Research progress of the inclusion of tau-leptons in the Higgs to four lepton decay channel with the ATLAS detector

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Abstract. The Standard Model, SM, Higgs boson to four lepton (either electrons or muons) decay channel has good signal to background ratio and can be used to reconstruct the Higgs boson invariant mass with a good resolution over an intermediate mass range Higgs boson. This makes the four lepton channel one the most relevant channels to study at the Large Hadron Collider, where a Higgs boson has been discovered with a mass of approximately 125 GeV. Although the Higgs boson to four lepton decay channel played an important role in this discovery, the decay leptons considered excluded tau leptons in the final state. Reasons for this lie in the hard-to-detect hadronic or leptonic tau decays. A study which includes tau leptons in the four lepton decay channel is beneficial to completing the picture of the Higgs boson search, particularly in the statistically limited vector-boson-fusion production mode. The implementation of tau decay to this channel is discussed.

1. Introduction

The unification of electroweak theory at the end of the 1960's and the later unification of the electroweak theory and quantum chromodynamics (QCD) lead to what is known today as the Standard Model (SM) of fundamental interactions [1]. The model's predictions of fundamental particle masses, widths and branching ratios are being experimentally matched with astonishing precision. The last piece of the puzzle for the SM is the discovery of the predicted Higgs boson, which is a product of spontaneous symmetry breaking in the SM [2, 3, 4]. The precise mass of the Higgs boson is not precisely predicted by the SM and the search for this elusive particle was performed at the Large Hadron Collider (LHC [5]) which is currently operational at CERN. The two experiments which shed light on this matter are the ATLAS [6] and CMS [7] experiments at the LHC. In July 2012 both ATLAS and CMS independently announced the discovery of a Higgs-like particle with a mass of around 125 GeV[8, 9]. By mid-March 2013 the experiments had confirmed that this particle is in fact a Higgs particle [10]. The LHC now aims to measure the properties of this Higgs boson and continue the quest of searching for hints of new physics. More research needs to be performed in order to tell whether this Higgs boson is in fact the SM Higgs boson, or if it is rather a Higgs boson from one of the more exotic theories, e.g. the Minimal Supersymmetric Standard Model (MSSM)[11]. This paper will introduce the concepts needed in order to expand on the signal sensitive four lepton decay channel (which was used extensively in the Higgs boson discovery) by including tau leptons, with the goal of ultimately including the tau decay into this channel to improve the Higgs boson's statistics.

Table 1. Cross sections are given for the center of mass energies $\sqrt{s} = 7$, 8 TeV in pb for the leading Higgs boson production mechanisms at m$_H$ = 125 GeV.

CME	ggF	VBF	WH	ZH	$t\bar{t}H$
$\sqrt{s} = 7$ TeV	15.3%	1.22%	0.57%	0.32%	0.09%
$\sqrt{s} = 8$ TeV	19.5%	1.58%	0.7%	0.39%	0.13%

2. The Discovery of a Higgs boson

The gauge theories from which the SM arises describe infinite range forces, i.e. massless mediators, such as photons and gluons. However, the weak force mediators, the Z^0 and $W^{\pm}$, are massive particles. Moreover, in the unperturbed theory, fermions are massless. The mechanism which gives rise to the introduction of masses was developed by R. Brout, F. Englert, G. Guralnik, C. R. Hagen, T. Kibble and P. Higgs [2, 3, 4]. The mechanism is a spontaneous symmetry breaking phenomena which introduces a new field with a corresponding scalar particle called the Higgs boson. In the current SM formulation the Higgs boson is an isospin doublet. The precise mass of the Higgs boson is however not predicted by the model and must be determined experimentally. If a Higgs boson exists, it will be produced by means of high energy proton collisions, like the ones performed at the LHC. The leading production mechanisms of the SM Higgs boson are: gluon-gluon fusion (ggF), Vector Boson Fusion (VBF), associated production with weak bosons (WH and ZH) and associated production with top quarks ($t\bar{t}H$). Table 1 displays the cross sections of the leading production mechanisms wrt. the center of mass energies reached at the LHC in the 2011 (7 TeV) and 2012-2013 (8 TeV) data collection periods.

The ATLAS detector is used to reconstruct the particles produced in the proton collision. The decay channels and branching ratios of a SM Higgs boson depends on the mass of the Higgs. Figure 1 shows the predicted SM Higgs branching ratios as a function of the Higgs boson mass m$_H$.

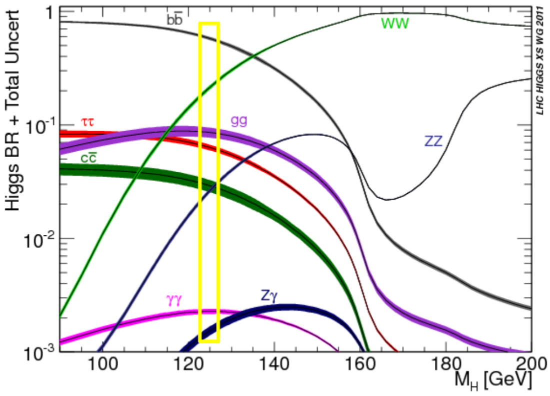

Figure 1. The SM Higgs branching ratios as a function of the Higgs boson mass m$_H$. The branching ratios of a Higgs boson of m$_H$ at approximately 125 GeV is highlighted.

The SM Higgs boson will decay according to the branching ratios predicted. It is therefore important to test as many decay channels as possible, in order to compare experimentally measured branching ratios to the predicted ones.

In 2012 a Higgs particle was found at the LHC with a mass of around 125 GeV [8, 9]. The primary channels used by ATLAS in the discovery where the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ ($\ell = e$, μ) and $H \rightarrow \gamma\gamma$. Figure 2 shows the distribution of the invariant mass of selected candidates compared to background expectation of the 4ℓ and $\gamma\gamma$ experiments at ATLAS. Both experiments show a significant deviation from the background expectation at approximately 125 GeV which lead to the Higgs boson discovery.

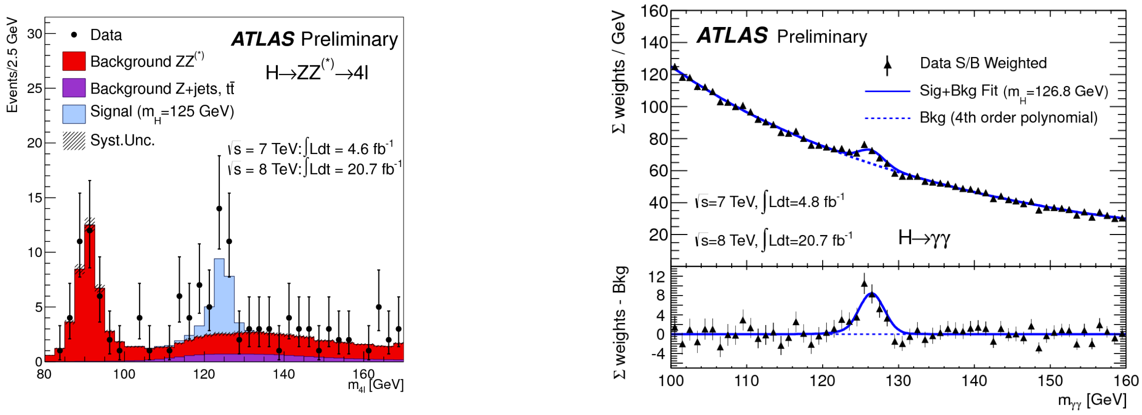

Figure 2. The distribution of the four-lepton (left) [12], and di-photon (right) invariant mass [8] for the selected candidates compared to the background expectation for the combined $\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV data sets.

3. Higgs to $ZZ^{(*)}$ to four lepton decay channel

The four lepton analysis will be introduced in this section, along with some of the lepton identification and selection criteria that where used [12]. This will lay a foundation for expanding the four lepton channel to include tau leptons.

The $H \to ZZ^{(*)} \to 4\ell$ ($\ell = e$, μ) decay mode has four final states: 4μ,$4e$,$2\mu 2e$ and $2e2\mu$. The $2\mu 2e$ and $2e2\mu$ states differ by flavour of pair closest to the Z mass. There are very few processes that decay to four leptons and hence this four lepton channel yields a good signal over background ratio. The only irreducible background to the four lepton channel comes from non-resonant ZZ production. There are also small background contributions from Z+jets and $t\bar{t}$ production.

In order to probe this channel, efficient reconstruction of electrons and muons was performed. Single- and di-lepton triggers where used to trigger events of interest (efficiency of $> 97\%$ for μ and 100% for e). Electron reconstruction required that electron candidates have energy depositions in the calorimeter associated with tracks in the inner detector (ID). Tracks had to be refitted with a Gaussian-Sum Filter in order to compensate for Bremsstrahlung energy loss (energy of a charged particle lost due to acceleration). To be consistent with electromagnetic showers, calorimeter showers had to meet certain identification criteria. The electron transverse momentum, p_{T}, can then be reconstructed from the energy depositions in the calorimeter and the track direction at the interaction point.

Muon candidates consist of ID tracks associated with complete or partial tracks in the muon spectrometer (MS). For complete MS tracks, ID and MS momentum measurements are combined to reconstruct the muon p_{T}. In the forward region of the detector (direction close to the beam pipe) tracks are reconstructed using MS tracks only, since this area lies outside the range of the ID. There is also a lack of MS coverage in the very central region of the detector (perpendicular to beam pipe from the interaction point). Here, tracks with ID and calorimeter measurements with $p_T > 15$ GeV are identified as muons.

In order to reconstruct the four lepton events, the analysis must search for two same-flavour opposite-sign lepton pairs in each event (quadruplet). Requirements are imposed on the impact parameter in order to reject muons from cosmic rays. Kinematic selection criteria are imposed on the electrons (muons). This includes rejecting electrons (muons) with transverse energy $E_T < 7$ GeV ($p_T < 6$ GeV) as well as minimum p_T requirements on each lepton of the quadruplet. The invariant mass of each of the di-lepton pairs is now reconstructed. The di-lepton pair with invariant mass closest to the Z mass ($m_Z \approx 91.2$ GeV) is known as the leading lepton pair, Z_1, while the other di-lepton pair is known as the sub-leading pair, Z_2. Only one quadruplet is chosen per event, corresponding to the quadruplet with m_{Z_1} and m_{Z_2} closest to m_Z. The reconstructed di-lepton masses must satisfy $50 < m_{Z_1} < 106$ GeV and $m_{min} < m_{Z_2} < 115$ GeV, where m_{min} is dependant on the total four lepton invariant mass, $m_{4\ell}$. Separation criteria on the lepton tracks are implemented. A requirement that all possible di-lepton combinations in a quadruplet have an invariant mass greater that 5 GeV removes any background from $J/\psi \to \ell\ell$. Further impact parameter and track- and calorimeter-based isolation requirements are applied to leptons in order to reduce Z+jets and $t\bar{t}$ backgrounds. Finally the four lepton invariant mass $m_{4\ell}$ is reconstructed.

Background and Higgs signal samples are produced using Monte Carlo (MC) simulations. MC samples, as well as data from the experiment, are passed throughout the analysis. As seen in figure 2, the invariant mass is reconstructed for the background and Higgs signal and compared to the data from the experiment. The data matches the MC predictions with a $m_H = 125$ GeV Higgs signal.

4. Including tau leptons in the analysis

Tau leptons where not included in the initial four lepton analysis since the tau lepton decays are difficult to identify from background processes. Furthermore, tau lepton decays contain neutrinos, which makes the reconstruction of the invariant masses non-trivial. In order to expand on the four lepton channel by including the tau leptons, one needs an efficient way to reconstruct these tau leptons, and ultimately reconstruct the Higgs boson's invariant mass. In this section I will outline the difficulties in doing this, and point to some possible solutions to these challenges.

The lifetime of a τ-lepton is not long enough to allow for its direct measurement in the detector. This forces us to have to reconstruct tau leptons from it's decay products. Tau leptons undergo either hadronic (τ_h) or leptonic (τ_l) decay. The reconstruction of τ-leptons is usually understood as a reconstruction of the hadronic decay modes, since it is difficult to distinguish leptonic modes from primary electrons and muons [13]. However, in reference [14], $Z \to \tau_h \tau_\ell$ events where reconstructed by identifying electrons (muons) with $E_T > 24$ GeV ($p_T > 20$ GeV) as τ_ℓ. This type of selection criteria, where energetic leptons are identified as taus, could possibly be used to include τ_ℓ in the four lepton analysis.

Tau leptons will undergo leptonic decay at a rate of approximately 17.41% for muons and 19.58% for electrons. Leptonic τ-decay occurs in the $\tau \to \ell\,\bar{\nu}_\ell \nu_\tau$ and $\tau \to \ell\,\bar{\nu}_\ell \nu_\tau \gamma$ channels, where $\ell = e\,\text{or}\,\mu$[15]. Hadronic τ-lepton decay occurs at a rate of 64.8% and has a characteristic 1-prong (one charged π) or 3-prong (three charged π) signature. The prong number refers to the number of charged particle tracks found from the same vertex in the detector. Hadronic τ-lepton decays, with one charged π, occur in the channels $\tau \to \pi^{\pm} \upsilon$ (22.4%) and $\tau \to n\pi^0\pi^{\pm}\upsilon$ (73.5%), while decays with three charged π occur as $\tau \to 3\pi^{\pm}\upsilon$ (61.6%) and $\tau \to n\pi^0 3\pi^{\pm}\upsilon$ (33.7%) [13]. The 1- and 3-prong channels are therefore dominated by $\pi^{\pm}$ and π^0 plus a small percent of $K^{\pm}$ detected by the same techniques used to detect pions. Hadronic τ-leptons can be distinguished from QCD jets by 1- or 3-track multiplicity in narrow cones deposited in the hadronic calorimeter. Furteremore, we expect to be able to supress most background to hadronic tau decay by considering in particular the VBF production mechanism. This particular mechanism has a very good signal to background ratio, and is easily identified by two signature quark-jets produced in the forward and backward regions of the detector. Although the cross section of the VBF mechanism is quite poor, the increase in the CME at the LHC will improve statistics considerably in this channel.

Since hadronic tau decay is the more trivial of the tau decay modes to identify, the analysis considered will look at the case where one $Z \to \tau_h \tau_h$ and the other $Z \to \ell\ell$ ($\ell = e, \mu$). A preliminary tau reconstruction has been use to reconstruct hadronic taus: tau candidates must have good calorimeter or calorimeter and track hits; a requirement is made on their pseudorapidity, η (a measure of the angle from the beam direction), such that the crack region of the detector is not considered; and tau kinematics require the candidates to have $p_T > 20$ GeV and $\eta < 2.47$. The event selection will be similar to the four lepton case, except that we require quadruplets with one opposite charge tau pair, and one opposite charge same flavour lepton pair. One should note that without specifically identifying τ_ℓ, this analysis will probe $ZZ \to \tau_h \tau_h \tau_\ell \tau_\ell$ and $ZZ \to \tau_h \tau_\ell \tau_h \tau_\ell$ decay modes as well. Efficient kinematic selection criteria will have to be identified in order to identify τ_ℓ, as explained before. The inclusion of an efficient τ_ℓ identification will also allow for the inclusion of $3\tau_h \tau_\ell$ and $\tau_h 3\tau_\ell$ final states into the analysis. The Missing Mass Calculator algorithm [16] is the last piece of the puzzle, allowing efficient tau lepton invariant mass reconstruction.

5. Results and Conclusion

Including tau leptons in the four lepton Higgs boson channel has been identified as a viable way to increase statistics on the newly discovered Higgs boson, particularly since the channel has a good signal to background ratio in the VBF production process. The inclusion of this channel will become particularly important when the LHC re-opens in 2015 at a higher CME and we have attained an increase in statistics. Identification of hadronic and leptonic taus is noted to be of primary importance in this analysis. At present the only channel that is being considered is the $H \to Z \to \tau_h \tau_h \ell\ell$ ($\ell = e, \mu$), for the sake of triviality. The preliminary hadronic tau selection criteria considered has performed inefficiently. Figure 3 shows η plots of the number of MC events (Higgs signal of $m_H = 125$ GeV) that pass electron, muon and tau selection. The

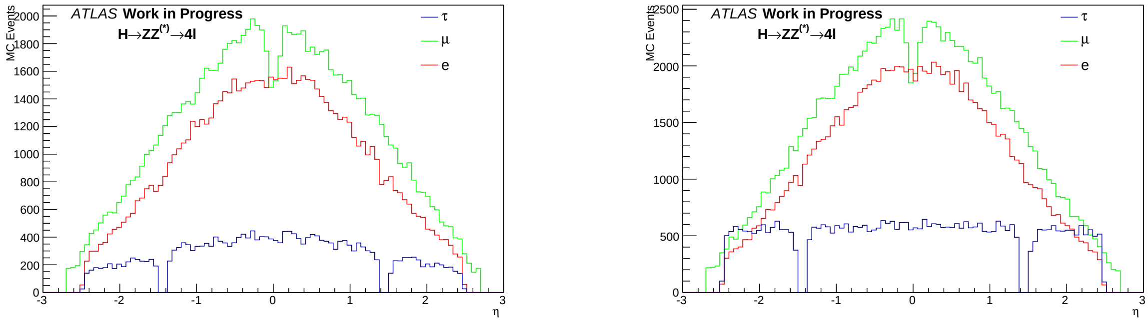

Figure 3. Histogram showing the pseudorapidity of reconstructed leptons of ggF (left) and VBF (right) Monte Carlo Higgs signal ($m_H = 125$ GeV) events.

tau statistics are low and the selection criteria will have to be re-evaluated in order to optimize the selection. The dip around $\eta = 0$ in the muon plot is due to the lack of MS coverage in the very central region discussed before. The lack of events in the tau plot at around $|\eta| = 1.5$ is due to explicitly removing tau candidates in the detector crack region. Once the hadronic tau selection has been optimized, focus will be aimed at reconstructing the tau masses, as well as identifying τ_ℓ, there by incorporating non trivial decay modes.

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