Tau leptons as a probe for new physics at LHC

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The tau leptons identification with ATLAS experiment will be possible already at the start of the data taking. The copious production of W and Z bosons decaying to the tau leptons will provide unique possibility to calibrate and understand identification of hadronically decaying tau’s above the QCD background already with few hundreds of pb⁻¹. With integrated luminosity of tens of fb⁻¹, tau leptons will become an excellent probe for searching for the SM and MSSM Higgs boson, SUSY or extra dimensions. In this paper, prospect for early physics and the new physics searches scenarios involving tau leptons are presented.

1. INTRODUCTION

The τ leptons are an excellent signature to probe new physics. As the heaviest leptons, they have the larger coupling to the Higgs boson both in Standard Model (SM) and Minimal Super Symmetric Model (MSSM). Theτ leptons interact only with electroweak force and so are not suffering from QCD higher order corrections, their production and decay are well separated in time and they give potential for measurement of the polarisation and parity of decaying heavier object. The spin correlations between decay products can provide efficient tool for suppressing irreducible background. Presently, we can profit from very good understanding about τ’s properties from the low-energy experiments. However, as several τ decay modes are possible and when decaying hadronically they show jet-like signature that makes them difficult to observe above huge QCD background in the pp collision experimental environment.

The observation of τ leptons play important role in the physics to be observed in the ATLAS experiment at the LHC. The main goal of this experiment is investigation of the nature of the electroweak symmetry breaking, and therefore the search for the Higgs boson. In particular the heaviest Higgs bosons in the MSSM can be observed through their decays to τ lepton pairs and the SM Higgs produced through Vector Boson Fusion can be observed when it decays to a tau pair. Tau leptons can also be an important signature for SUSY and extra dimensions searches.

The tau leptons observation with the ATLAS experiment will be possible already at the start of the data taking in year 2008 with large statistics of W → τν and Z → ττ. Those processes used as control channels will be important for detector calibration, background normalisation for Higgs searches, for tuning reconstruction and identification algorithms.

Tau final states are challenging from the experimental point of view. Since it will not be possible to discriminate between prompt light leptons and leptons from the τ-decays, the hadronic decay modes will serve as signature of tau production. A very good identification of hadronically decaying τ’s is thus decisive for the huge QCD jet background rejection [1]. The tau’s energy cannot be measured directly as neutrinos in the τ decay carry off energy and gives rise to missing transverse energy, therefore it is crucial to have a very good E_{T}^{miss} resolution in the detector for channels requiring reconstruction of the invariant mass of the object decaying to tau leptons.

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2. TAUS IN FIRST DATA

With start of the ATLAS physics data taking in 2008, a well considered strategy is necessary for the good understanding of the detector performance from in situ calibration and the realistic estimation of the Standard Model background channels: $Z \to \tau\tau$ and $W \to \tau \nu$. Those processes will be the most abundant sources of the $\tau$ leptons. For an integrated luminosity of $100 \, pb^{-1}$ which corresponds to the few weeks of data collecting with luminosity $\sim 10^{32}$ one can expect $\sim 60000$ $W \to \tau \nu$ events with hadronic decay of $\tau$ and $\sim 3500$ $Z \to \tau\tau$ events with one tau hadronic decay. Those numbers of events assume loose trigger cuts, 80% efficiency for $\tau$ trigger and 50% efficiency for tau identification thus requires a performant $\tau$-ID and $E_T^{miss}$ trigger from the very start of data taking. The counting experiment is foreseen for $W \to \tau \nu$ channel. Its first step will be to reproduce the characteristic evidence in hadronic $\tau$ decays track spectrum after background subtraction. The low-luminosity operation will give possibility to prepare procedures to control and tune trigger by studying tau and $E_T^{miss}$ thresholds offline. Similar studies can be performed for $Z \to \tau\tau$ channel where observation will be easier because of lepton trigger use and better signal to background ratio, but worse statistics, 10 times less events produced. The $Z \to \tau\tau$ channel offers also the possibility to use same sign (lepton-hadron) events as control channel for background to opposite sign one. The invariant mass of the visible decay products of the $\tau$ lepton pair will provide handle to control calibration of the hadronic taus.

3. TAUS IN SM HIGGS SEARCHES

At the LHC, the production cross-section for a SM Higgs boson is dominated by gluon-gluon fusion and most of the Higgs discovery channels make use of it [2]. However it is very difficult to distinguish the signal process from the overwhelming QCD background. The second largest cross-section comes from the fusion of vector bosons radiated from initial-state quarks. For $m_H < 2m_Z$, vector boson fusion (VBF) amounts in leading order to $\sim 20\%$ of the total production cross-section and becomes more important with increasing Higgs mass. In this production mode, the Higgs boson is accompanied by two jets in the forward regions of the detector, originating from the initial quarks that emit the vector bosons. In addition, central jet activity is suppressed due to the lack of color exchange between the quarks. This feature can be used as a veto on additional jet activity in the region between two quark jets against QCD background. When a mass of the Higgs is relatively small ($115 < m_H < 140 \, GeV$), VBF with $H \to \tau \tau$ plays an important role for Higgs discovery [3] and is particularly interesting for a measurement of the Higgs boson coupling to fermions in the low mass region ($< 140 \, GeV$), since beyond the $bb$ decay mode no other direct fermion decay mode is accessible at the LHC. For this channel, both lepton-hadron (l-h) and lepton-lepton (l-l) $\tau\tau$ decays are considered. The following backgrounds are dominant: $tt$ production, QCD and electroweak $WW + jet$ production, and $Z + jet$ production.

The large mass of decaying Higgs boson and its large $p_T$, results in high velocities of the $\tau$’s from the Higgs boson decay and therefore the approximation that the charged decay product di-
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rection is close to the $\tau$ direction can be made at the leading order (collinear approximation). The neutrino energies are obtained solving a system containing the two $p_T^{\text{miss}}$ components. The distribution of the reconstructed $\tau\tau$ invariant mass for $e\mu$ final state is shown in Fig. 1 for a Higgs boson signal of 120 GeV above the background for integrated luminosity of $30 \, fb^{-1}$. The mass resolution obtained is $\sim 12$ GeV. After combination of all decay channels, an observation of a Higgs boson in the $\tau\tau$ decay mode looks feasible over the mass range from 115 to 140 GeV with an integrated luminosity of $30 \, fb^{-1}$ as shown in Fig. 2.

![Figure 2](image1.png)

Figure 2. ATLAS sensitivity for the discovery of a SM Higgs boson for an integrated luminosity of $30 \, fb^{-1}$ A systematic uncertainty of $\pm 10\%$ on the background has been included for the VBF.

4. TAUS IN MSSM HIGGS SEARCHES

In the MSSM, two Higgs doublets are required, resulting in 5 physical states: $H^{+,-}$, $h$ (neutral lighter scalar), $H$ (neutral heavier scalar) and $A$ (neutral pseudoscalar). At the tree level their masses can be computed in terms of only two parameters, typically $m_A$ and $\tan\beta$ (the ratio of the vacuum expectation values of the two doublets). Various decay modes accessible also in the case of the SM Higgs boson are predicted. In addition, $H \rightarrow \tau\tau$ and $A \rightarrow \tau\tau$ rates are strongly enhanced with respect to the SM case over a large region of the parameter space. The observation of a charged Higgs boson would be a clear sign of new physics beyond the SM. Fig. 3 shows the $5\sigma$ discovery contours for the MSSM individual channels in the $(m_A; \tan\beta)$ plane for an integrated luminosity of $30 \, fb^{-1}$ per experiment (ATLAS and CMS). Almost the whole parameter space is completely covered and channels containing $\tau$’s in decay products can extend the discovery potential to regions of large masses (above 500 GeV) and $\tan\beta > 25$.

![Figure 3](image2.png)

Figure 3. The $5\sigma$ discovery contour plot for $30 \, fb^{-1}$ per Atlas and CMS experiment.
4.1. Neutral Higgs

$A$ and $H$ can be produced via two different mechanisms: for low values of $\tan\beta$, the direct production is dominant and significantly larger than in the SM case. For large values of $\tan\beta$, the production is dominated by $qq, gg \rightarrow bbA/H$ (associated production). For $m_A > 150$ GeV, the $H$ and $A$ bosons are degenerated in mass, so the signal rates in the channel can be added. For the large $\tan\beta$, $H/A$ couple dominantly to the heaviest down-type quark, the $b$-quark. The branching ratio of the $A/H$ into $b$-quark pairs is $\sim 90\%$ while $\sim 10\%$ decay into $\tau$ pairs but the $H \rightarrow \tau\tau$ channel provides the cleanest signature. All the final states of $\tau$’s decays ($l-l, l-h, h-h$) were investigated and all of them contribute (at different $m_A$) to the discovery potential [4,5]. The following backgrounds are dominant: $W+\text{jets}, t\bar{t}, Z+\text{jets}, bb$ ($l-h$) and QCD jets ($h-h$). The presence of $b$-jets in the associated production ($bbA/H$) provides additional rejection against the main backgrounds. The reconstructed $A/H$ signal above the backgrounds, for $h-h$ mode and for mass $m_A = 800$ GeV is presented in Fig. 4 for an integrated luminosity of $30\ fb^{-1}$. The achieved resolution is $127$ GeV [5] and is similar to the one from $l-h$ mode.

4.2. Charged Higgs

In the MSSM the charged Higgs can be produced in the decays of the top quark, if kinematically allowed, $tt \rightarrow H^{++}bWb$. For $m_{H^{++}} < m_t$, the production channels are $gg(qq) \rightarrow tbH^{+}\!-\!$ and $qq \rightarrow H^{+}\!-\!$. Some of the most promising decay channels of the charged Higgs are: below the top-quark mass, the $H^{++} \rightarrow \tau\nu$, while above the top-quark mass, $H^{++} \rightarrow tb$. Unlike the $tb$ decay mode which suffers from large irreducible backgrounds, the $\tau\nu$ channel could be free of such backgrounds, thereby extending the discovery potential beyond that achieved in the $tb$ channel, especially at large $\tan\beta$. This channel does not offer the possibility for the observation of a resonance peak above the background, only the transverse mass can be reconstructed because of the presence of the neutrino in the final state. The backgrounds come from single top, $Wt$, and $tt$ productions with one $W \rightarrow \tau\nu$. Thus, the transverse mass is kinematically constrained to be less than the $W$-boson mass while in the signal, the upper bound is the $H^{+}\!-\!$ mass. Furthermore, because the charged Higgs is scalar and the $W$-boson a vector, the polarisation of the decay $\tau$ in the signal is different from the background case. The differences in the event topology and in the $\tau$ polarisation have been used to suppress the backgrounds [6], so that above the $W$ mass threshold, the background in this channel is relatively small as shown in Fig. 5. As the result, although there is no reconstruction of the resonance peak in this channel, the Higgs mass can be extracted from the transverse mass distribution using a likelihood method. The systematic effects include the background shape, rate and the energy scale. The overall relative precision in this channel ranges from $1.3\%$ at $m_{H^{++}} = 226$ GeV to $3.1\%$ at $m_{H^{++}} = 511$ GeV for an integrated luminosity of $100\ fb^{-1}$ [7].

The determination of $\tan\beta$ can be achieved by measuring the rate in the $H^{++} \rightarrow \tau\nu$ channel. Assuming a $10\%$ uncertainty on the luminosity, the relative precision of $\tan\beta$ ranges from $15.4\text{-}7.3\%$ for $\tan\beta = 20$ to $50$, at low luminosity. For an integrated luminosity of $300\ fb^{-1}$, the precision improves to: $7.4\%$ at $\tan\beta = 20$ and to $5.4\%$ at $\tan\beta = 50$ [7] as shown in Fig. 6.

![Figure 4. Signal $A/H$ for $m_A = 800$ GeV above the backgrounds, composed of $t\bar{t}, W \!+\! jet, QCD 2\!-\!jet and Z \!+\! jets events. An integrated luminosity of $30\ fb^{-1}$ is assumed. $h\!-\!h$ decay mode. [5]](image-url)
5. TAUS IN LARGE EXTRA DIMENSIONS

In models where extra dimensions open up at the TeV scale, small neutrino masses can be generated without implementing the seesaw mechanism. These models postulate the existence of additional spatial dimensions of size R where gravity and perhaps other fields freely propagate while the SM degrees of freedom are connected to (3+1)-dimensional wall (4D) of the higher dimensional space. The right handed neutrino can be interpreted as a singlet with no quantum numbers to constrain it to the SM brane and thus, it can propagate into the extra dimensions just like gravity. In the MSSM scenario $H^+$ decays to the right-handed $\tau$ through the Yukawa coupling: $H^+ \rightarrow \tau_R \bar{\nu}$. The $H^-$ decay to left-handed $\tau$ is completely suppressed. However, in the scenario of singlet neutrino in large extra dimensions, $H^-$ can decay to both right-handed and left-handed $\tau$’s depending on the model parameters. The reconstruction of the transverse mass is not enough to distinguish between the MSSM and the singlet neutrino in large extra dimensions. The differences in these two scenarios are best seen in the distribution of $p_\tau/E_\tau-jet$, the fraction of the energy carried by the charged track [8] which is shown in Fig. 7. In MSSM, this distribution peaks near 0 and 1 while in $H^- \rightarrow \tau_L \bar{\psi}$ (\(\psi\) is a bulk neutrino) from large extra dimensions and in the backgrounds, this distribution peaks in the center. The backgrounds are very small, and as concluded in previous section, the discovery reach is limited by the signal size itself. Therefore the observation of a signal in the transverse mass distribution and in the distribution of the fraction of the energy carried by the charged track should help determine whether the scenario is MSSM or not. To obtain the model parameters the measurement of the polarization asymmetry between $H^- \rightarrow \tau_L \bar{\nu}$ and $H^- \rightarrow \tau_L \bar{\psi}$ can be used.

6. TAUS IN SUPERSYMMETRY

If supersymmetry (SUSY) exists at the electroweak scale, then its discovery at the LHC should be straightforward [2]. If SUSY is found at the LHC, hadronic $\tau$ decays will be an important signature for it [9]. Since there are two distinct mass eigenstates of the supersymmetric partners of the left and right-handed $\tau$, vital information about the SUSY breaking mechanism can be obtained if these states can be detected and distinguished. In particular the helicity of the taus can be used to constrain the SUSY model. The very small Yukawa couplings of the first two generations lead one to expect that selectron and smuon, will have almost the same masses and couplings. The larger Yukawa couplings of the staus
affect not only the \( \tilde{\tau}_L-\tilde{\tau}_R \) mixing but also both the renormalization group evolution of the soft mass terms from the SUSY-breaking scale to the electroweak scale and the \( \tilde{\chi}\tilde{\tau} \) couplings, the \( \tilde{\chi} \) being mixtures of the electroweak gauginos and the Higgsinos. Thus the physics of staus is generally quite different from that of selectrons and smuons. It is therefore of great importance to understand how well the final states containing taus can be reconstructed at the LHC.

If SUSY is discovered at the LHC, then many studies of the masses and decay products of the supersymmetric particles will be carried out. Methods such as looking for kinematic endpoints in mass distributions and using these to determine combination of masses have proven generally useful. By using these methods, the fundamental parameters of the underlying theory can be determined with precision of a few percent [2]. The study of the third generation particles will play a particularly important role because the Yukawa couplings of the third generation are much larger than those of the first two generations, so that the mixing between the left and right sfermion states is more important. This mixing, which is enhanced for \( \tan\beta >> 1 \) splits the mass eigenstates and also gives non-trivial polarization of the produced \( \tau \)'s.

7. CONCLUSIONS

ATLAS has a wide discovery potential for new physics and sensitivity to a large variety of \( \tau \) lepton signatures. Channels involving taus can be used not only as the discovery signatures for SM and MSSM Higgs boson(s), Supersymmetry and extra dimensions but also for determination of the new particles masses, their polarisation and couplings. This results are important not only for a new physics discovery but also for its better understanding.

Physics analyses on the observability of the \( Z \to \tau\tau \) and \( W \to \tau\nu \) signatures with the first data taking at the LHC will give possibility to prepare procedures to control and to monitor the efficiencies for signal observability and suppression of the backgrounds (control samples, prescaled trigger, etc.)

REFERENCES

1. F. Tarrade, Reconstruction and identification of hadronic tau-decays in ATLAS, see talk in this proceedings.

Figure 7. The distribution of the ratio of the charged pion track momentum in one prong \( \tau \) decay to the \( \tau \)-jet energy [8].