Selection and categorization of reconstructed objects in boosted $hh \to b\bar{b}\tau^-\tau^+$ events

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Contents

1 Introduction .......................... 2
  1.1 Particle physics and the Standard Model ......................... 2

2 Higgs physics .......................... 3
  2.1 Higgs mechanism .......................... 3
  2.2 Higgs boson pair production and decays ......................... 3

3 The ATLAS experiment at the LHC .......................... 5
  3.1 Large Hadron Collider at CERN .......................... 5
  3.2 ATLAS .................................. 5

4 Simulation framework ...................... 7

5 Decay of Higgs boson pairs to di-τ + di-b final states ............ 8
  5.1 Tau leptons .......................... 8
  5.2 Bottom quarks .......................... 8
  5.3 Boosted $hh \to bb\tau\tau$ .......................... 9

6 Event selection .......................... 9
  6.1 Old overlap removal of objects .......................... 10
  6.2 New overlap removal of objects .......................... 10

7 Results and Conclusion .................... 16

References ................................ 18
1 Introduction

1.1 Particle physics and the Standard Model

The Standard Model (SM) is the theoretical framework describing successfully the fundamental particles that the universe is made of and the three fundamental forces that govern them. It contains three generations of fermions and the three forces between them are mediated by four force carriers (gauge bosons). The strong interaction is mediated by gluons, while W and Z bosons mediate the weak interaction. The electromagnetic force is carried by the photon [1]. Along with the matter particles and the force carriers, an essential component of the SM is a Higgs boson, the existence of which was predicted in the 1960s. It was observed by the ATLAS and CMS experiments at CERN’s Large Hadron Collider (LHC), as announced on 4th July 2012 [2, 3]. The Higgs boson is an elementary spin-0 particle with a measured mass of 125 GeV. A summary of the SM particles is shown in Figure 1.

Despite explaining nearly all experimental results and accurately predicting various phenomena, the SM cannot explain the mass hierarchy and cannot account for e.g. dark matter, gravity, and the asymmetry between matter and anti-matter in the universe. The SM can be extended to account for the neutrinos having a mass.
2 Higgs physics

2.1 Higgs mechanism

The mechanism responsible for giving mass to all particles was developed by Robert Brout, François Englert, Peter Higgs, Gerald Guralnik, Carl Hagen and Tom Kibble [5, 6, 7]. The SM is based on a quantum field theory (QFT), where all fundamental particles are described as excitations of quantum fields. In QFT each non-interacting field is described by a Lagrangian of the form:

\[ \mathcal{L} = \mathcal{L}_{\text{mass}} + \mathcal{L}_{\text{kin}} \]  

However, having the \( \mathcal{L}_{\text{mass}} \) term in the Lagrangian makes the theory non-renormalisable. This problem is solved by a spontaneous electroweak symmetry breaking (EWSB). The Higgs mechanism postulates the existence of a complex scalar doublet \( \Phi(x) \) with a corresponding potential

\[ V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \]  

where \( \lambda > 0 \) and \( \mu^2 < 0 \). Due to those bounds on the parameters, the Higgs potential does not have a minimum at \( \Phi = 0 \) and therefore the vacuum expectation value (vev) is shifted to a non-zero value. This Higgs potential, \( V(\Phi) \), adds couplings of the Higgs field to the gauge fields, to fermions and to itself, generating mass terms for all the particles that the Higgs field couples to [1, 8, 9].

2.2 Higgs boson pair production and decays

The observation of the Higgs boson at the LHC in 2012 has been followed by measurements regarding its properties and if its behaviour is in accordance with the SM predictions. Thus, it is necessary to measure the Higgs self-interactions arising from the Higgs mechanism. This can be done by probing the Higgs boson pair production which is mediated by an off-shell Higgs boson, as displayed in Figure 2a. A Higgs boson pair can also be produced by other interactions like the Higgs-fermion Yukawa interactions, shown in Figure 2b.

The two diagrams interfere destructively, resulting in a small cross section in the SM, \( \sigma_{hh} = 33.4 \text{ fb at } 13 \text{ TeV} [11] \). This process is sensitive to possible deviations of the amplitudes from their SM values, hence it is interesting for testing new physics. One such example is
the two Higgs doublet model (2HDM) which describes e.g. the Higgs sector of the Minimal Supersymmetric extension of the SM (MSSM) [12]. Figure 3 displays a Higgs pair production process and a decay channel of interest for checking the 2HDM or other beyond the SM (BSM) theories. The Higgs boson pair is produced via gluon-gluon fusion, which is the dominant production process, through the decay of an intermediate state, where X is either a spin-2 graviton or a scalar resonance. In the decay chain of interest for this project, one Higgs boson decays to two $b$-quarks and one to two $\tau$-leptons.

Figure 3: Resonant Higgs boson pair production and decay into a $bb\tau^-\tau^+$ final state.

Figure 4 shows the branching ratios of the Higgs boson decay channels as a function of its mass. The decay process $hh \rightarrow bb\tau^-\tau^+$ has a relatively clean final state compared to...
the most probable $hh \rightarrow b\bar{b}b\bar{b}$ and a relatively large branching ratio (7.4%) compared to $hh \rightarrow b\bar{b}\gamma\gamma$, which has a very clean signature due to the narrow di-photon system.

3 The ATLAS experiment at the LHC

3.1 Large Hadron Collider at CERN

The Large Hadron Collider is the largest and most powerful particle accelerator in the world. It is a circular hadron accelerator and collider with a circumference of 27 km, installed in a tunnel at CERN in Geneva. The LHC accelerates protons or ions which collide at energies in the TeV scale, making it possible to probe different predictions from particle physics theories. The first data-taking period (Run I) lasted from 2010 to 2012, while the collision energy reached $\sqrt{s} = 7 - 8$ TeV. After a long shutdown from 2013 to 2015 the energy increased to $\sqrt{s} = 13$ TeV (Run II, recently completed). The four main experiments at the LHC are ALICE, ATLAS, CMS and LHCb, as seen in the overview of Figure 5.

![Figure 5: The CERN accelerator complex [14].](image)

3.2 ATLAS

The ATLAS (A Toroidal LHC ApparatuS) detector is one of the multi-purpose detectors at the LHC and can measure a wide variety of signals in order to study the physical processes that arise from the proton-proton collisions. It consists of different sub-detectors, which are the inner detector, the electromagnetic and hadronic calorimeters and the muon spectrometer, as illustrated in Figure 6. In particular, the inner detector (tracker) measures the charged particle momentum by reconstructing their trajectories. A 2 T solenoid magnet is placed outside the inner detector, providing a strong field in which charged particles bend. The electromagnetic calorimeter is used in order to measure the energy as well as identify electrons/positrons and photons, while the hadronic calorimeter is used for energy measurement.
of charged and neutral hadrons. The energy, position and shower shape of electrons, photons and hadronic jets are measured with high precision by the calorimeters. The calorimeter system is able to disentangle the electrons/positrons and photons from showers coming from high-$p_T$ hadrons, tau decays and QCD-induced backgrounds up to an energy scale of TeV. The muon spectrometer is responsible for the muon identification after all other particles (except neutrinos) get stopped and absorbed by the calorimeter [15, 16].

The ATLAS cartesian coordinate system has its origin in the nominal collision point with the $z$-axis indicating the beam direction, while the $x$-axis points towards the center of the LHC ring and the $y$-axis upwards. The angle around the beam axis is defined by the azimuthal angle $\phi$, while the polar angle $\theta$ is the one measured from the beam axis. The latter can be replaced by the pseudorapidity $\eta = -\ln(tan(\theta/2))$, which is invariant under longitudinal boosts. The distance between two variables in the pseudorapidity-azimuthal plane is given by $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$. Also a commonly used variable is the transverse momentum, defined as $p_T = \sqrt{p_x^2 + p_y^2}$. Some of the important characteristics of the ATLAS detector are summarized in Table 1.

Table 1: Performance of the ATLAS detector. The units of $E$ and $p_T$ are GeV [16].
4 Simulation framework

The production of Monte Carlo (MC) simulated samples includes several steps: event generation, parton showering, hadronization and detector simulation. The event generation involves simulation of the interactions between quarks and gluons in the proton-proton collision, while the detector simulation accounts for the interaction of particles arising from the generator with the detector material. The energy deposited in each sensitive element of the detector is also calculated. Then, the simulated energy deposits have to be turned into a detector response, looking alike with the raw data from the real detector.

For the signal sample, Randall-Sundrum gravitons (RSG) with an assumed mass of 1.5 TeV, the event generation is performed with MadGraph [19], while the parton shower is modelled with Pythia8 [20]. All the plots produced within the study presented in this report are edited with ROOT [21]. As one can observe later, the plotted variables are distributed over the raw number of events, or over the sum of weights. A raw number of (MC) events does not have any physical meaning, while the sum of weights represents the exact expected number of events, since it includes all the necessary scale factors and the re-weighting to the correct integrated luminosity. The scale factors are used so that the simulation of physics objects is corrected based on variations between their expected and measured properties. It is worth mentioning that the two distributions should have the same shapes for a large number of events, so that the studies can be performed on any one of them.

The framework used for this project is the CxAOD Framework, which is a RootCore based framework. Its main point is to take the derived analysis output data (DxAOD) and produce calibrated output data. The CxAODMaker is used for this step and the output format is called CxAOD. These files can be further processed by the CxAODReader package, in which the code used in this project is implemented.
5 Decay of Higgs boson pairs to di-$\tau$ + di-$b$ final states

5.1 Tau leptons

Tau leptons are the heaviest of the three charged leptons in the SM with a mass of 1.7768 GeV [22]. They decay almost immediately with a mean life time of 290.3 fs [22]. The $\tau$ is the only lepton heavy enough to decay in both lighter leptons and hadrons. Its decay is characterized by the intermediate state of a neutrino $\nu_\tau$ and an off-shell W boson decaying to either $l\nu_l$, where $l$ is either electron or muon, or two quarks as shown in Figure 8. The $\tau$ decay is referred to as leptonic when the W boson decays to a neutrino and its corresponding charged lepton. If it decays to quarks, the $\tau$ decay is referred to as hadronic.

![Figure 8: Feynman diagram of common $\tau$ decays by an emission of an off-shell W boson.](image)

The leptonic decay of $\tau$ leptons has a branching fraction of 35% while the hadronic decays are the most common, with a branching fraction of 65%. This study will concentrate on the hadronic decay mode. Tau leptons in this mode decaying into one charged pion are called 1-prong, while those decaying into three charged pions are called 3-prong.

In a hadron collider experiment like ATLAS at the LHC, quark- and gluon-initiated jets dominate. Therefore, it is necessary to discriminate these QCD-induced jets from $\tau$ leptons that decay hadronically, which also form jets in the calorimeter. The most essential difference is that the decay products of $\tau$ leptons in the hadronic mode, $\tau_{had}$, have a more narrow, collimated shape and low charged track multiplicity (1 or 3 tracks) in the inner detector. QCD-induced jets have in principle a wider shape with more particles, which, among other characteristics, is used to differentiate $\tau$ decays from regular jets.

5.2 Bottom quarks

Bottom quarks form $B$-hadrons with a finite lifetime and hence a decay length of a few millimetres. The identification of heavy-flavour jets is based on impact parameter information and the presence of a secondary vertex. $B$-hadrons usually decay within the beam pipe, and therefore the displaced vertex must be reconstructed by extrapolating charged particle tracks. This is performed by a vertex detector installed close to the beam pipe. The identification of $b$-jets is performed by special $b$-tagging algorithms.
5.3 Boosted hh → bbττ

In this study we are interested in signatures arising from the production of high-mass resonances decaying into Higgs boson pairs. A so-called boosted analysis is used for those hh systems in which the Higgs bosons have higher Lorentz boosts, preventing the Higgs boson decay products from being resolved in the detector as separate τ- and b-jets. Instead, the decay products are collimated and each Higgs boson candidate consists of a single large-radius jet (LRJ) for the bb system and another one for the ττ system [23, 24].

6 Event selection

The objective of this project is to study the event selection and categorization that will be suitable for the background estimation methods used within the analysis while ensuring a high signal acceptance in the signal region. The event selection and categorization starts with an overlap removal of the detector objects. In this process we assign the large-radius jets to di-b and di-τ candidates aiming for the best possible distinction between the two systems. The main goal of this study is to revise the current overlap removal, which was motivated by other analyses, assuming that it is not designed in the best possible way, since it is not consistent with the data-driven method used to estimate how often quark/gluon-initiated jets are misidentified as di-τ objects. Our system is defined by preselection and selection cuts, where only the large-radius jets with a transverse momentum p_T above 200 GeV, |η| < 2.4 and a constituent mass above 50 GeV are kept. Later on a few more cuts are applied, as discussed later in the report, so that after implementing the overlap removal of objects and using the 1.5 TeV RSG signal sample, we can configure a cut flow table.

In order to distinguish di-b and di-τ objects, we can use extra parameters, like the multivariate technique of Boosted Decision Trees (BDTs) [25], which can, in general, give a good separation between variables that are characteristics of the objects in question. There is a classification of di-τ objects in pass di-τ and fail di-τ identification (ID) based on the di-τ
BDT score that they get. If it is lower than the predefined BDT threshold, they get a fail ID, while if it is higher than the BDT threshold they get a pass ID. Furthermore, the selected di-$b$ objects are divided in 0-tag, 1-tag and 2-tag regions based on the number of $b$-tagged sub-jets. Explicitly, the selected large-radius jet does not have any $b$-tagged sub-jets in the 0-tag region, it has one $b$-tagged sub-jet in the 1-tag region and two $b$-tagged sub-jets in the 2-tag region. The code we use in the CxAOD framework, mentioned in Section 4, includes certain steps regarding the way the objects in each event are selected. First we go through the old overlap removal and afterwards we discuss the revised approach.

6.1 Old overlap removal of objects

First, if a di-$\tau$ candidate has a di-$\tau$ ID BDT score $> 0.72$, it is selected. The second step is the selection of a di-$b$ candidate, which is performed if there is a large-radius jet with two $b$-tagged track-jets. In case there are no large-radius jets with two $b$-tagged track-jets, but instead there is a large-radius jet with one $b$-tagged track-jet, then a di-$b$ candidate is anyway selected. Further, if there are no $b$-tagged large-radius jets and also the di-$\tau$ candidate has not been selected yet, then the large-radius jet with the highest di-$\tau$ ID BDT score is selected. Finally, since the di-$b$ candidate has not been selected so far, the leading $p_T$ large-radius jet, i.e. the one which has the highest transverse momentum, is selected as the di-$b$ candidate.

The current overlap removal is a good choice for selecting signal events, however it is not consistent with the Fake Factor (FF) method, which is a data-driven method used to estimate how often quark/gluon-initiated jets are misidentified as di-$\tau$ objects, as mentioned previously. In more detail, the current overlap removal does not apply the same selection criteria to di-$\tau$ objects that satisfy the di-$\tau$ ID BDT threshold and to those that do not. The priority is given to a ($b$-tagged) di-$b$ candidate over a fail di-$\tau$ candidate. The FF is defined as the ratio of pass- over fail-ID\textsuperscript{1} di-$\tau$ candidates in the control region where it is measured. This is assumed to be equal to the ratio of pass- over fail-ID di-$\tau$ candidates in the signal region, where the FF is applied. This equality is valid when the ”pass” and ”fail” di-$\tau$ candidates are selected in the same way, which is not the case for the current overlap removal. Consequently, a new approach has to be tested so that a proper FF estimation can be performed, while it should also be confirmed that the acceptance would not be significantly reduced.

6.2 New overlap removal of objects

The new approach of selecting objects per event consists of two steps. First, the di-$\tau$ candidate, for being selected, would have to be a large-radius jet with only two sub-jets, and potentially also three, and with a di-$\tau$ ID BDT score greater than some lower cut as well. It should be noted here that if two candidates are found to satisfy the criteria, the subleading candidate in $p_T$ is the preferred one. The latter is based on the test that was performed during the study and it is justified by the results of Figure 13. An explanation is given later in this section. Second, the remaining leading in $p_T$ large-radius jet is selected as a di-$b$

\textsuperscript{1}Even for the fail-ID criterion, a BDT score of at least 0.4 is still required.
The second approach is better motivated as it selects all di-\(\tau\) candidates in the same way (those that have a di-\(\tau\) ID BDT score greater and lower than the threshold). Similarly, this is also the case for the di-\(b\) selection because there is no dependence on how the N-\(b\)-tag regions are defined. In this way there will be no bias in the selection and potentially a better background modelling will be achieved.

The new approach is tested on our signal (Randall-Sundrum gravitons at 1.5 TeV). First, it is essential to determine a couple of parameters based on truth studies, in order to extract information that would allow to assess the new selection. Therefore, we check the list of generated truth particles, we find \(\tau\)-leptons and \(b\)-quarks coming from a Higgs boson pair decay and the reconstructed objects are then geometrically matched to truth di-\(\tau\) and di-\(b\) objects, using \(\Delta R < 0.3\) criteria.

We begin by plotting the di-\(\tau\) BDT score for true di-\(b\) and true di-\(\tau\), and as it can be seen in Figure 10, we can distinguish them quite clearly. True di-\(\tau\) objects have a higher di-\(\tau\) BDT score as expected.

![Figure 10: Di-\(\tau\) BDT score for truth-matched di-\(b\) and true di-\(\tau\) objects. The blue line with the star corresponds to truth-matched di-\(b\), while the red one with the circle corresponds to the truth-matched di-\(\tau\).](image)

Next, we plot the number of \(b\)-tagged track-jets within the large-radius jet which is matched to the true di-\(\tau\) system, shown in Figure 11. The ”-1” bin corresponds to those cases where there is no LRJ that can be matched to the true di-\(\tau\) system, which probably indicates that the value of \(\Delta R = 0.3\) for the matching is too small. What we deduce from the plot is how often a di-\(\tau\) is misidentified as one or two \(b\)-tagged track-jet.
Figure 11: Number of $b$-tagged track-jets within the LRJ which is matched to a true di-$\tau$ system.

Since the LRJ is matched to the true di-$\tau$, we do not expect any of them to be $b$-tagged at all, however some appear to be and this is something that should be investigated in further studies. It is worth mentioning that $b$-tagging algorithms will always mis-tag some $\tau$-jets as $b$-jets. The larger the $b$-tagging efficiency, the larger the mis-tag rate for the $\tau$-jets as well. Nonetheless, this is a useful plot since it justifies the fact that we do not start selecting the di-$b$ candidate before the di-$\tau$ candidate.

Afterwards, we plot the number of sub-jets within the di-$\tau$ object that is matched to true di-$b$. As shown in Figure 12(a) it is either two or three, while in Figure 12(b) the number of sub-jets within the di-$\tau$ candidate matched to true di-$\tau$ really peaks around two. Both truth-matched di-$\tau$ and di-$b$ objects have low sub-jet multiplicity, but that is more pronounced for truth-matched di-$\tau$ objects.
Figure 12: Number of sub-jets within the di-$\tau$ candidate objects.

Figure 13 illustrates the index of the large-radius jet to which the true di-$\tau$ and true di-$b$ are matched. Large-radius jets are ordered in $p_T$ in a vector, hence the index points out which component of the vector we are looking at. Therefore, the 0 bin refers to the first large-radius jet in the list, while the 1 bin refers to the second one, etc. In the first subfigure we notice that true di-$\tau$ objects are usually matched to the subleading large-radius jet (lower $p_T$), while the second subfigure suggests that the true di-$b$ objects are usually matched to the leading large-radius jet (higher $p_T$). On average we expect the di-$b$ system to have a greater transverse momentum $p_T$ than the di-$\tau$ system. The reconstructed di-$\tau$ candidate
matched to the true di-τ will have a softer $p_T$ spectrum due to the presence of more energetic neutrinos in the hadronic decay of a τ-lepton. The above is confirmed by Figure 14.

![Figure 13: Index of LRJ to which the di-τ (a) or di-b (b) object is matched.](image)

Thus, it is justified why if both leading and subleading candidates satisfy di-τ candidate requirements, we prefer to take the subleading one in the selection.
Last, we plot the azimuthal angle $\Delta \Phi$ between the true di-$\tau$ and missing transverse energy (MET). This is arising from neutrinos in the $\tau$ decay, so it is expected that the MET direction in $\Phi$ is close to the di-$\tau$ candidate direction. In order to ensure that the MET $\Phi$ direction is well defined, the cut $\text{MET} > 20$ GeV was used as a part of the event preselection.

![Figure 14: Azimuthal angle between true di-$\tau$ and missing transverse energy.](image)
7 Results and Conclusion

As it has already been mentioned, a cut flow table is generated after the implementation of the overlap removal and the use of the RSG signal sample at 1.5 TeV. We repeated the same procedure three times, one for the old overlap removal, one for the new overlap removal for a lower di-τ BDT cut of 0.4 and one for a lower di-τ BDT cut of 0.5. In the new approach, a criterion, for a di-τ object being selected, is to have a di-τ ID BDT score greater than some lower cut, being either 0.4 or 0.5. This lower cut needs to be below 0.72, which is the di-τ ID BDT threshold, so that fail di-τ objects are selected as well. The table is provided below.

Table 2: Cut flow table

<table>
<thead>
<tr>
<th>Cut</th>
<th>Old Overlap Removal</th>
<th>New Overlap Removal with 0.4 lower BDT cut</th>
<th>New Overlap Removal with 0.5 lower BDT cut</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N events</td>
<td>sum of weights</td>
<td>N events</td>
</tr>
<tr>
<td>Initial</td>
<td>36041.00</td>
<td>2.16</td>
<td>36041.00</td>
</tr>
<tr>
<td>20GeVMETCut</td>
<td>35113.00</td>
<td>2.10</td>
<td>35113.00</td>
</tr>
<tr>
<td>SelectDTagF</td>
<td>28790.00</td>
<td>1.72</td>
<td>23630.00</td>
</tr>
<tr>
<td>*FailDTagD</td>
<td>9755.00</td>
<td>0.58</td>
<td>8186.00</td>
</tr>
<tr>
<td>*PassDTagD</td>
<td>17565.00</td>
<td>1.05</td>
<td>14870.00</td>
</tr>
<tr>
<td>*0Tag</td>
<td>3572.00</td>
<td>0.21</td>
<td>4449.00</td>
</tr>
<tr>
<td>*1Tag</td>
<td>11678.00</td>
<td>0.70</td>
<td>9268.00</td>
</tr>
<tr>
<td>*2Tag</td>
<td>12070.00</td>
<td>0.72</td>
<td>9339.00</td>
</tr>
<tr>
<td>*PassDTagD0Tag</td>
<td>2290.00</td>
<td>0.14</td>
<td>1996.00</td>
</tr>
<tr>
<td>*PassDTagD1Tag</td>
<td>7487.00</td>
<td>0.45</td>
<td>6323.00</td>
</tr>
<tr>
<td>*PassDTagD2Tag</td>
<td>7788.00</td>
<td>0.47</td>
<td>6551.00</td>
</tr>
</tbody>
</table>

The first column of the table contains the list of cuts that were applied with both old and new overlap removals, while the following columns include the number of events and sum of weights (defined in Section 4) that corresponds to each cut. In the left the results for the old approach are presented, while in the middle the results for the new approach with a lower di-τ BDT cut at 0.4 are demonstrated. In the right part of the table we can see the results for the new overlap removal but with a higher di-τ BDT cut. The cut flow counts the number of events after every cut. As seen in Table 2, a 20 GeV cut in the missing transverse energy is first applied. In the next cut we select the di-τ and di-b candidates. The following entries in the ”Cut” column are not actual cuts, but pointers to the number of events in each region. Thus, one can look at the events for the fail and pass di-τ ID, for 0- or 1- or 2-tags in di-b objects, as well as for the cases where we request both pass di-τ events and N-tag di-b events, where N is either 0, 1 or 2.

Our goal is to have di-τ and di-b clearly distinguished in the signal region, which is the ”2-tag” and ”PassDTagD2Tag” region, so that a proper analysis can be done. Comparing the different approaches, we conclude that the new overlap removal does not significantly degrade the acceptance. With a high cut on the di-τ BDT score we can achieve similar acceptance in the signal region. However, this will lower statistics in the ”fail” di-τ region. Namely, one can look at the sum of weights for the new overlap removal with a BDT cut of 0.5, being 0.68 for the ”2-tag” signal region, which is quite closer to the relevant value (0.72) for the old procedure compared to the lower value of 0.56 for the new procedure with a lower BDT cut of 0.4. A higher BDT cut lowers the probability for a truth-matched di-b object to be selected as a di-τ candidate. The problem currently is that if we have a low
di-τ ID BDT score cut, like 0.3 or 0.4, it is not enough in order to distinguish between di-τ and di-b objects and we lose acceptance because we select di-b as a di-τ candidate. In order to select more events this cut could be lowered by exploiting the ∆Φ distribution that can help distinguishing di-b from di-τ candidates, however this is beyond the scope of this study.
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