with high $p$ and $p_T$. All selected pairs of protons and pions are combined to form a $\Lambda^0$ candidate. A cut on the $\chi^2$ of the $\Lambda^0$ vertex fit is applied ($< 9$) to be sure that the tracks come from the a common vertex and discriminate true from combinatorial (fake) $\Lambda^0$ candidates.

The reconstructed invariant mass of $\Lambda^0$ candidates is required to be in a mass window of 20 MeV/c$^2$ around the nominal mass. The parameters of the gaussian fit (Fig. 16) of the $\Lambda^0$ mass distribution of MC signal events are

$$\begin{align*}
\sigma_{M(\Lambda^0)} &= 1.90 \pm 0.01 \, \text{MeV}/c^2, \\
\mu_{M(\Lambda^0)} &= 1115.80 \pm 0.03 \, \text{MeV}/c^2,
\end{align*}$$

(10)

much smaller than the requested 20 MeV/c$^2$. This loose cut gives us access to the $\Lambda^0$ mass sidebands which are used to study the combinatorial background.

Photons coming from combinatorial processes have lower energy, whereas those coming from heavy $B$ hadrons, like $\Lambda_b^0$, are highly energetic and have larger $E_T$. A cut of $E_T > 2.5$ GeV for the photon candidate is thus required. A cut is also applied on the photon confidence level, which allows to separate neutral from charged deposits in the ECAL.

The $\Lambda^0_b$ candidate is reconstructed as the sum of the 4-momenta of the $\Lambda^0$ and the photon. The reconstructed $\Lambda^0_b$ candidate undergoes similar requirements as the $\Lambda^0$, without the requirements about the vertex quality, as no vertex can be reconstructed with a particle decaying away from the $\Lambda^0_b$ vertex and a neutral particle in the final state. Instead, the $\chi^2$ of MTDOCA gives an estimation on the $\Lambda^0_b$ decay vertex position and a cut at 7 has been applied.
Table 1: Requirements from the StrippingLb2L0Gamma line for the decay $\Lambda^0_b \rightarrow \Lambda^0\gamma$, selecting $LL \Lambda^0$ candidates.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Variable</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$, $\pi^-$ tracks</td>
<td>$\chi^2_{IP}$ from PV</td>
<td>$&gt; 16$</td>
</tr>
<tr>
<td></td>
<td>Min($\chi^2$/ NDOF) of track fit</td>
<td>$&lt; 2$</td>
</tr>
<tr>
<td></td>
<td>Max($\chi^2$/ NDOF) of track fit</td>
<td>$&lt; 3$</td>
</tr>
<tr>
<td></td>
<td>Ghost probability</td>
<td>$&lt; 0.4$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>$p_T$</td>
<td>$&gt; 300$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>Momentum</td>
<td>$&gt; 2000$ MeV/c</td>
</tr>
<tr>
<td>$p$</td>
<td>$p_T$</td>
<td>$&gt; 800$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>Momentum</td>
<td>$&gt; 7000$ MeV/c</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>$</td>
<td>M_{\Lambda^0}(\text{PDG}) - M_{\Lambda^0}</td>
</tr>
<tr>
<td></td>
<td>Vertex $\chi^2$</td>
<td>$&lt; 9$</td>
</tr>
<tr>
<td></td>
<td>$p_T$</td>
<td>$&gt; 1000$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>$IP$</td>
<td>$&gt; 0.05$ mm</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$E_T$</td>
<td>$&gt; 2500$ MeV</td>
</tr>
<tr>
<td></td>
<td>Confidence level</td>
<td>$&gt; 0.2$</td>
</tr>
<tr>
<td>$\Lambda^0_b$</td>
<td>$</td>
<td>M_{\Lambda^0_b}(\text{PDG}) - M_{\Lambda^0_b}</td>
</tr>
<tr>
<td></td>
<td>$p_T$</td>
<td>$&gt; 1000$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>Sum of $p_T$ of $\Lambda^0$ and $\gamma$</td>
<td>$&gt; 5000$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{MTDOC}$</td>
<td>$&lt; 7$</td>
</tr>
</tbody>
</table>

4 Event selection

An offline selection is applied on the data sample in order to enhance the signal over background ratio as much as possible. First, some loose cuts (called preselection cuts) are applied in order to reduce to size of the data sample. Then the background is studied and separated into two sub-samples. Finally a cut-based selection is applied and compared with a multivariate analysis.
4 EVENT SELECTION

Figure 16: Distributions of the Λ⁰ invariant mass for MC signal events. A simple gaussian fit is applied to estimate the mass resolution.

4.1 Preselection cuts

We need first to ensure that the reconstructed Λ⁰ baryons are true Λ⁰’s, and not random combinations of two tracks; the distribution of the fake Λ⁰ hadrons (proton and pion candidates not coming from a Λ⁰ hadron) versus the distribution of the true ones need to be separated. The procedure used for this purpose is the following:

1. All the events in the Λ⁰ mass sidebands, defined as the events populating the Λ⁰ mass distribution beyond 5σ around the mean (Rel. 10), are considered to be fake Λ⁰. The limits of the Λ⁰ mass sidebands are 1109.3 and 1122.3 MeV/c² (Fig. 17).

2. The total number of fake Λ⁰’s in the Λ⁰ sidebands is approximated by a linear extrapolation between the lower and the Λ⁰ upper mass sidebands, as illustrated in Fig. 17.

3. The distribution of any observable for true Λ⁰’s is obtained by subtracting the total background distribution by the distribution of fake Λ⁰’s from Λ⁰ sidebands weighted by its proportion in the total background.

With this method, the behavior of the true Λ⁰ hadrons from the background can be revealed and this type of background can be differentiated from the background made of fake Λ⁰.

The kaon can easily be misidentified as a proton (see Fig. 6). Before studying the Λ⁰ baryons, we need to select a pure sample of proton and pions tracks. The Particle IDentification (PID) variables ProbNN are used. They combine information all the PID variables from the calorimeter, the RICH and the muon systems, as well as some tracking information. The x_ProbNN provides the bayesian probability for a particle x to be identified as a particle y. The preselection cuts for data are chosen to be higher than 0.2 for the pion ProbNNpi (Fig. 18a) and the proton ProbNNp (Fig. 18b).
4.1 Preselection cuts

Figure 17: Distributions of the $\Lambda^0$ invariant mass. The blue histogram contains events from the $\Lambda^0_b$ mass sidebands and the red one contains MC signal events. The green and yellow vertical lines show the $\Lambda^0$ signal mass window limits (1111.9 and 1119.7 MeV/$c^2$), respectively the sidebands limits (1109.3 and 1122.3 MeV/$c^2$) beyond which all the $\Lambda^0$ candidates are considered as fake $\Lambda^0$. The areas in the mass sidebands are extrapolated (hatched part) to determine to total number of fake $\Lambda^0$ in the background.

Figure 18: Particle identification for the pion (a) and proton (b). The blue histogram contains events from the $\Lambda^0_b$ mass sidebands and the red one contains MC signal events. The yellow and green histograms contain the $\Lambda^0$ mass sidebands events where the $\Lambda^0$ candidate is a fake, respectively true $\Lambda^0$, scaled by their respective proportions in the $\Lambda^0$ mass sidebands. The green vertical line shows the preselection cut applied at 0.2.
However, the PID variables are not well modeled in MC, as it can be seen in Fig. 18, where the MC distribution has not the same shape as the true $\Lambda^0$ distribution, thus the PID efficiency can not be used directly from the simulation. To overcome that, a data-driven method is used via the PIDCalib package, developed by the LHCb Particle IDentification group. The PID calibration procedure [35] exploits very well reconstructed decays with clean identification of the particles and very large statistics, such as $\Lambda \rightarrow p\pi^-$ for proton and $D^+(2010)^+ \rightarrow D(K^-\pi^+)\pi^+_s$ for kaon. In these modes, only kinematic variables are used in the selection so that pure samples of protons and kaons are obtained without applying PID cuts. A binning of data is done in kinematic variables (momentum, transverse momentum, number of tracks and pseudo-rapidity\textsuperscript{4}). The idea behind that is that in each bin all tracks of same species will have the same RICH identification decision. The efficiency of a given ProbNN at each bin is then computed and can be assigned as a weight for each track.

Usually, a PID reweighting procedure is applied to obtain properly distributed variables for a given PID cut. Instead, in our case efficiencies for pions and protons of a cut at 0.2 have been obtained from the PIDCalib calibration tables and will be used to scale the MC sample when an efficiency or a FOM computation is involved:

- **proton:**
  - 80% efficiency for proton
  - 2.2% misidentification as pion
  - 17.4% misidentification as kaon

- **pion:**
  - 98% efficiency for pion
  - 25% misidentification as proton
  - 29.6% misidentification as kaon

Reweighting has not been performed in this work and can be a development axis for next studies.

The impact parameter is a powerful tool to remove background of prompt particles. A cut on the impact parameter of the $\Lambda^0$ hadron allows to eliminate the prompt real $\Lambda^0$ but also the prompt fake $\Lambda^0$ which mostly come from a combination of prompt tracks. There is already a cut at 0.05 mm from the stripping (Table 1). A loose cut on the $\Lambda^0$ impact parameter is used as a preselection to reduce the data sample, before applying a tighter cut to isolate the signal. The events with a $\Lambda^0$ impact parameter smaller than 0.1 mm are discarded, as shown in Fig. 19a. A cut of the $\chi^2_{IP}(\Lambda^0)$ has also been considered but it is less efficient in background rejection than a cut on the impact parameter.

In order to reduce the background containing random photons, a cut on the transverse energy of the photon is applied at $E_T > 3000$ MeV (Fig. 19b). Looser cuts from $E_T > 2500$ MeV to $E_T > 2960$ MeV have already been applied at the L0 trigger\textsuperscript{5}.

\textsuperscript{4} Pseudo-rapidity is defined as $\eta = -\ln (\tan (\theta/2))$, where $\theta$ is the angle between the momentum of the particle and the beam axis.

\textsuperscript{5} The L0 uses different cuts, depending on the version, at 2500, 2720, 2860 and 2960 MeV.
4.1 Preselection cuts

The blue histogram contains events from the $\Lambda_0^0$ mass sidebands and the red one contains MC signal events. The yellow and green histograms contain the $\Lambda^0$ mass sidebands events where the $\Lambda^0$ candidate is a fake, respectively true $\Lambda^0$, scaled by their respective proportions in the $\Lambda^0$ mass sidebands. The vertical line shows the preselection cut applied at 0.1 mm for the impact parameter of the $\Lambda^0$ (a) and 3000 MeV/c for the transverse momentum of the photon (b).

The effect of the preselection cuts is summarized in the Table 2. The total efficiency of all the preselection cuts after the stripping and the triggers on the MC signal events is

$$\epsilon_{\text{MC signal}}^{\text{pres|trigger}} = 34.4 \pm 0.5\%,$$

while around 90% of the background has been rejected. We can note that after selecting LL $\Lambda^0$'s, the preselections on PID, IP($\Lambda^0$) and $p_T(\gamma)$ are very efficient in the ratio signal/background, especially the IP($\Lambda^0$) cut.

The proportion of fake $\Lambda^0$ in the $\Lambda^0$ signal mass window slightly changes after each cut (Table 2). The only large change occurs after the PID cut; this cut aims only at removing fake proton and pions, i.e. fake $\Lambda^0$ s. The cut on IP($\Lambda^0$) restores the proportion of fake $\Lambda^0$, as it cuts as much prompt true and fake $\Lambda^0$ candidates, but true $\Lambda^0$ candidates happen to be in bigger proportions in the whole background (65%).

Table 2: Effect of each preselection cut on the number of events and the proportion of fake $\Lambda^0$ in chronological order. The proportion of fake $\Lambda^0$ given in this table is computed by the number of fake $\Lambda^0$ in the $\Lambda^0$ signal mass window divided by the total number of events in the $\Lambda^0$ signal mass window.

<table>
<thead>
<tr>
<th>cuts</th>
<th>$\Lambda_0^0$ sidebands</th>
<th>MC signal</th>
<th>fake $\Lambda^0$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0 and HLT1</td>
<td>10,331,532</td>
<td>6834</td>
<td>11.5</td>
</tr>
<tr>
<td>LL tracks</td>
<td>4,287,276</td>
<td>2717</td>
<td>9.75</td>
</tr>
<tr>
<td>ProbNN &gt; 0.2</td>
<td>2,540,629</td>
<td>2717</td>
<td>2.68</td>
</tr>
<tr>
<td>IP($\Lambda^0$) &gt; 0.1 mm</td>
<td>640,053</td>
<td>2396</td>
<td>9.76</td>
</tr>
<tr>
<td>$E_T(\gamma)&gt; 3$ GeV</td>
<td>607,399</td>
<td>2390</td>
<td>9.52</td>
</tr>
</tbody>
</table>
4.2 Background study

Before applying the final selection, we study the behavior of some of the observables in the background, defined as the events populating $\Lambda^0_0$ mass sidebands.

![Graphs](image)

Figure 20: Distribution of the impact parameter of the pion (a) and proton (b) candidates. Blue histogram contains events from the $\Lambda^0_0$ mass sidebands and red histogram contains MC signal events. The yellow (green) histogram contains the $\Lambda^0$ mass sidebands events where the $\Lambda^0$ candidate is a fake (true) $\Lambda^0$, scaled by its proportion in the $\Lambda^0_0$ mass sidebands.

After the cuts on PID of the tracks, we are left in the $\Lambda^0_0$ mass sidebands with mostly pure samples of protons and pions. Their origin can be deducted from their impact parameter distributions: if they come from the PV, they will have a low IP while if they come from the decay of a long-lived particle, they will have a high IP. As shown in Fig. 20, the daughters of true $\Lambda^0$ have a larger IP than the random proton and pions forming a fake $\Lambda^0$.

The pion and proton candidates from a fake $\Lambda^0$ candidate are expected to come from PV, therefore the corresponding $\Lambda^0$ has also a low vertex separation (Fig. 21). On the other hand, a double structure appears in the vertex separation distribution of the true $\Lambda^0$'s, whose understanding requires more thorough study.

To verify that this distribution is not due to a problem in the reconstruction of the $\Lambda^0$ vertex, we investigated several distributions. Among them, the $z$-position\(^6\) difference ($\Delta z$) between the reconstructed $\Lambda^0$ vertex and the first VELO hit ($z_{1\text{st hit}}$) of the pion track as a function of $z_{1\text{st hit}}$ is shown on Fig. 22\(^7\). This plot performs a tomography of the VELO, revealing the known geometry of the silicon detector layers: until 30 cm in the beam direction there is a high density of layer whereas after 30 cm, only few layers are present.

The pattern observed in Fig. 22a allows us to distinguish two types of LL $\Lambda^0$ candidates, that we will call LL1 and LL2:

- **LL1 $\Lambda^0$ candidates**: The pion track first hit $z$-position is smaller than 27 cm in the

---

\(^6\) The $z$-axis origin is the interaction point
\(^7\) Similar pattern is observed with the proton.
4.2 Background study

Figure 21: Distribution of the $\Lambda^0$ vertex separation. Blue histogram contains events from the $\Lambda^0_b$ mass sidebands and red histogram contains MC signal events. The yellow (green) histogram contains the $\Lambda^0$ mass sidebands events where the $\Lambda^0$ candidate is a fake (true) $\Lambda^0$, scaled by its proportion in the $\Lambda^0_b$ mass sidebands.

VELO. It is the zone with the highest signal over background ratio (80% of the signal for 50% of the background) and the best vertex resolution due to the high density of layers (and consequently VELO hits associated to the tracks), our analysis will concentrate on these candidates.

The limit has been chosen at 27 cm, discarding the last two modules of this region, in order to have the cleanest possible sample. In these modules, most of the tracks have a negative $\Delta z$, which means than the first hit is located before the $\Lambda^0$ vertex and has been wrongly associated to the track. From a MC study of this kind of events, it has been observed that the $\Lambda^0$ vertex position is still properly measured compared to the dimension of the flight distance (the $\Lambda^0$ can fly up to 800mm, as shown in Fig. 21) but these events are few, so as precautionary principle, have not been included in the LL1 sample.

- **LL2 $\Lambda^0$ candidates:** they are candidates for which the first VELO hit $z$-position of the pion track is larger than 27 cm in the VELO. This zone of the VELO contains half of the background for only 20% of the signal. Because of the smaller number of VELO hits associated to the tracks, the $\Lambda^0$ vertex has a larger resolution than for LL1 candidates.

As fake $\Lambda^0$ candidates mostly come from PV, they have a small vertex separation (Fig. 21), therefore the majority of them are located in the LL1 $\Lambda^0$ candidates zone (82% of the total number of fake $\Lambda^0$'s), populating the peak at $\Delta z = 80$ mm in Fig. 22a. It can be illustrated by an one dimensional plot of $\Delta z$ with the separation of true and fake $\Lambda^0$ candidates (Fig. 24). An overlap between the fake $\Lambda^0$ region and the signal region is also observed. Similarly, the Fig. 23 shows the two-dimensional plot of $\Delta z$ as a function of $z_{1\text{st}hit}$ for the events in the $\Lambda^0$ mass sidebands (Fig. 23) and reveals the peak of fake $\Lambda^0$'s. The shape of this peak can be explained by the fact that as the proton and pions are mostly prompt (see Fig. 20), the reconstructed $\Lambda^0$
Figure 22: 2D plots of $\Delta z$ versus the $z$-position of first hit $z_{1\text{st hit}}$ for pion tracks for (a) $\Lambda^0$ mass sidebands events and (b) MC signal events. $\Delta z$ stands for the difference between the $z$-position of the reconstructed $\Lambda^0$ vertex and the $z_{1\text{st hit}}$.

Figure 23: 2D plots of $\pi^- \Delta z$ versus the $z$-position of first hit $z_{1\text{st hit}}$ for the pion track, for the $\Lambda^0$ mass sidebands events in the $\Lambda_b^0$ mass sidebands (fake $\Lambda^0$ candidates). $\Delta z$ stands for the subtraction of $z_{1\text{st hit}}$ by the $z$-position of the reconstructed $\Lambda^0$ vertex.

Figure 24: Distribution of $\Delta z$ for pion tracks. Blue histogram contains events from the $\Lambda_b^0$ mass sidebands and red histogram contains MC signal events. The yellow (green) histogram contains the $\Lambda^0$ mass sidebands events where the $\Lambda^0$ candidate is a fake (true) $\Lambda^0$, scaled by its proportions in the $\Lambda_b^0$ mass sidebands.

After defining these two types of LL $\Lambda^0$ candidates, the $\Lambda^0$ vertex separation is plotted for each of the types (Fig. 25b and 25a) illustrating the different proportion of LL2 in signal and background.

The three different contributions from fake, true LL1 and true LL2 $\Lambda^0$'s are clearly separated in the 2D plot of the $\Lambda^0$ vertex separation as a function of $z_{1\text{st hit}}$ (Fig. 26a). The true LL1 $\Lambda^0$'s
Figure 25: Distribution of the $\Lambda^0$ vertex separation. The blue histogram contains events from the $\Lambda^0_b$ mass sidebands and red histogram contains MC signal events. The black (pink) histogram contains the $\Lambda^0$ mass sidebands events with LL1 (LL2) $\Lambda^0$ candidates.

show a signal-like behavior (Fig. 26b).

The origin of the structure seen in the vertex separation of the true $\Lambda^0$’s has been interpreted as the reflect of the $\Lambda^0$ momentum distribution of the background (Fig 27b). The $\Lambda^0_b$ background seems to favor the association of a photon candidate to a large momentum $\Lambda^0$ candidate, which consequently has a larger vertex separation.

The main features of the two track types LL1 and LL2 are reported in Table 3.

Table 3: Features of LL1 and LL2 $\Lambda^0$ candidates. The fraction of fake $\Lambda^0$’s in the $\Lambda^0$ signal mass window is the number of fake $\Lambda^0$’s divided by the number of events in the $\Lambda^0$ signal mass window, all in the $\Lambda^0_b$ mass sidebands. The fake $\Lambda^0$ percentage is the proportion of fake $\Lambda^0$ in all the the $\Lambda^0$ candidates from $\Lambda^0_b$ mass sidebands.

<table>
<thead>
<tr>
<th></th>
<th>LL1</th>
<th>LL2</th>
</tr>
</thead>
<tbody>
<tr>
<td>z-position of first hit of the pion</td>
<td>$z &lt; 270$ mm</td>
<td>$z &gt; 270$ mm</td>
</tr>
<tr>
<td>$\Lambda^0_b$ mass sidebands (% of total)</td>
<td>317’052 (52%)</td>
<td>290’347 (48%)</td>
</tr>
<tr>
<td>Signal MC events (% of total)</td>
<td>1967 (82%)</td>
<td>423 (18%)</td>
</tr>
<tr>
<td>Fake $\Lambda^0$’s in the zone</td>
<td>55%</td>
<td>12.9%</td>
</tr>
<tr>
<td>Fake $\Lambda^0$’s in $\Lambda^0$ signal mass window in the zone</td>
<td>19.6%</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

4.3 Figure of merit

The figure of merit (FOM) is computed as

$$FOM = \frac{S}{\sqrt{S + B}},$$

where $B$ is the expected number of background events in the $\Lambda^0_b$ signal mass window and $S$ in the number of expected signal events. The FOM reflects the significance of the signal yield and
Figure 26: Correlation between $z_{1\text{st}\text{hit}}$ and the vertex separation of the $\Lambda^0$ candidates from (a) events of the $\Lambda^0_b$ mass sidebands and (b) MC signal events (b). The binning has been chosen such that each bin contains one VELO module.

Figure 27: Distributions of the $\Lambda^0$ momentum. Red histogram contains MC signal events and blue histogram contains events from the $\Lambda^0_b$ mass sidebands. The black (pink) histogram contains LL1 (LL2) $\Lambda^0$ candidates.
4.3 Figure of merit

is used to optimize the selection.

The expected number of signal events $S$ for the $\Lambda_0^b \rightarrow \Lambda^0 \gamma$ decay in the data of 2011 and 2012 is given by

$$S = L \cdot \sigma(pp \rightarrow b\bar{b}X) \cdot 2f_{\Lambda_b} \cdot \mathcal{B}(\Lambda_0^b \rightarrow \Lambda^0 \gamma) \cdot \mathcal{B}(\Lambda \rightarrow p\pi^-) \cdot \epsilon_{\text{acc}} \cdot \epsilon_{\text{sel}},$$

where

- $L$ is the integrated luminosity. In 2011 and 2012 the recorded integrated luminosity in LHCb is $1.107 \pm 0.019$ fb$^{-1}$ and $2.082 \pm 0.024$ fb$^{-1}$, respectively [36]. The total integrated luminosity for the data used in this analysis is thus

$$L = (3.126 \pm 0.021) \text{ fb}^{-1}.$$  (14)

- $\sigma_{\text{tot}}(pp \rightarrow b\bar{b}X)$ is the full $\eta$ region cross-section of a $b\bar{b}$ pair from $p-p$ collisions. The cross section depends on the energy of the collision and it has only been measured for a center-of-mass energy of $\sqrt{s} = \text{TeV}$ by LHCb [37] as $\sigma_{\text{tot}}(pp \rightarrow b\bar{b}X) = (284 \pm 20 \pm 49)$ µb. The data sample for this analysis contains data from 2011 at 7 TeV but also data from 2012 at 8 TeV. We extrapolate this value for $\sqrt{s} = 8$ TeV and use an average cross-section weighted by the integrated luminosity of each data sample:

$$\sigma_{\text{tot}}(pp \rightarrow b\bar{b}X) = \frac{L(7\text{TeV})\sigma_{\text{tot}}(7\text{TeV}) + 8L(8\text{TeV})\sigma_{\text{tot}}(7\text{TeV})}{L(7\text{TeV}) + L(8\text{TeV})} = 310.5 \pm 57.9 \mu\text{b}^{-1}. \quad (15)$$

- $f_{\Lambda_b}$ is the probability that the quark $b$ hadronizes into a $\Lambda_0^b$, called fragmentation fraction. The factor 2 takes into account the two quarks $b$ and $\bar{b}$. The fraction $f_{\Lambda_0^b}/f_d$, where $f_d$ is the probability that a quark $b$ hadronizes with a quark $d$, has been measured in LHCb in 2014 [38]. The fragmentation fraction depends on the $p_T$ of the $\Lambda_0^b$. Taking as value of $p_T(\Lambda_0^b)$ the mean on the distributions after the preselection (7.5 GeV, Fig. 28), and using $f_d = 0.401 \pm 0.007$ [39], we get

$$f_{\Lambda_b} = 17.1 \pm 4.0 \% \quad (16)$$

- $\mathcal{B}(\Lambda_0^b \rightarrow \Lambda^0 \gamma)$ is the branching ratio of the decay $\Lambda_0^b \rightarrow \Lambda^0 \gamma$, estimated [7] to be in the range

$$\mathcal{B}(\Lambda_0^b \rightarrow \Lambda^0 \gamma) = (3 - 10) \cdot 10^{-5}. \quad (17)$$

We will take $6.5 \cdot 10^{-5}$ as a mean value, and the effect of the two extreme values will be accounted for.

- $\mathcal{B}(\Lambda \rightarrow p\pi^-)$ is the branching ratio of the decay $\Lambda \rightarrow p\pi^-$. It has been measured [1] as

$$\mathcal{B}(\Lambda \rightarrow p\pi^-) = 63.9 \pm 0.5 \%. \quad (18)$$

- $\epsilon_{\text{gen}}$ is the generator efficiency, i.e. the fraction of produced events that are in the acceptance of the detector. This number is obtained at the Monte-Carlo simulation for the specific $\Lambda_0^b \rightarrow \Lambda^0 \gamma$ decay as

$$\epsilon_{\text{gen}} = (50.3 \pm 0.3) \%. \quad (19)$$
• $\epsilon_{sel}$ is the selection efficiency, i.e. the fraction of events that passed the trigger, the stripping and the offline selections over the total generated events. When optimizing the FOM, we also require the signal events to be in the $\Lambda^0$ signal mass window.

HLT2 efficiency is low (10% on top of HLT1 for the MC signal) and will not be applied to the signal MC to have enough statistics for the FOM optimization (more details on the trigger efficiency will be given in Section 5). As the HLT2 efficiency is mostly TIS, it should not affect the distributions of the different observables used in our selection. The HLT2 efficiency after preselections is estimated to be:

$$
\begin{align*}
\epsilon_{S|\text{HLT2|presel}}^S &= 10.4 \pm 0.6 \% \text{ for MC signal and}
\epsilon_{B|\text{HLT2|presel}}^B &= 45.6 \pm 0.1 \% \text{ for } \Lambda^0_b \text{ mass sidebands,}
\end{align*}
$$

and is applied to the expected background $B$ and signal $S$ estimations in the FOM. Furthermore, as previously explained (Section 4.1), the number of expected signal $S$ has to be multiply by the efficiency of the PID cut on MC which is

$$
\epsilon_{PID}^S = 0.98 \cdot 0.8 = 78.4 \%.
$$

Finally, the FOM will be computed for the LL1 $\Lambda^0$ candidates (Sec. 4.2). By adding all these conditions, the selection efficiency becomes:

$$
\epsilon_{sel}^S = \epsilon_{sel|\text{gener.}} \cdot \epsilon_{S|\text{HLT2|presel}}^S \cdot \epsilon_{PID}^S
$$

The expected number of background events $B$ is computed by extrapolating the $\Lambda^0_b$ upper mass sidebands in the signal mass window after selection. Only the upper mass sideband is used because it is expected to contain only combinatorial background while the lower mass sidebands might also contain partially reconstructed $\Lambda^0$ (or $B$ hadrons). For consistency, the events are also required to be in the $\Lambda^0$ signal mass window and multiplied by $\epsilon_{B|\text{HLT2|presel}}^B$.

### 4.4 Cut-based selection

After applying the L0 and HLT1 trigger and the preselection, two types of $\Lambda^0$ candidates have been revealed: the LL1 and the LL2. The selection will concentrate on the LL1 $\Lambda^0$'s, which are the most promising ones due to the higher signal over background ratio. An event selection based on few selected observables is established. These variables are chosen because their distributions show the clearest separation power between signal and background:

- the $\Lambda^0_b$ transverse momentum,
- the $\Lambda^0$ transverse momentum,
- the $\Lambda^0$ vertex separation $\chi^2$ and
- the $\Lambda^0$ impact parameter.
First the cuts will be optimized one after the other on the four selected observables, then the decision will be verified with a four-dimensional FOM optimization. The optimization is done on events populating the $\Lambda^0$ signal mass window, as this is the zone of interest for this study. As explained previously, the background estimation is done for the events of the $\Lambda^0_b$ upper mass sidebands.

We begin with an expected signal of 184 events and an estimated background of 49,917 (which gives a FOM of 0.8). The $\Lambda^0_b$ transverse momentum is used first because its background rejection power seems high with a simple cut (Fig. 28). A cut at the stripping level at $p_T > 1\text{ GeV}/c$ has already been applied (Table 1). The FOM is obtained and the best cut is found to be $p_T(\Lambda^0_b) > 7.2\text{ GeV}/c$, as illustrated in Fig. 29. With this cut, the expected signal yield is of 89 events while the estimated background in the signal mass window is 5179, which leads to a figure of merit of 1.2.

![Figure 28: Distribution of the $\Lambda^0_b$ transverse momentum after preselections. Blue histogram contains data events from the $\Lambda^0_b$ mass sidebands and red histogram contains MC signal events. The green vertical line shows the cut at 7.2 GeV/c which gives the maximal FOM.](image)

![Figure 29: Figure of merit for a cut on $\Lambda^0_b$ transverse momentum.](image)

The transverse momentum is the next observable used to optimize the FOM (Fig. 30). A cut at the stripping level at $p_T > 1\text{ GeV}/c$ has already been applied (Table 1). The best cut is found to be $p_T(\Lambda^0) > 3.4\text{ GeV}/c$, which leads to an expected signal yield is of 58 events and an estimated background in the signal mass window of 992 events, leading to a figure of merit of 1.8 (Fig. 31).

Then the $\chi^2_{VS}$ of the $\Lambda^0$ candidates is used (Fig. 32). The best cut is found to be $\chi^2_{VS}(\Lambda^0) > 500$, which leads to an expected signal yield of of 53 events and an estimated background in the signal mass window of 661, corresponding a figure of merit of 2.0 (Fig. 33).

Finally, we cut on the impact parameter of the $\Lambda^0$ candidates (Fig. 34). The best cut is found to be $\text{IP}(\Lambda^0) > 0.2\text{ mm}$ (Fig. 35), which leads to an expected signal yield is of 27 events and an
4 EVENT SELECTION

Figure 30: Distribution of the $\Lambda^0$ transverse momentum after cut on $p_T$ ($\Lambda^0_b$). Blue histogram contains data events from the $\Lambda^0_b$ mass sidebands and red histogram contains MC signal events. The green vertical line shows the cut at 3.4 GeV/c which gives the maximal FOM.

Figure 31: Figure of merit for a cut on $\Lambda^0_b$ transverse momentum.

Figure 32: Distribution of the $\Lambda^0 \chi^2_{VS}$ after cuts on $p_T$ ($\Lambda^0_b$) and $p_T$ ($\Lambda^0$). Blue histogram contains data events from the $\Lambda^0_b$ mass sidebands and red histogram contains MC signal events. The green vertical line shows the cut at 500 which gives the maximal FOM.

Figure 33: Figure of merit for a cut on $\Lambda^0_b$ transverse momentum.
estimated background in the signal mass window of 67, giving a final figure of merit of

\[
\text{FOM}_{\text{cut-based}} = 2.8
\]  

(23)

4.5 Multivariate analysis

The separation between background and signal needs complex understanding of the correlation between the variables, therefore a multivariate approach is applied. A boosted decision tree (BDT) [40, 41] is constructed using the scikit-learn python machine-learning package [42].

A decision tree is a sequence of binary splits of data into nodes, where the final nodes, called leaves, decide if an event is signal or background. It is called a classifier as the output is a binary response: signal or background. A decision tree is built with the following procedure:

As the correlation between the variables is high, the order of the cuts will and the result obtained after applying the cuts is not optimal. To improve the situation, all the cuts are applied simultaneously by optimizing a four-dimensional figure of merit. The best cuts for each variable are shown in Table 4 and are reasonably close to from the ones previously chosen, which indicates a consistency in the results. The obtained maximal yields are

\[
\begin{align*}
S_{4D} &= 36 \pm 26 \quad (17 \pm 5 - 55 \pm 17), \\
B_{4D} &= 86 \pm 1, \\
\text{FOM}_{4D} &= 3.3 \pm 1.6 \quad (1.6 \pm 0.5 - 4.6 \pm 1.6),
\end{align*}
\]

(24)

where the two values in parenthesis are computed with the two extreme values of the \( \text{BR}(\Lambda_b^0 \to \Lambda^0 \gamma) \) (3 and 10 \( \cdot 10^{-5} \)). It is a noticeable improvement of the previous procedure.

Figure 34: Distribution of the \( \Lambda^0 \) impact parameter after cuts on \( p_T(\Lambda_b^0), p_T(\Lambda^0) \) and \( \chi^2_{\text{VS}}(\Lambda^0) \). Blue histogram contains data events from the \( \Lambda_b^0 \) mass sidebands and red histogram contains MC signal events. The green vertical line shows the cut at 0.40 mm which gives the maximal FOM.

Figure 35: Figure of merit for a cut on \( \Lambda_b^0 \) transverse momentum.
Table 4: Performance of the cut-based selection, once with simple cuts applied one after the other, once with all simple cuts applied in the same time.

<table>
<thead>
<tr>
<th>Cut</th>
<th>$p_T(A_b)$ [MeV/c]</th>
<th>$p_T(\Lambda)$ [MeV/c]</th>
<th>$\chi^2_{VS}(\Lambda^0)$</th>
<th>IP($\Lambda^0$) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D cuts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>89</td>
<td>58</td>
<td>53</td>
<td>27</td>
</tr>
<tr>
<td>B</td>
<td>5179</td>
<td>992</td>
<td>661</td>
<td>67</td>
</tr>
<tr>
<td>FOM</td>
<td>1.1</td>
<td>1.8</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td>4D cuts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>7250</td>
<td>2200</td>
<td>2000</td>
<td>0.40</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. The data sample is randomly split into two samples of approximately same size: the training sample and the test sample. The training sample will be used for the training of the tree while the test sample will be kept intact until the end of the training and will be used to test the final classifier (this is a general procedure for all multivariate methods).

2. The training procedure starts in the root node (Fig. 36): a cut is chosen in the variable that gives the best separation gain between signal and background and the training sample is split in two nodes according to the cut.

3. This process is repeated for each node until a maximal depth or number of leaves is reached, or until the leaf is pure background or pure signal.

4. In the end, each leaf gives a binary decision of background or signal according to the majority of training events that go into one or the other category.

![Figure 36: Illustration of the procedure of a decision tree [41].](image)
A boosted decision tree [40] is an ensemble method that combines different trees, resulting in a more powerful classifier. It starts with a single tree, with unweighted events. If a training event have been misclassified by this tree, *i.e.* if a signal event has been classified as background leaf or vice-versa, then the weight of that event is increased, or *boosted*. A second tree is build by using the new weighted events and the procedure is repeated. The score of the event for each tree is computed by giving it a score of 1 if it has been classified as background by the leaf and −1 for signal. The renormalized sum of all the (weighted) scores (between −1 and 1) gives the final score; the higher the score is, the higher the probability for this event to be signal. After being trained, the classifier gives the score (*or BDT output*) of any input event.

The data sample used for training the BDT is a random sample of 2000 events from the Λ0b mass sidebands as background and the whole sample of MC signal (1966 events) as signal. In both cases, events are located in the Λ0 mass window and correspond to LL1 Λ0 candidates. The PID calibration is not used in the MC sample, but the efficiencies obtained from it are used for computing the figure of merit. The following variables have been given as input parameters: \(p_T(\Lambda_0^0), p_T(\Lambda^0), p_T(p), \text{MTDOCA}(\Lambda_0^0), \text{IP}(\Lambda^0), \text{and VS}(\Lambda^0)\). The importance of each of these variables after training in the BDT is illustrated in Fig. 37.

![Figure 37: Importances of the variables of the BDT.](image)

The Receiver Operating Characteristic (ROC) curve illustrates the performance of a BDT by showing the background rejection over the signal efficiency of the test sample. The closest to 1 is the area of the ROC curve, the higher is the performance. The overtraining of the classifier, *i.e.* the tendency of a classifier to learn the statistical fluctuation “by heart”, is evaluated by comparing the BDT output of the training and the test samples and checking they are as close as possible. The BDT used for this analysis has been kept simple (low number of maximum number of leaves, low depth) in order to avoid overtraining which could be very dangerous in our samples as the MC statistics are limited. Figure 40 shows that no large overtraining is observed.

In order to make sure that the BDT is complex enough, we use the learning curve, which is obtained by performing the training and testing procedure using subsamples of the training and testing samples of increasing sizes. For each of these steps, the score of the obtained BDT is plotted (Fig. 39); the score used in this case is the accuracy of the BDT, which is defined as...
the fraction of correct decisions taken by the BDT. The learning curves of the test and training samples should be as close as possible, keeping at the same time the highest possible performance. In our case, we can see in Fig. 39 that the test score is 2% lower than the learning score. The BDT could be more complex as the curves have still not reached a plateau, but as statistics are very limited, it is safer to keep the BDT simple to avoid larger overtraining.

Figure 40: BDT outputs for the signal and background training and test samples. This plots gives an indication on the overtraining of the BDT.

The expected signal and background in the signal mass window as a function of the BDT output cut are shown in Figs. 41 and 42. The FOM has been computed for each cut on the BDT output, with $S$ estimated with the mean value of the interval for $BR(\Lambda^0 \rightarrow \Lambda^0 \gamma) \times 6.5 \times 10^{-5}$ and its two extremes values ($3$ and $10 \times 10^{-5}$), as illustrated in Fig. 43. The BDT cut that gives the
4.5 Multivariate analysis

maximal FOM and is relevant for the three different figures of merit is 0.4, with the following expected yields:

\[
\begin{align*}
S_{\text{BDT}} &= 85 \pm 26 \quad (39 \pm 12 - 130 \pm 40) \\
B_{\text{BDT}} &= 586 \pm 1 \\
FOM_{\text{BDT}} &= 3.3 \pm 1.1 \quad (1.6 \pm 0.5 - 4.9 \pm 1.6)
\end{align*}
\]

where the two values in parenthesis are computed with the two extreme values of the $BR(\Lambda^0_b \rightarrow \Lambda^0 \gamma)$. This is a similar FOM than the one obtained with the 4D cut-based procedure, but the BDT analysis allows to keep a higher signal yield. We will use this BDT cut as our final selection cut.

Figure 41: Expected background in the $\Lambda^0$ signal region and in the $\Lambda^0$ signal mass window as a function of cuts on BDT output.

Figure 42: Expected signal in the $\Lambda^0$ signal mass window as a function of cuts on BDT output.

Figure 43: Figure of merit as a function of cuts on the BDT outputs for three possible branching fractions of the signal decay.
4.6 Mass fit

Now that the selection procedure has been fixed, a fit of the $\Lambda^0_b$ mass distribution is performed in order to extract the signal from data, the shape of which is obtained from the MC sample for the $\Lambda^0_b \to \Lambda^0 \gamma$ decay.

![Figure 44: Double tail Crystal Ball fit of the MC signal.](image)

The simulated signal is fitted with a two-tail Crystal Ball (CB) probability distribution function (PDF) (Fig. 44), given by [43]:

$$f(x; \alpha_L, n_L, \alpha_R, n_R, \mu_B, \sigma) = N \cdot \begin{cases} 
A_L (B_L - \frac{x - \mu_B}{\sigma})^{-N}, & \text{for } \frac{x - \mu_B}{\sigma} \leq -|\alpha_L| \\
A_R (B_R - \frac{x - \mu_B}{\sigma})^{-N}, & \text{for } \frac{x - \mu_B}{\sigma} \geq |\alpha_R| \\
\exp\left(-\frac{(x - \mu_B)^2}{2\sigma^2}\right), & \text{for } -|\alpha_L| < \frac{x - \mu_B}{\sigma} < |\alpha_R|. 
\end{cases}$$

where

$$\begin{align*}
A_L &= \left(\frac{n_L}{|\alpha_L|}\right)^{n_L} \exp\left(-\frac{|\alpha_L|^2}{2}\right), \\
B_L &= \frac{n_L}{|\alpha_L|} - |\alpha_L|, \\
A_R &= \left(-\frac{n_R}{|\alpha_R|}\right)^{n_R} \exp\left(-\frac{|\alpha_R|^2}{2}\right), \\
B_R &= -\frac{n_R}{|\alpha_R|} + |\alpha_R|,
\end{align*}$$

and $N$ is the normalization factor. The fit has been applied on the simulation without the HLT2...
trigger; as it is mostly TIS, the shape of the signal will not be affected however we will benefit from higher statistics.

The shape parameters obtained from the MC fit are used to fix the signal in the fit to the data; the mean ($\mu$) of the data fit has been fixed at the nominal $\Lambda_0$ mass from the Particle Data Group [1]. No signal events have been found in the data, as shown in Fig. 45.

![Figure 45: Double tail Crystal Ball fit of the data.](image)

5 Trigger efficiency

As our efficiency loss is dominated by the trigger part, we describe in detail in this section the selected trigger decisions discussed briefly in Sec. 2.4. Here, the trigger efficiency is computed as the number of MC events that passed the trigger divided by the total number of MC events passing the offline selection and before applying the trigger.

5.1 L0 efficiency

The used L0 trigger lines are L0Photon and L0Electron. Combined with a logical OR, they produce an efficiency of

$$\epsilon_{\text{TOS}}^{\text{L0Photon}} = 91.2 \pm 0.7\%.$$ (27)

The requirements of these lines [44] and their efficiencies are given in Table 5. We can see that the efficiency lost by the requirements for the photon is partially recovered by the electron trigger line (Table 5). This is due to the fact that the SPD identifies only 60% of the electromagnetic candidates as photons, because the remaining ones convert into electron-positron pairs, mostly in the first muon chamber (M1) [45]. Combining both photon and electron lines is thus more efficient than loosen the $E_T$ cuts for both [23]. Two additional lines (L0PhotonHi and L0ElectronHi) are thus introduced with a tighter cut at $E_T > 4.2$ GeV for a use as input the HLT1 HLT1TrackPhoton line.
Table 5: Requirements of the selected L0 trigger lines. TIS and TOS intrinsic efficiency of the L0 trigger lines on the MC signal events, after the whole selection.

<table>
<thead>
<tr>
<th>SPD multiplicity</th>
<th>$E_T$ [GeV]</th>
<th>$\epsilon_{L0}^{TOS}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0Photon</td>
<td>&lt; 600</td>
<td>(2.5 – 2.9) 52.9 ± 1.3</td>
</tr>
<tr>
<td>L0Electron</td>
<td>&lt; 600</td>
<td>(2.5 – 2.9) 39.4 ± 1.2</td>
</tr>
</tbody>
</table>

The L0Hadron could allow to recover low energy photons, but combinatorial background largely increases as the photon $E_T$ threshold decreases. In the case of this study, large combinatorial background levels prompts us to select high $E_T$ photons, with a cut at 3000 MeV applied as preselection.

5.2 HLT1 efficiency

The only lines that are relevant for TOS events are Hlt1TrackAllL0 and Hlt1TrackPhoton. The photon line Hlt1TrackPhoton requires the event to pass the L0PhotonHi or L0ElectronHi triggers, in order to loosen the cuts on the track $p_T$ and $p$ with respect to the Hlt1TrackAllL0 line. For TIS events, the following lines have been taken: Hlt1TrackPhoton, Hlt1TrackAllL0, Hlt1TrackMuon, and Hlt1SingleElectronNoIP. The efficiency of each line on top of the L0 trigger are computed after the whole selection and reported in Table 6. The Hlt1SingleElectronNoIP was taken because it had some non-zero efficiency before the selection, however its effect became null after the selection.

Table 6: Efficiency of selected lines for HLT1 trigger, on top on the L0 trigger.

| Line                      | $\epsilon_{HLT1|L0}$ [%] | $\epsilon_{TIS_{HLT1|L0}}$ [%] |
|---------------------------|--------------------------|-------------------------------|
| Hlt1TrackAllL0            | 45.5 ± 1.3               | 16.3 ± 1.0                    |
| Hlt1TrackPhoton           | 36.3 ± 1.3               | 18.9 ± 1.0                    |
| Hlt1TrackMuon             | -                        | 1.8 ± 0.4                     |
| Hlt1SingleElectronNoIP    | -                        | 0                             |

Logical OR of all 52.4 ± 1.3 23.5 ± 1.1

The TOS efficiency can be roughly explained by trying each requirement of the trigger on our signal MC. Our signal is made of two tracks: the proton and the pion and each HLT1Track requirement should be satisfied by one of the two tracks. The requirements for the relevant HLT1 trigger track lines for our study compared to the stripping line are given in Table 7 [44]. For both Hlt1TrackAllL0 and Hlt1TrackPhoton lines, the requirement is at least 9 VELO hits, less than 3 VELO missing hits and at least 16 total hits. The requirements on kinematic variables slightly changed between 2011 and 2012, with the tightest cuts listed in Table 7. Most of the TOS efficiency is lost because of the tight cut on the $p_T$ of the tracks (see Fig. 46).
Table 7: Comparison of selected TOS HLT1 track lines cuts with the stripping cuts.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TrackAllL0</td>
<td>&gt; 1.5</td>
<td>&gt; 10</td>
<td>&gt; 1.7</td>
<td>&gt; 0.1</td>
<td>&gt; 16</td>
</tr>
<tr>
<td>TrackPhoton</td>
<td>&gt; 2</td>
<td>&gt; 6</td>
<td>&gt; 1.2</td>
<td>&gt; 0.1</td>
<td>&gt; 16</td>
</tr>
<tr>
<td>Stripping</td>
<td>&gt; 3</td>
<td>&gt; 7</td>
<td>&gt; 0.8</td>
<td>-</td>
<td>&gt; 16</td>
</tr>
</tbody>
</table>

Figure 46: Maximum $p_T$ (left) and $p$ (right) of the proton or pion tracks for the decay $\Lambda^0_b \rightarrow \Lambda^0 (\rightarrow p\pi^-)\gamma$. Blue histogram contains data events in the $\Lambda^0_b$ mass sidebands and red histogram contains MC signal events. Vertical lines show the cut applied by the HLT1 trigger.

The efficiency of the HLT1 trigger on top of the L0 trigger and its total efficiency are

\[
\begin{align*}
\epsilon_{LT1|L0}^{TIS||TOS} & = 62.6 \pm 1.3 \% \\
\epsilon_{LT1}^{TIS||TOS} & = 56.9 \pm 1.3 \%
\end{align*}
\]

5.3 HLT2 efficiency

Only the 2-body topological lines can give TOS efficiency for our signal decay. Since their efficiency is nonetheless low (Table 8), all non-prescales HLT2 lines will be used as TIS to improve the signal yield (Table 11).

Table 8: Efficiency of the HLT2 lines on top of the HLT1 trigger.

| Line                                    | $\epsilon_{LT2|LT1}^{TIS}$ [%] |
|-----------------------------------------|--------------------------------|
| Hlt2Topo2BodyBBDT_TOS                  | 0.7 $\pm$ 0.3                  |
| Hlt2RadiativeTopoTrack_TOS             | 0.9 $\pm$ 0.3                  |
| Hlt2RadiativeTopoPhoton_TOS            | 0.9 $\pm$ 0.3                  |
| TIS lines                               | 9.8 $\pm$ 1.0                  |
| TIS || TOS                              | 11.2 $\pm$ 1.1                 |

The main loss of efficiency the in HLT2 topological lines is due to the cuts on momentum and transverse momentum on the pion track, since in HLT2 only tracks that have $p > 5$ GeV/c...
(Fig. 47a and 47b) and $p_T > 500$ MeV/c (Fig. 47c and 47d) are reconstructed. The HLT1 trigger already requires tight cuts on $p$ and $p_T$ but for only one of the tracks. As the proton has a high $p_T$ compared to the pion, it allowed the $\Lambda^0$ to pass the HLT1 trigger, which is not any more the case for HLT2.

Figure 47: Up: Momentum distributions for the pion (a) and the proton (b). Down: transverse momentum for the pion (c) and proton (d). Blue histogram contains data events in the $\Lambda^0_b$ mass sidebands and red histogram contains signal MC events. The green vertical is the cuts applied by the HLT2 trigger on all the tracks ($p_T > 500$ MeV/c and $p > 5000$ MeV/c).

Another important source of efficiency loss in the HLT2 topological is the $\Lambda^0_b$ corrected mass. As the topological trigger only sees the $\Lambda^0$, the corrected mass corresponds to that of the $p\pi$ combination, which is calculated wrongly because the flight direction used is that from the PV to the $\Lambda^0$ vertex, and not the $\Lambda^0_b$ one. As a consequence, the corrected mass, shown in Fig. 48, will be

$$m_{\Lambda} < m_{\text{corr}} \ll m_{\Lambda_b}.$$  \hfill (29)

Since the BBDT of the topological lines largely penalizes low corrected mass values, a big part of the TOS efficiency is lost.
5.4 Improvements for Run II

Figure 48: Corrected mass of the $\Lambda_b^0$ for the MC signal events, compared with the $\Lambda^0$ mass distribution.

A summary of the triggers TIS and TOS efficiencies can be found in Table 9. We can see that the HLT2 TOS trigger can not be used alone in Run I for the $\Lambda_b^0 \rightarrow \Lambda^0 \gamma$ decay; with an efficiency of 0.8%, it doesn’t accept almost any signal. The TIS has been used to recover this loss of efficiency, but it still leaves us with very low trigger efficiency. In conclusion, the trigger lines for $\Lambda_b^0 \rightarrow \Lambda^0 \gamma$ have to be improved in Run II.

Table 9: Efficiency of each stage of the trigger on the MC signal events, after the selection. The notation $X|Y$ stands for the efficiency of the level $X$ trigger after the level $Y$ trigger.

<table>
<thead>
<tr>
<th></th>
<th>$\epsilon^{TOS}$ [%]</th>
<th>$\epsilon^{TIS}$ [%]</th>
<th>$\epsilon^{TIS\mid TOS}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>91 ± 0.7</td>
<td>-</td>
<td>91 ± 0.7</td>
</tr>
<tr>
<td>HLT1</td>
<td>52.4 ± 1.3</td>
<td>23.5 ± 1.1</td>
<td>62.6 ± 1.3</td>
</tr>
<tr>
<td>HLT1</td>
<td>47.7 ± 1.3</td>
<td>21.4 ± 1.0</td>
<td>56.9 ± 1.3</td>
</tr>
<tr>
<td>HLT2</td>
<td>1.3 ± 0.4</td>
<td>9.8 ± 1.0</td>
<td>11.2 ± 1</td>
</tr>
<tr>
<td>HLT2</td>
<td>0.8 ± 0.2</td>
<td>5.6 ± 0.6</td>
<td>6.4 ± 0.6</td>
</tr>
</tbody>
</table>

5.4 Improvements for Run II

For Run II, an exclusive HLT2 line for the $\Lambda_b^0 \rightarrow \Lambda^0 \gamma$ decay, where the $\Lambda^0$ is LL, has been added. This line benefits from the studies performed in this work and from several changes in the trigger:

- the lower reconstruction thresholds allow to keep the full pion $p_T$ spectrum, and
- the fill-by-fill calibration allows to use offline-quality PID variables in the selection, which help in significantly lowering the rate at no efficiency cost.
The $\Lambda_0^b$ candidates are built by combining $\Lambda^0$ candidates filtered according to the selection in Table 10 with photons that are TOS in L0 ($L0\text{Photon}$ or $L0\text{Electron}$). The values of the cuts for $\Lambda^0$ IP and $p_T$, and $\Lambda_0^b$ $p_T$ and $\chi^2_{\text{MTDOCA}}$ have been chosen through a 4D optimization, in which the signal efficiency, calculated with respect to the number of L0 TOS and HLT1 passed events, has been maximized for a given output rate. The other cuts were motivated by the selection used in the stripping or from the shared $\Lambda^0$ available in the HLT2, shown in Table 10. Additionally, alternative variables, such as the MTDOCA or the $\Lambda^0 \chi^2_{\text{IP}}$, have also been tested, and showed similar performance (an example can be seen in Fig. 49); it was decided to keep the same ones as in the stripping.

After discussions with the trigger group, the chosen cuts correspond to a rate of $\sim 24$ Hz, for which the efficiency over L0 TOS and HLT1 passed events is around 86%. While this doesn’t directly correspond to the efficiency we could observe in the final selection in Run II, it gives a very good idea of the huge improvement in trigger efficiency for the $\Lambda_0^b \rightarrow \Lambda^0 \gamma$ decay, of easily an order of magnitude, that can be achieved thanks to this exclusive line.

Table 10: Cuts applied for the new exclusive trigger line for the $\Lambda_0^b \rightarrow \Lambda^0 \gamma$ decay in Run II.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Variable</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>tracks</td>
<td>$p_T$</td>
<td>$&gt; 250$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>Momentum</td>
<td>$&gt; 2000$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{\text{IP}}$</td>
<td>$&gt; 36$</td>
</tr>
<tr>
<td></td>
<td>max($\chi^2 / \text{NDOF}$) of track fit</td>
<td>$&lt; 3$</td>
</tr>
<tr>
<td>$p$</td>
<td>PIDp</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>$</td>
<td>M_{\Lambda^0}(\text{PDG}) - M_{\Lambda^0}</td>
</tr>
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<td>Vertex $\chi^2$</td>
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<td>Proper time</td>
<td>$&gt; 2$ ps</td>
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<td></td>
<td>$p_T$</td>
<td>$&gt; 1500$ MeV/c</td>
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<td>IP from PV</td>
<td>$&gt; 0.1$ mm</td>
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<tr>
<td>$\gamma$</td>
<td>$E_T$</td>
<td>$&gt; 2000$ MeV</td>
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<td>TOS</td>
<td>$L0\text{Photon}$ or $L0\text{Electron}$</td>
</tr>
<tr>
<td></td>
<td>Sum of children $p_T$</td>
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<td>$\Lambda_0^b$</td>
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<td>$\chi^2_{\text{MTDOCA}}$</td>
<td>$&lt; 9$</td>
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6 Conclusion

The $Λ_b^0 \to Λ^0γ$ decay plays an important role in the determination of the photon polarization and the search of new physics. A search for this decay has been performed using the 3 fb$^{-1}$ data sample by the LHCb experiment at CERN during Run I (2011–2012) in a blinded analysis. This decay is particularly challenging because of the presence of a photon in the final state combined with the long-lived $Λ^0$ baryon precluding the $Λ^0_b$ vertex reconstruction. Furthermore, significant part of the signal is lost due to the very low efficiency of the HLT2 trigger (Table 8).

A preselection procedure is first established on the long tracks sample using some loose cuts on PID, $Λ^0$ impact parameter, and transverse energy of the photon. The event selection is done in two different ways: a cut-based selection on four selected observables and a Boosted Decision Tree (BDT), built to take the complex correlations between the variables into account. Because of the low statistics of the signal MC sample, the BDT parameters have been selected with a compromise between small overtraining and good performance. The trained BDT shows a similar performance than the cut-based selection; assuming a branching ratio of $6.5 \cdot 10^{-5}$, a signal significance of $3σ$ is expected (Fig. 43).

The data have been unblinded and no signal has been observed. The trigger efficiency is explained in details and a new exclusive HLT2 trigger line for Run II is proposed, which requirements are based on the results of this analysis. This would give a HLT2 efficiency of 80%, which is more than one order of magnitude from the HLT2 efficiency with the Run I trigger lines, and should allow to observe $Λ_b^0 \to Λ^0γ$ signal in the next run.
### Table 11: HLT TIS lines.

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<th>HLT TIS lines</th>
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<tr>
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