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Search for new physics with τ s at the LHC

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Abstract

This report reviews the analysis methods involving τ which can be used for discovering new physics at the LHC. Emphasis is given to the techniques currently proposed to include the τ in an efficient trigger scheme.

1 Introduction

Analyses based on the τ reconstruction are expected to be very helpful in the discovery of new physics at the LHC; in some part of the supersymmetric [1] (SUSY) parameter space, their use will be essential. This report reviews the possible ways of exploiting τ production at the LHC for Higgs bosons and sparticle searches in different supersymmetric scenarios. Standard Model (SM) and SM-like Higgs boson production are excluded from this report and can be found elsewhere in these proceedings [2].

Although the subject of this report is the discovery of new physics with signatures containing τ s, it should not be forgotten the important SM physics program that can be carried out with τ s, mainly concerning the properties of the τ itself, its rare decays, the physics of W and Z bosons and the test of lepton universality in boson decays.

The first part of this paper is devoted to trigger strategies. Preliminary results obtained at CMS for the inclusion of τ s from the level-1 (L1) to the High Level Trigger (HLT) scheme are presented and discussed.

2 Triggering and identifying τ s at the LHC

2.1 Level-1 and Level-2

Including τ in the trigger scheme at the LHC is a necessity, not an auxiliary requirement. The 40 MHz collision rate and the huge p-p cross section impose severe constraints on the definition of trigger logics, which need to be fast and reliable. The desired final rate for a τ trigger (single or double lepton tag) needs to go down to a few Hz. The trigger design is complicated by the presence of minimum bias events as well as by the contribution of out-of-time bunch crossing (typically 17.3 minimum bias events and 8 out-of-time bunch crossings are superimposed to the interesting event in high luminosity conditions).

The elaboration of a τ trigger should use the specific characteristics of its decays, which are mostly hadronic (65%), of which 77% with just one charged hadron (one-prong decays). They are characterized by low multiplicity jets which are generally very collimated given the τ mass and the energies involved at the LHC. The leptonic decays are included in the lepton (e, μ) triggers.

The L1 τ trigger exploits a generic jet trigger based only on the calorimetric information [3]. Candidate jets are built out of groups of 12x12 ECAL and HCAL towers (the CMS layout can be found in [4]) whose central 4x4 transverse energy (E_T) is larger than the E_T of all its 4x4 neighbours. Starting from those, a τ jet is required to have small E_T (less than a few GeV) in all the 4x4 neighbours. Moreover, the desired reduction rate at the L1 (down to a few KHz for the τ trigger) is reached with a further cut on the calorimetric energy requiring at least 90 GeV of E_T in case of one τ in the event and 60 GeV in case of two [3].

At L2 an additional cut on the jet isolation reduces further the rate by a factor five. The isolation is defined according only to electromagnetic calorimetry, and specifically:

$$p_{\text{iso}} = \Sigma E_T^{\text{e.m.}}(R < 0.40) - \Sigma E_T^{\text{e.m.}}(R < 0.13) < 5\text{GeV} \quad (1)$$

where $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is the opening angle of a cone around the jet direction in the (η, ϕ) plane.

2.2 High level trigger

After the calorimetric τ trigger, the rate needs to be brought further down by using the tracking without compromising the efficiencies. For the evaluation of a possible trigger technique the testbench signal of neutral Higgs bosons into $\tau\tau$ was used, considering QCD events as the main background [3, 5].

The basic tracking information come from the pixel detector [4] which allows a relatively fast track reconstruction over three layers. The tracking procedure identifies all interaction vertices in the event and the highest momentum track with a good calorimetric τ jet matching. This track, if any, also identifies the “signal” interaction primary vertex. Two cones are defined around this track with opening angles R_s and R_i called signal cone and isolation cone and illustrated in Fig. 1. Tracks in both cones are reconstructed and a τ candidate jet is found only if tracks lie in the signal cone. The angles R_s and R_i and the jet-track matching angle R_m are optimized to maximize the separation between signal and background. The best values found are $R_m=0.1$ and $R_s=0.05$. In Fig. 2 the achieved efficiency on the signal versus the efficiency on the background as a function of R_i is shown, for low and high luminosities. A possible value for R_i is 0.3, leading to an efficiency on the $H \rightarrow \tau\tau$ signal of about 40%.

The use of the full tracker information was also tried. Because a global track reconstruction is impossible within the tight time constraints imposed by the HLT, only a regional track reconstruction is performed around the candidate

Figure 1: Visual representation of the isolation criteria imposed to a τ jet; tr_1 identifies the leading track in the jet, R_s the signal cone, R_m the jet-track matching cone and R_i the isolation cone.

jet direction. A selection procedure, identical to that developed for the pixel, is consecutively applied. The trigger selection exploiting the full tracker has a performance better than that with the pixels alone; it also allows a cut on the reconstructed momenta to be applied, but the timing is worse at least by a factor two.

Tau triggers can be combined with e or μ triggers improving the efficiency on channels like $H \rightarrow \tau\tau \rightarrow \ell\nu_\ell\tau_{jet}$, where $\ell=e,\mu$, by 5-10% with no increase in the background and with a very modest price in extra CPU-time needed for the selection. Refinements of the techniques, cut optimization and studies of the best use of τ triggers in the different analyses are still ongoing.

2.3 Offline τ identification

The offline analyses refine the τ jet selection aiming at reducing the QCD background and the contamination due to leptons coming from boson decays. The methods investigated in CMS involve cuts on the jet properties themselves, like the low charged multiplicity, the isolation conditions and the momentum of the leading track, cuts on the reconstructed τ impact parameter and cuts on the τ reconstructed decay vertex in the many-prong decays. The possibility of exploiting also the reconstructed invariant mass of the decay products is still under investigation.

3 MSSM Higgs boson production

In the Minimal Supersymmetric extension of the Standard Model (MSSM) the couplings of the Higgs bosons to the fermions of the third family (τ s, b's) are enhanced with $\tan\beta$. At moderate and high values of $\tan\beta$, the dominant production mechanism of neutral Higgs bosons is in association with b quarks ($gg \rightarrow b\bar{b}H/A$ with branching fraction of 90% for $\tan\beta=10$) [6]. Charged Higgs boson production occurs via g-b ($gb \rightarrow H^\pm t$) or g-g ($gg \rightarrow H^\pm$) fusion, and the most promising detection decay channel is $H^\pm \rightarrow \tau\nu_\tau$ [6].

In all cases the most important backgrounds involve W or Z production in association with jets, with the bosons decaying into $\tau\nu_\tau$ or $\tau\tau$ and QCD jets. The $b\bar{b}$ background can be particularly important when τ leptonic decays are looked for. Essential tools for an efficient analysis are the b tagging, the impact parameter reconstruction and the energy flow determination, important to improve the resolution on the missing energy. Therefore calorimetry and tracking play a major rôle in the following analyses.

Figure 2: Efficiency of the calorimetric and pixel trigger selection in CMS on the Higgs boson signal as a function of the efficiency on the main background and for several values of the isolation cone opening angle. The curves are shown for two different values of the Higgs boson mass and for two different configurations of the detector, with (not staged) and without (staged) the third pixel layer. Low luminosity (left) and high luminosity (right) conditions are presented.

3.1 Neutral Higgs bosons

The heavy neutral MSSM Higgs boson production at the LHC which involves decays of the boson into $\tau\tau$ is investigated in all possible final states ($bb\tau_{\text{jet}}\tau_{\text{jet}}$, $bb\ell\tau_{\text{jet}}$, $bb\ell\ell$) according to the τ decays [7, 5].

Excesses of events can be observed in invariant mass distributions which, in $\tau\tau$ decays, can be reconstructed under the assumption that the missing neutrinos escape in the direction of the τ decay products. Since in the event there is no additional missing energy, the τ momenta can be determined by projecting the missing momentum along the τ directions. The Higgs boson mass can therefore be written as:

$$m_H = \sqrt{2(E_{\tau_1} + E_{\nu_1})(E_{\tau_2} + E_{\nu_2})(1 - \cos \theta_{\tau_1\tau_2})}, \quad (2)$$

where E_{ν_1} and E_{ν_2} are the projected components of the missing momentum and $\theta_{\tau_1\tau_2}$ the angle between the two τ jets.

The determination of the mass depends on the missing momentum resolution and the angle between the jets according to the relation $\delta m_H = \delta p_T^{\text{miss}} / \sin \phi_{\tau_1\tau_2}$. For this reason, back-to-back jet configurations must be rejected. Moreover, due to finite and usually poor resolution on the missing energy it may happen that the neutrino energies result to be negative. These events are discarded and this also provides an efficient tool to reject the background.

Figure 3 shows two examples of reconstructed mass with full CMS simulation in two different channels and at different generated Higgs boson masses and values of $\tan \beta$. From the number of signal events it is possible to identify 5σ contours for the Higgs boson discovery as a function of the point in the parameter space. This is shown, for the CMS and ATLAS experiments [8, 7, 9], in Fig. 4 in the $(m_A, \tan \beta)$ plane for fixed values of the other MSSM parameters and for an integrated luminosity of 30/fb. The two experiments essentially agree on the expected sensitivity.

In case of a discovery of a neutral Higgs boson the $\tan \beta$ value could be indirectly measured via a cross section measurement and assuming all other parameters known. The expected relative error on $\tan \beta$ for the same value of the luminosity can reach, in the most optimistic scenario, 15% per experiment, where the error is totally dominated by the systematic contributions of the theoretical uncertainty on the cross section and the branching ratios and by the error on the luminosity.

3.2 Charged Higgs bosons

The presence of $\tau\tau$ in the final state is also very important for the detection of charged Higgs bosons, because of the large production rate and the relatively clean final state. The main backgrounds to $gb \rightarrow H^\pm t$ and $gg \rightarrow H^\pm$ are

Figure 3: Neutral MSSM Higgs boson mass reconstructed in $\tau\tau$ channel. Left: in the lepton and jet channel for $m_A=200 \text{ GeV}/c^2$ and $\tan\beta=20$. Right: in the jet-jet channel for $m_A=500 \text{ GeV}/c^2$ and $\tan\beta=30$.

Figure 4: 5σ discovery contours, for CMS and ATLAS, for the MSSM neutral Higgs boson decaying into τ s with all possible final states as a function of $\tan\beta$ and m_A for an integrated luminosity of 30/fb.

represented by $t\bar{t}$ or W +jets where a τ decay of the boson is involved. The b tagging, the full reconstruction of the hadronic t decay and a cut on the transverse mass of the τ with the missing momentum greatly help in reducing all backgrounds. Moreover, in this channel, the different τ polarisation states can be exploited. Given the different spin of the decaying bosons, $H^\pm$ or $W^\pm$, the τ polarization is different in the signal and the backgrounds. Neutrinos from the τ s in $H^\pm$ decays are preferentially emitted in the direction opposite to the τ flight direction. Harder pions are thus expected in τ jets from $H^\pm$, and a cut on the fraction of the reconstructed τ energy taken by the hardest pion can help in further discriminating signal and backgrounds.

Figure 5 shows the 5σ CMS discovery limits of the MSSM $H^\pm$ in the $(m_A, \tan\beta)$ plane for fixed values of the other MSSM parameters and for 30/fb of luminosity [8].

Figure 5: 5σ discovery contours, for CMS, for the MSSM charged Higgs boson decaying into $\tau\nu$ as a function of $\tan\beta$ and m_A and for an integrated luminosity of 30/fb.

4 Sparticle production

If SUSY exists at the electroweak scale, gluinos and squarks can be copiously produced at the LHC. If R-parity is conserved, the lightest supersymmetric particle (LSP) is stable. If in addition, the LSP is neutral and colourless to satisfy cosmological arguments like the presence of non baryonic dark matter in the Universe, it interacts only weakly with matter and escapes undetected at the LHC. The final state therefore consists of standard fermions and missing energy. Reconstruction of final states with τ s is of fundamental importance in the discovery of SUSY, especially for high values of $\tan\beta$, where the Yukawa couplings for the third fermion generation are larger. Moreover, in mSUGRA [1], the $\tilde{\tau}$ is predicted to be the lightest slepton, therefore it decays into τ final states. Already for moderate values of $\tan\beta$ the decay of χ_2^0 into $\chi_1^0\tau^+\tau^-$ largely dominates over all possible decays.

In general, in mSUGRA, the abundance of τ in the final state increases with $\tan\beta$ reaching large amounts in certain regions of the parameter space. As an example, for $m_0 < m_{1/2}$ [1] and $\tan\beta=35$ the probability of having at least one τ per event at the LHC can reach 80%. The ability of triggering on τ s is also important for SUSY discovery, even though in mSUGRA scenarios the trigger scheme is simpler because of the presence of a large missing energy from the undetected LSP.

If supersymmetry is discovered at the LHC, it will also be very important to measure the properties of the supersymmetric particles, in particular their masses. The typical decay chain in mSUGRA events is $\tilde{g} \rightarrow b\tilde{b} \rightarrow b\tilde{b}\chi_2^0 \rightarrow b\tilde{b}\ell\ell\chi_1^0$. Because of the two-body decay of the χ_2^0 the di-lepton invariant mass in the decay chain has a sharp edge which depends on the sparticle masses involved, according to the equation:

$$m_{\ell\ell}^{\max} = \frac{1}{m_{\tilde{\ell}}} \sqrt{(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\chi_1^0}^2)}, \quad (3)$$

where $m_{\ell\ell}^{\max}$ is the end-point of the di-lepton invariant mass. By measuring the end-point of the di-lepton mass spectrum relations between slepton and neutralino masses can therefore be inferred. As pointed out already, for high values of $\tan\beta$, the leptons in the above formulae are mostly τ s, which can spoil the reconstruction of the decay end-point because of their decays containing neutrinos. It was however demonstrated by the ATLAS collaboration that a sensitivity to the end-point in the $\tau\tau$ mass spectrum remains at the level of 5 GeV/c² with a luminosity of 30/fb. This sensitivity is obtained by using only τ hadronic decays and by subtracting the same-sign di- τ mass distribution to greatly reduce the contribution of the MSSM backgrounds. The SM backgrounds are reduced with a cut on the missing E_T . The resulting distribution is presented in Fig. 6, where the expected distribution is compared to the distribution that would be obtained if the τ s did not decay.

Figure 6: Di- τ invariant mass distribution from mSUGRA chain decays in the ATLAS detector for an integrated luminosity of 30/fb. The same-sign τ - τ mass distribution have been subtracted. The expected distribution is compared to the distribution that would be observed, should the tau not decay in the detector.

5 Other searches

Signatures containing τ s are not a prerogative of the mSUGRA scenario. In what follows two other relevant cases of new physics involving τ s in the final states are presented.

5.1 Gauge mediated SUSY breaking theories

In gauge mediated SUSY breaking (GMSB) theories [10] gravity is no longer the carrier of the SUSY breaking to the visible sector; it is replaced by gauge forces. The relevant phenomenological aspect of these theories is that the gravitino, $\tilde{G}$, becomes the LSP and there are essentially two possible next-to-lightest supersymmetric particle candidates (NLSP), the neutralino χ_1^0 and the $\tilde{\tau}$. Moreover, an important feature of GMSB is that the lifetime of the NLSP is directly related to the energy scale at which the SUSY breaking occurs. This lifetime is essentially unconstrained, with possible values ranging from micrometers to kilometers. As a consequence, in all cases in which the $\tilde{\tau}$ is the NLSP, the following experimental signatures at the LHC can occur, as a function of the $\tilde{\tau}$ lifetime (compared with the length of the detector L_{det}) [11]:

- $c\tau_{\tilde{\tau}} \gg L_{\text{det}}$: the $\tilde{\tau}$ behaves as a heavy muon;
- $c\tau_{\tilde{\tau}} \approx L_{\text{det}}$: the $\tilde{\tau}$ decays into the detector producing detectable kinks in tracks with production of τ in the final states. The NLSP lifetime can be measured;
- $c\tau_{\tilde{\tau}} \ll L_{\text{det}}$: the $\tilde{\tau}$ decay causes an increase of the $\tau\tau$ cross section.

Analyses to probe GMSB theories at the LHC with the use of τ s are still under development.

5.2 Lepton flavour violation searches

Renewed interest arised about searches for lepton flavour violation (LFV) after the recent results on possible neutrino mixing signals. Signals of lepton flavour violation can be observed in forbidden τ decays like $\tau \rightarrow \mu\gamma$ or $\tau \rightarrow \mu\mu\mu$. In what follows the latter decay, studied in detail in CMS [12], is considered.

Searches for $\tau \rightarrow \mu\mu\mu$ can be performed by using τ s originating from standard processes at the LHC. The most abundant source is given by meson decays, other sources are provided by boson decays like $Z \rightarrow \tau\tau$ or $W \rightarrow \tau\nu$. After triggering, however, it turns out the the most promising source is given by the W sample, because of the large missing momentum in the event from the neutrino and because it is less contaminated by the huge QCD

background. The background is indeed composed by $b\bar{b}$ and $c\bar{c}$ production where the three muons can come either from the same or from two different quarks. Combinatorial backgrounds and all backgrounds producing resonances decaying into $\mu^+\mu^-$ can be suppressed with mass cuts.

The presence of this experimentally very clean decay can therefore be observed in the invariant mass distribution of the three muons, as shown in Fig. 7. The input branching ratio for the decay $\tau \rightarrow \mu\mu\mu$ was set to the known limit, which at the time of the analysis corresponded to 1.9×10^{-6} [13].

Figure 7: Three-muon invariant mass from a signal of neutrinoless tau decay with branching fraction $1.9 \cdot 10^{-6}$ in CMS, compared with the background.

Figure 7, obtained for an integrated luminosity of only 10/fb, already presents a spectacular evidence for such a signal under the form of a narrow peak. The expected resolution on the three muon invariant mass is expected to be about $15 \text{ MeV}/c^2$. With 30/fb, CMS and ATLAS alone should be able to set a 95% CL limit on the $\tau \rightarrow \mu\mu\mu$ branching ratio to 3.8×10^{-8} , a factor of about 50 smaller than the limit reported in [13].

It should not be forgotten that Supersymmetry can quite naturally accomodate lepton flavour violation. The latter can also be determined and measured within SUSY [14], by studying the third family of leptons, where LFV is expected to be larger: in large parts of the parameter space in mSUGRA models the decay $\chi_2^0 \rightarrow \tilde{\tau}\mu \rightarrow \chi_1^0\tau\mu$ is particularly promising, yielding a 12σ expected evidence for only 10/fb in one experiment and a decay branching ratio for $\chi_2^0 \rightarrow \tilde{\tau}\mu$ of 10%.

6 Conclusions

Beside testing the Standard Model, the use of τ is important for the discovery of supersymmetry at the LHC in large regions of the parameter space.

Discovery of both SUSY particles and neutral or charged MSSM Higgs bosons can be achieved by studying final states containing τ s, especially in regions of the MSSM parameter space with high $\tan\beta$ where $\tilde{\tau}$ s become the lightest sleptons and where the Yukawa couplings of the third generation are stronger. The study of final states with τ s is also mandatory for all those models where $\tilde{\tau}$ are NLSP like gauge mediated SUSY theories, as well as to probe the existence of lepton flavour violation both within the SM and the MSSM.

The reconstruction of τ s in the final state allows SUSY properties like the sparticle masses or the Higgs boson masses to be measured, and the value of $\tan\beta$ to be determined

In order to perform these measurements, efforts are being made to include τ s in the trigger schemes of the experiments, using also its hadronic decays. The feasibility of this task has been demonstrated by CMS in the important case of neutral MSSM Higgs boson. In order to achieve reasonable rates and large enough efficiency, the tracking

systems need to be used inside the trigger. Refinements in the τ offline reconstruction are also ongoing.

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