Mass reconstruction studies in semileptonic $t\bar{t}H(H \to b\bar{b})$ channel

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Abstract

Forecasted to be one of the leading channels in a measurement of the fermionic coupling, λ_{tH}, which is the only coupling constant with an expectation value ~ 1, $t\bar{t}H$ ($H \to b\bar{b}$) is becoming a very interesting channel for a direct Higgs decay observation. However, this channel has a low $S/\sqrt{B}$ ratio, as it suffers from large background contributions. This report presents a study of irreducible ($t\bar{t}b\bar{b}$) background effects on a Higgs mass reconstruction in a semileptonic decay channel of $t\bar{t}H$ production using a simulated data from PYTHIA 8 Monte Carlo (MC) generator at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV.

Contents

1 Introduction

After the Higgs boson discovery on the 4th of July in 2012, Particle Physics searches did not stop. As both ATLAS and CMS collaborations confirmed the Higgs boson to have a mass of 125 GeV, this arose even more questions about the existing particle models. With mass of 125 GeV, the Higgs is too light to reject Supersymmetry (SUSY) and too heavy to reject multiverse models. In order to fully understand whether it really is a Standard Model (SM) particle, more precise measurements of its parameters such as mass, charge or spin are needed. Furthermore, a successful measurement of the coupling constant, λ_{tH}, between the heaviest SM particle, t-quark, and the Higgs boson would explain the mass appearance and could enhance our understanding of the dark matter.

In section 2 of this report, a brief introduction to the Large Hadron Collider (LHC) physics and to the ATLAS experiment will be made, followed by a motivation to study Higgs decays in $t\bar{t}H(H \to b\bar{b})$ channel. Section 4 will describe the signature of the Higgs-decay event in the aforementioned $t\bar{t}H(H \to b\bar{b})$ channel. Some recent results as well as a detailed procedure of Higgs mass reconstruction will be described step-by-step in section 5, whilst the last section of this report will concentrate on future objectives of this study and its applications.

2 LHC and ATLAS

The Large Hadron Collider (LHC) contains four major experiments: ATLAS, CMS, ALICE, and LHCb - other three being: LHCf, TOTEM, and MoEDAL. Currently, the LHC is the most powerful hadronic collider in the world with a center-of-mass energy being $\sqrt{s} = 8$ TeV, which will be increased up to $\sqrt{s} = 14$ TeV in 2015 during Run II. Therefore, all the results discussed in this report will present measurements both at $\sqrt{s} = 8$ TeV and at $\sqrt{s} = 14$ TeV in order to predict differences in expected values during Run II.

2.1 LHC

The LHC is located on the border of France and Switzerland, and it has replaced the previously run Large Electron Positron (LEP) collider. The current instantaneous luminosity of the LHC reaches 7×10^{33} $cm^{-2}s^{-1}$ and it will be increased up to 2×10^{3} $cm^{-2}s^{-1}$ in the Run II.

2.2 ATLAS

A Toroidal LHC ApparatuS, or shorter - ATLAS - is one of the two general purpose detectors (the other one being CMS), and one of the four biggest experiments run at the LHC. Its essential objective is to discover New Physics. Currently, the integrated luminosity at the ATLAS (and CMS) reaches up to 27.03 fb^{-1} for proton-proton, 29.85 nb^{-1} for proton-lead, and 167.4 μb^{-1} for lead-lead collisions. Increase in these values is expected during the next LHC Run.

The coordinate system used in ATLAS defines ϕ as the angle in the transverse plane $x-y$, and θ as the angle to the beam-axis, z. The parameter called rapidity is then defined as

$$y = \frac{1}{2} ln\left(\frac{E + p_z}{E - p_z}\right), \tag{1}$$

where E stands for the energy and p_z is the momentum in the z-direction. A pseudo-rapidity then can be defined as

$$\eta = \frac{1}{2} ln\left(\frac{|p| + p_z}{|p| - p_z}\right) = -ln[tan(\theta/2)], \tag{2}$$

where $|p|$ is the magnitude of the particle's momentum, p. Pseudo-rapidity is more advantageous than a rapidity because y differences are Lorentz-invariant under longitudinal boosts, it is also easier to measure η, and therefore it will be used in the definition of the distance, ΔR:

$$\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}, \tag{3}$$

where i and j are indices of the particles.

3 $t\bar{t}H(H \to b\bar{b})$ channel

At the moment, there are 4 leading channels (as described in Section 3.2) in the direct observation of the Higgs' decays, with a $H \to b\bar{b}$ being a candidate to the fifth channel once it achieves the sufficient signal strength. This channel is difficult because of very low signal cross section, and because of large multiplicity of jets in the final state. Those jets can be paired in many different ways, giving different solutions (this is the reason for combinatorial background to rise), and a successful and efficient b-tagging algorithm is necessary. The semi-leptonic channel was chosen to maximise the signal sensitivity. A large amount of data is necessary in order to obtain a sufficient signal strength. With an increase in integrated luminosity during LHC Run II, this can be achieved, and the $t\bar{t}H(H \to b\bar{b})$ is a potential channel to look for New Physics.

3.1 Higgs decay

Other decay channels observed at the ATLAS experiment are: $H \to ZZ^{(*)}$ (branching ratio: 3%) $\to 4l$, which is often called the "golden channel" due to a very large signal-to-background ratio, ($S/\sqrt{B}$), $H \to \gamma\gamma$ (branching ratio: 0.2%) having a high mass resolution and a high efficiency, $H \to WW^{(*)}$ (branching ratio: 21%) channel, where $e\nu\mu\nu$ is the most sensitive final state for mixed flavour final states with the highest branching ratio for the Higgs at the mass $m_H > 130$ GeV (i.e. a SUSY Higgs), and a fermionic $H \to \tau\tau$ (branching ratio: 6%) channel, which is often combined with $H \to b\bar{b}$ in order to maximise the signal strength. The fermionic $H \to \tau\tau$ channel has a large branching fraction around $m_H = 125$ GeV. Our chosen $H \to b\bar{b}$ channel has the largest branching ratio (57%) for $m_H = 125$ GeV, however it also suffers from a very large hadronic QCD background. Only the production in association with gauge bosons, W or Z, is considered so far. The first three channels are the most sensitive ones, whilst $H \to \tau\tau$ and $H \to b\bar{b}$ are important in measuring the coupling of the Higgs boson to fermions.

3.2 Background to $t\bar{t}H$

There are several types of background contributing to reduce the $S/\sqrt{B}$ ratio: irreducible background - coming from Quantum Chromodynamics (QCD) and Electroweak (EW) $t\bar{t}b\bar{b}$ decays (as shown in Figure 1), reducible background - from $t\bar{t}jj$ decays when light jets are misidentified as b-jets, and other backgrounds such as $W + jets$, tW, and QCD, including a combinatorial background which appears from mis-pairing of b-jets in the signal events. Hence, it is very important to identify b-jets correctly in order to make reducible background as small as possible.

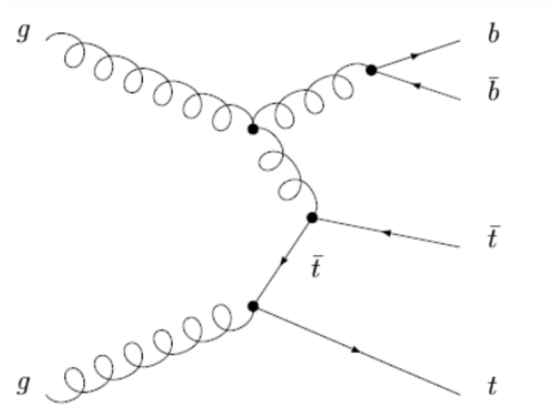

Figure 1: Example of an irreducible background coming from $t\bar{t}b\bar{b}$ decays (QCD)

3.3 Fermionic coupling

It is confirmed for the Higgs to be a $J^{PC} = 0^{++}$ boson being responsible for electroweak symmetry breaking, as there are evidences of its relative couplings to W/Z bosons versus photons. The notation $J^{PC} = 0^{++}$ means that it is a spin-0, i.e. scalar, boson with a positive parity and with no charge. Some SUSY models disagree with this, and predict the parity to be in 0^- state, while SM favours 0^+ state. The angular variables in $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ channels were used in the spin and parity study. The possibilities for the Higgs to be a 2^- (pseudo-tensor) or a 2^+ (graviton-like) particle were excluded by the measurements favouring 0^+ state. However, to confidently state that the Higgs boson is a SM particle, a full set of parameters are necessary to be measured, however, only one fermionic coupling was directly measured up to now, through $H \to \tau\tau$. There are two more interesting fermionic couplings to complete the picture: λ_{bH} and λ_{tH}, with later one being the only coupling with a predicted value close to 1. The study of the coupling constants could have strong influence in either confirming or rejecting the theory of SUSY because the values of coupling constants in SUSY differ from those in SM.

4 Event signature

There are three possibilities for a $t\bar{t}$ final state: $2l2\nu2j$, a very clean final state, however, it has a branching ratio of only 10%, $l\nu4j$, a semi-clean final state with a branching ratio of 45%, and a $6j$ final state, also with a high branching ratio of 45% but causing a low signal-to-background ratio due to a high number of incorrectly tagged b-jets. Therefore, a semi-leptonic $t\bar{t}H$ channel was chosen in order to improve the signal-to-background ratio. It is also easier for a trigger to identify a lepton in the final state rather than a hadron. Figure 2 shows a sample event signature, for $t\bar{t}H(H \to b\bar{b})$ where one W decays leptonically (in this case, W^-), the other W decays hadronically, and the Higgs boson decays to two b-quarks. The final state has six jets, one lepton, and some missing energy, which is carried away by a neutrino. Out of six jets, there are four b-tagged jets (two b-quarks from a top and anti-top decays, and the other two are coming from the Higgs decay).

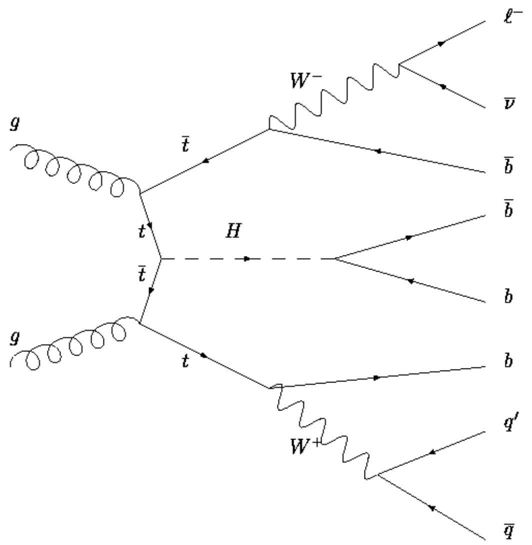

Figure 2: Feynman diagram for a semi-leptonic Higgs decay in the $t\bar{t}H(H \to b\bar{b})$ channel [9]

5 Mass reconstruction

Due to their mass, the heavy particles such as the Higgs boson, the $W^{\pm}$, and the top quarks are short-lived and they weakly decay further. These heavy particles are reconstructed using their decay products, which is done using a TDR method [6]. All the events shown in the subsequent distributions have been produced with a MC PYTHIA 8 event generator.

5.1 Generator-level reconstruction

First of all, the decay of the $W^{\pm}$ is reconstructed: whether it has decayed into two leptons ($W \to l\nu_l$ with a branching ratio of 32%), or if it has hadronically decayed into two light quarks ($W \to q\bar{q}$, branching ratio 68%). Then the Higgs boson is reconstructed through its decay products, b- and $\bar{b}$-quarks. If a b-quark is found, it is checked if its parent is the Higgs, otherwise, it must have come from the top decay. When all six hadronic partons are identified, the Python dictionaries with particles' Lorentz vectors are saved.

5.2 Selection

We make a selection of jets (narrow cones of hadrons and other particles produced during the process of hadronisation) before doing a parton-to-jet matching. A lower cut of 25 GeV is applied to the transverse momentum, p_T, and an upper cut of 4.5 is applied to the absolute pseudorapidity, $|\eta|$. An AntiKt4Truth algorithm with a radius of 0.4 is used to construct jets out of paticles. Due to angular correlations of particles and the cuts applied, not all of the jets are efficiently reconstructed in the final state. Figure 3 and Figure 4 show the p_T distributions (normalised to 1) of partons and jets, respectively. Comparisons of p_T between a parton and jet for different centre-of-mass energies are shown in Figure 5 and Figure 6, showing that there are more events with higher p_T at the higher $\sqrt{s}$, i.e. during Run II.

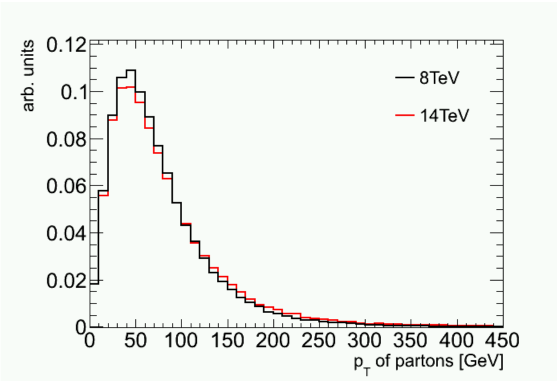

Figure 3: Transverse momentum, p_T, distribution of the six partons used in a parton-to-jet matching.

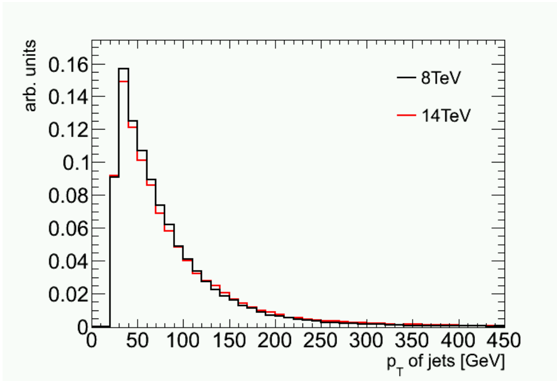

Figure 4: Transverse momentum, p_T, distribution of the jets (passed η and p_T cuts) and used in a parton-to-jet matching.

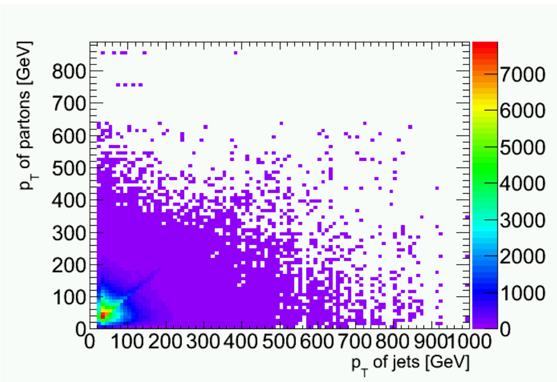

Figure 5: p_T of partons against p_T of jets at $\sqrt{s} = 8$ TeV in 10,000 events.

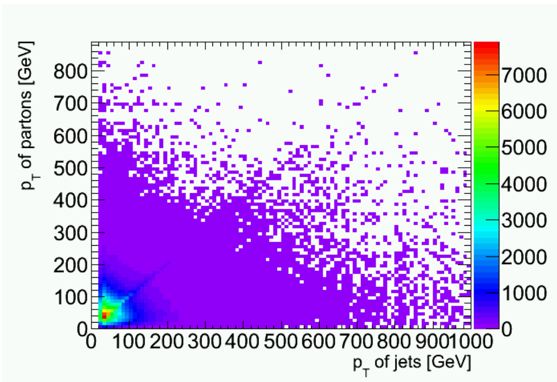

Figure 6: p_T of partons against p_T of jets at $\sqrt{s} = 14$ TeV in 10,000 events.

5.3 Angular distances: ΔR

We loop over the selected jets and six partons, and calculate their distance, ΔR between a jet and a parton to perform matching. Overall, partons consist of four b-quarks (two of which are coming from the Higgs decay) and two light quarks coming from the $W^{\pm}$ decay. The minimum distance, ΔR, distribution between two b-quarks coming from the Higgs (Figure 7), between a b-quark from the Higgs decay and any other b-quark (Figure 8), and between a b-quark coming from the Higgs and any other quark in event (Figure 9) show that sometimes other b-quarks and the light quarks are closer to the b-quark from the Higgs, and are located within the jet.

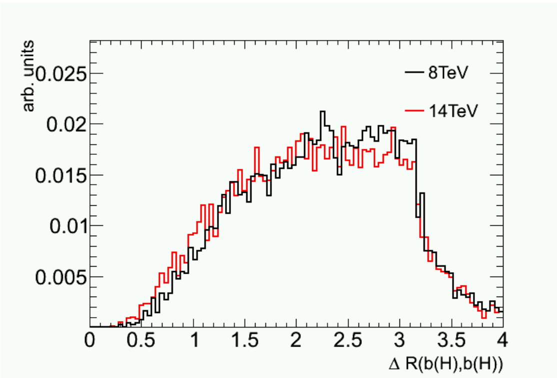

Figure 7: ΔR between 2 b-quarks from the Higgs decay.

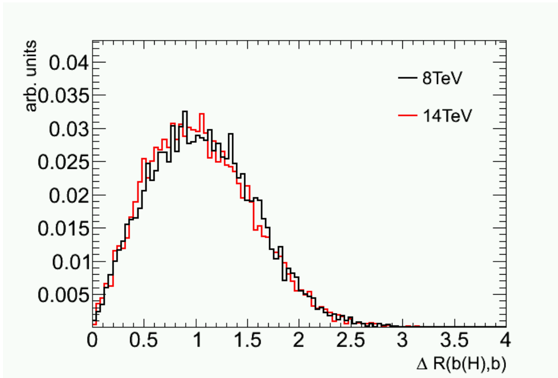

Figure 8: Minimum ΔR between a b-quark from the Higgs decay and any other b-quark.

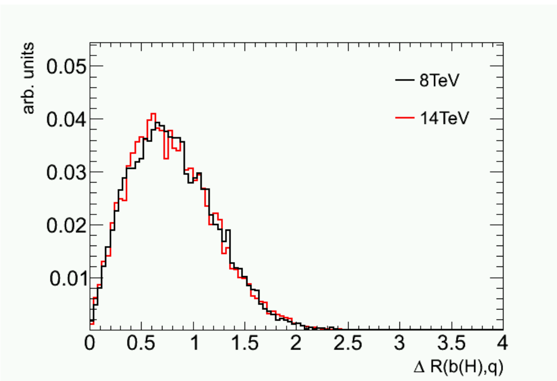

Figure 9: Minimum ΔR between a b-quark from the Higgs decay and any other quark in general.

5.4 Parton-to-jet matching

After the distance, ΔR, between jets and a particular parton is calculated, a parton is assigned the closest jet. Figure 10 shows the minimum ΔR between any of the two b-

quarks from the Higgs decay and the jets assigned to them, whilst Figure 11 and Figure 12 represent the minimum ΔR between b-quarks (excluding b-quarks from the Higgs decay) and the jets assigned, and between the light-quarks and their assigned jets, respectively.

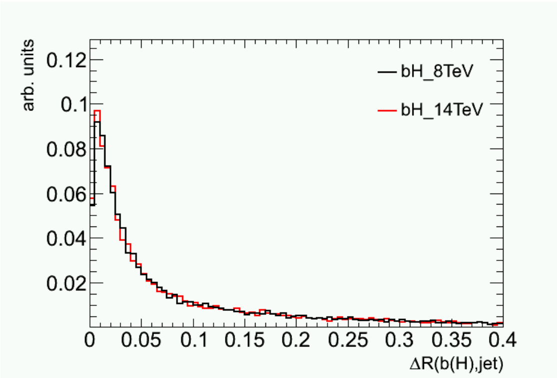

Figure 10: Minimum ΔR between any of the b-quarks from the Higgs decay and the jets assigned to them.

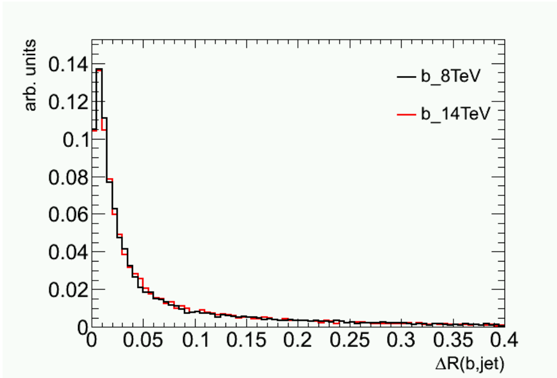

Figure 11: Minimum ΔR between any of the b-quarks (excluding those from the Higgs decay) and the jets assigned to them.

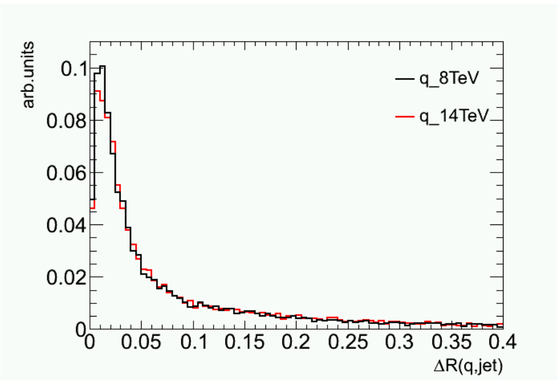

Figure 12: Minimum ΔR between any of the light quarks from the $W^{\pm}$ decay and the jets assigned to them.

Then another loop is entered which checks if the same jet has not been assigned twice to different partons. The complete statistics for a run with 10,000 events for each of the centre-of-mass energies is presented in Table 1. It shows how many partons have been assigned distinct jets. Two additional plots present the largest ΔR in each of the reconstructed events. Figure 13 shows the largest ΔR for partly (when partons have been assigned six not-necessarily distinct jets) reconstructed events and Figure 14 shows the largest ΔR for fully reconstructed events only, i.e. when all six partons have been assigned distinct jets. These can be used further as an estimation of a goodness of the jet-matching tool.

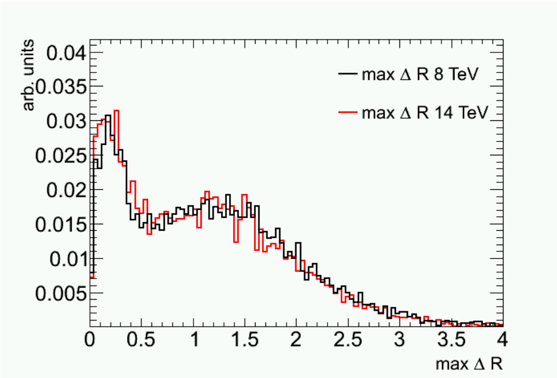

Figure 13: The largest ΔR for partly (including fully) reconstructed events.

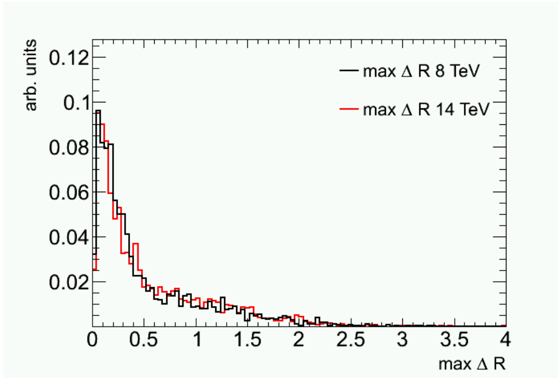

Figure 14: The largest ΔR for only fully reconstructed events.

Table 1 also summarises how many jets from those which have been assigned more than once, have been mis-assigned to the b-quarks or to the light quarks (from the $W^{\pm}$) instead of being assigned to the b-quarks from the Higgs decay. Events where both light quark, q, and light anti-quark, $\overline{q}$, have been assigned the same jet (named as misassigned $q\overline{q}$ jets) could be easily reconstructed and, consequently, it could improve the goodness of a jet-matching tool.

Table 1: Parton-to-jet matching

	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 14$ TeV
# of events	10,000	10,000
with 6 different jets	23.8%	27.6%
with 5 different jets	44.9%	44.2%
with 4 different jets	25.2%	23.5%
with 3 different jets	5.7%	4.3%
with 2 different jets	0.4%	0.3%
with 1 different jet	0.0%	0.0%
with 0 different jets	0.0%	0.0%
% of misassigned b jets	36.4%	33.6%
% of misassigned W jets	77.0%	71.2%
% of misassigned $q\overline{q}$ jets	5.4%	5.8%

5.5 Results

Finally, events with six distinct parton-to-jet matches, i.e. fully reconstructed, can be used in the mass of the Higgs boson reconstruction. Figure 15 shows an invariant mass of the two b-jets, i.e. the mass of the Higgs, for a partly reconstructed event, whereas Figure 16 shows invariant mass of two b-jets in the case of a fully reconstructed event. A sharper peak around 125 GeV can be seen in the second case that suggests better identification of Higgs due to improved resolution which could improve the signal strength.

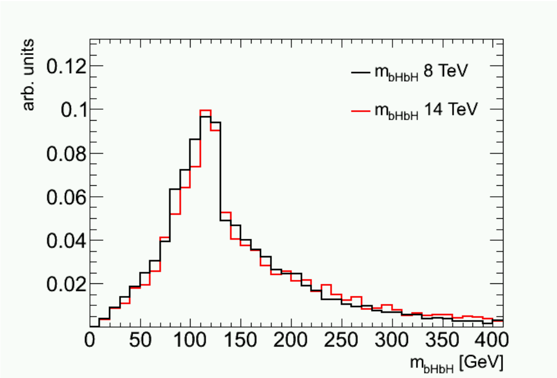

Figure 15: Invariant $m_{b(H)b(H)}$ for a partly-reconstructed event.

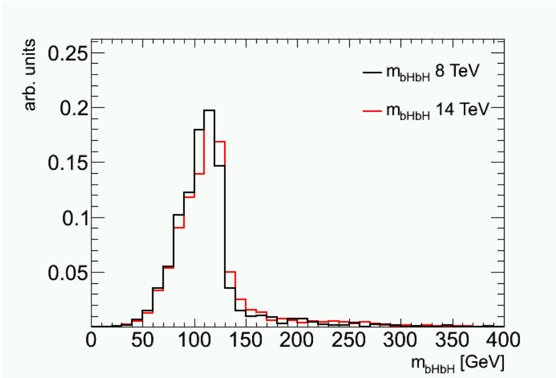

Figure 16: Invariant $m_{b(H)b(H)}$ for a fully-reconstructed event.

6 Conclusions and further objectives

The report briefly introduced to the process of the generator-level reconstruction of the Higgs boson mass. The results agreed with the theoretical prediction of $m_{b(H)b(H)} = 125$ GeV. Also, some statistics of the event reconstruction was carried, showing that most of the events were only partly-reconstructed (with 5 final-state jets instead of 6). A deeper study of the reducible background could be carried out in order to implement its effects into the current algorithm. This should result in more events being fully-reconstructed, which would consequently bring in much higher precision into the mass measurements.

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