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Probing the MSSM Higgs Sector via Weak Boson Fusion at the LHC

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Abstract

In the MSSM weak boson fusion produces the two CP even Higgs bosons with a combined strength equivalent to the production of the Standard Model Higgs boson. The $\tau\tau$ decay mode — supplemented by $\gamma\gamma$ — provides a highly significant signal for at least one of the CP even Higgs bosons at the LHC with reasonable luminosity. The accessible parameter space covers the entire physical range which will be left unexplored by LEP2.

I. INTRODUCTION

The search for the Higgs boson and the origin of spontaneous breaking of the electroweak gauge symmetry is one of the main tasks of the CERN Large Hadron Collider (LHC). Within the Standard Model (SM), a combination of search strategies will allow a positive identification of the Higgs signal [1]: for small masses ($m_H \lesssim 140$ GeV) the Higgs boson can be seen as a narrow resonance in inclusive two-photon events and in associated production in the $t\bar{t}H$, $b\bar{b}H$ and WH channels with subsequent decay $H \to \gamma\gamma$ [2–4]. For large Higgs masses ($m_H \gtrsim 130$ GeV), the search in $H \to ZZ^{(*)} \to 4\ell$ events is promising. Additional modes have been suggested recently: the inclusive search for $H \to WW^* \to \ell\ell\not{p}_{\rm T}$ [5], and the search for $H \to \gamma\gamma$ or $\tau\tau$ in weak boson fusion events [6,7]. With its two forward quark jets, the weak boson fusion possesses unique characteristics which allow identification with a very low level of background at the LHC. At the same time, reconstruction of the $\tau\tau$ invariant mass is possible; modest luminosity, of order of 30 fb^{-1}, should suffice for a 5σ signal.

In the minimal supersymmetric extension of the SM the situation is less clear [1]. The search is open for two CP even mass eigenstates, h and H, for a CP odd A, and for a charged Higgs boson $H^\pm$. For large $\tan\beta$, the light neutral Higgs boson may couple much more strongly to the $T_3 = -1/2$ members of the weak isospin doublets than its SM analogue. As a result, the total width can increase significantly compared to a SM Higgs boson of the same mass. This comes at the expense of the branching ratio $B(h \to \gamma\gamma)$, the cleanest Higgs discovery mode, possibly rendering it unobservable and forcing the consideration of alternative search channels. Even when discovery in the inclusive $\gamma\gamma$ channel is possible, observation in alternative production and decay channels is needed to measure the various couplings of the Higgs resonance and thus identify the structure of the Higgs sector [8].

In this Letter we explore the reach of weak boson fusion with subsequent decay to $\tau\tau$ for Higgs bosons in the MSSM framework. We will show that, except for the low $\tan\beta$ region which is being excluded by LEP2, the weak boson fusion channels are most likely to produce significant h and/or H signals.

II. NEUTRAL HIGGS BOSONS IN THE MSSM

Some relevant features of the minimal supersymmetric Higgs sector can be illustrated in a particularly simple approximation [9]: including the leading contributions with respect to G_F and the top flavor Yukawa coupling, $h_t = m_t/(v s_\beta)$. The qualitative features remain unchanged in a more detailed description. All our numerical evaluations make use of a renormalization group improved next-to-leading order calculation [10,11]. The inclusion of two loop effects is not expected to change the results dramatically [12]. Including the leading contributions with respect to G_F and h_t, the mass matrix for the neutral CP even Higgs bosons is given by

$$\begin{aligned}\mathcal{M}^2 &= m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + m_Z^2 \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + \varepsilon \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \\ \varepsilon &= \frac{3 m_t^4 G_F}{\sqrt{2}\pi^2} \frac{1}{s_\beta^2} \left[\log \frac{M_{\rm SUSY}^2}{m_t^2} + \frac{A_t^2}{M_{\rm SUSY}^2} \left(1 - \frac{A_t^2}{12 M_{\rm SUSY}^2} \right) \right]. \end{aligned} \tag{1}$$

Here s_β, c_β denote $\sin\beta, \cos\beta$. The bottom Yukawa coupling as well as the higgsino mass parameter have been neglected ($\mu \ll M_{\rm SUSY}$). The orthogonal diagonalization of this mass matrix defines the CP even mixing angle α. Only three parameters govern the Higgs sector: the pseudo-scalar Higgs mass, m_A, $\tan\beta$, and ε, which describes the corrections arising from the supersymmetric top sector. For the scan of SUSY parameter space we will concentrate on two particular values of the trilinear mixing term, $A_t = 0$ and $A_t = \sqrt{6} M_{\rm SUSY}$, which commonly are referred to as no mixing and maximal mixing.

Varying the pseudoscalar Higgs boson mass, one finds saturation for very large and very small values of m_A – either m_h or m_H approach a plateau:

$$\begin{aligned} m_h^2 &\simeq m_Z^2 (c_\beta^2 - s_\beta^2)^2 + s_\beta^2 \varepsilon \qquad \text{for} \quad m_A \to \infty \\ m_H^2 &\simeq m_Z^2 + s_\beta^2 \varepsilon \qquad\qquad\quad \text{for} \quad m_A \to 0. \end{aligned} \tag{2}$$

For large values of $\tan\beta$ these plateaus meet at $m_{h,H}^2 \approx m_Z^2 + \varepsilon$. Smaller $\tan\beta$ values decrease the asymptotic mass values and soften the transition region between the plateau behavior and the linear dependence of the scalar Higgs masses on m_A. These effects are shown in Fig. 1, where the variation of m_h and m_H with m_A is shown for $\tan\beta = 4, 30$. The small $\tan\beta$ region will be constrained by the LEP2 analysis of Zh, ZH associated production, essentially imposing lower bounds on $\tan\beta$ if no signal is observed.[1]

The theoretical upper limit on the light Higgs boson mass, to two loop order, depends predominantly on the mixing parameter A_t, the higgsino mass parameter μ and the soft-breaking stop mass parameters, which we treat as being identical to a supersymmetry breaking mass scale: $m_Q = m_U = M_{\rm SUSY}$ [10]. As shown in Fig. 1, the plateau mass value hardly exceeds ~130 GeV, even for large values of $\tan\beta$, $M_{\rm SUSY} = 1$ TeV, and maximal mixing [12]. Theoretical limits arising from the current LEP and Tevatron squark search as well as the expected results from Zh, ZH production at LEP2 assure that the lowest plateau masses are well separated from the Z mass peak.

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[1] Although the search for MSSM Higgs bosons at the Tevatron is promising [13] we only quote the Zh, ZH analysis of LEP2 [14] which is complementary to the LHC processes under consideration. The LEP2 reach is estimated by scaling the current limits for $\mathcal{L} = 158$ pb^{-1} and $\sqrt{s} = 189$ GeV [14] to $\mathcal{L} = 100$ pb^{-1} and $\sqrt{s} = 200$ GeV.

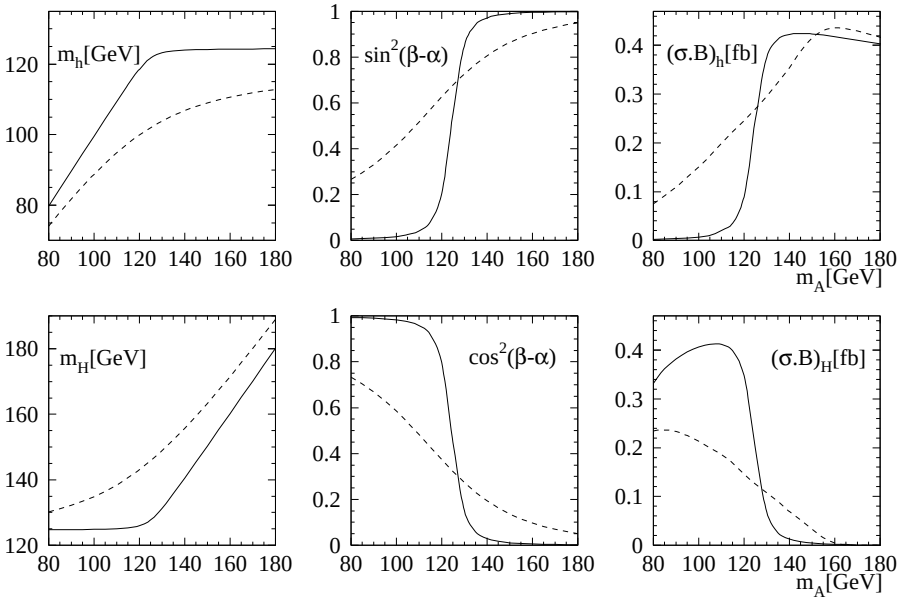

Figure 1. Variation of Higgs boson masses, couplings to gauge bosons, and signal rate, $\sigma \cdot B(\tau\tau)$, for the CP even MSSM Higgs bosons as a function of the pseudoscalar Higgs mass. The complementarity of the search for the lighter h (upper row) and heavier H (lower row) is shown for $\tan\beta = 4, 30$ (dashed, solid lines). Other MSSM parameters are fixed to $\mu = 200$ GeV, $M_{\rm SUSY} = 1$ TeV, and maximal mixing.

The production of the CP even Higgs bosons in weak boson fusion is governed by the hWW, HWW couplings, which, compared to the SM case, are suppressed by factors $\sin(\beta-\alpha), \cos(\beta-\alpha)$, respectively [15]. In the m_h plateau region (large m_A), the mixing angle approaches $\alpha = \beta - \pi/2$, whereas in the m_H plateau region (small m_A) one finds $\alpha \approx -\beta$. This yields asymptotic MSSM coupling factors of unity for h production and $|\cos(2\beta)| \gtrsim 0.8$ for the H channel, assuming $\tan\beta \gtrsim 3$. As a result, the production cross section of the plateau states in weak boson fusion is essentially of SM strength. In Fig. 1 the SUSY suppression factors for $\sigma(qq \to qqh/H)$, as compared to a SM Higgs boson of equal mass, are shown as a function of m_A. The weak boson fusion cross section is sizable mainly in the plateau regions, and here the h or H masses are in the interesting range where decays into $\bar{b}b$ and $\tau^+\tau^-$ are expected to dominate.

Crucial for the observability of a Higgs boson are the $\tau\tau$ or bb couplings of the two resonances. Splitting the couplings into the SM prediction and a SUSY factor, they can be written as

$$\begin{aligned} h_{bbh} &= \frac{m_b}{v}\left(-\frac{\sin\alpha}{\cos\beta}\right) = \frac{m_b}{v}\Big(\sin(\beta-\alpha) - \tan\beta\ \cos(\beta-\alpha)\Big), \\ h_{bbH} &= \frac{m_b}{v}\quad\frac{\cos\alpha}{\cos\beta}\quad = \frac{m_b}{v}\Big(\cos(\beta-\alpha) + \tan\beta\ \sin(\beta-\alpha)\Big) \end{aligned} \tag{3}$$

and analogously for the τ couplings. Since for effective production of h and H by weak boson fusion we need $\sin^2(\beta-\alpha) \approx 1$ and $\cos^2(\beta-\alpha) \approx 1$, respectively, the coupling of the observable resonance to $\bar{b}b$ and $\tau\tau$ is essentially of SM strength. The SUSY factors for the top and charm couplings are obtained by replacing $\tan\beta \to -1/\tan\beta$ in the final expressions above. They are not enhanced for $\tan\beta > 1$. This leads to $\bar{b}b$ and $\tau\tau$ branching ratios very similar to the SM results. In fact, in the plateau regions they somewhat exceed the SM branching ratios for a given mass.

The $\tau\tau h$ and $\tau\tau H$ couplings vanish for $\sin\alpha = 0$ and $\cos\alpha = 0$, respectively, or $\sin(2\alpha) = 0$. In leading order, as well as in the simple ε-approximation given in eq.(1), this only happens in the unphysical limits $\tan\beta = 0, \infty$. Including further off-diagonal contributions to the Higgs mass matrix might introduce a new parameter region for the mixing angle α: the off-diagonal element of the Higgs mass matrix and thereby $\sin(2\alpha)$ can pass zero at finite m_A and $\tan\beta$. Indeed, by also considering the dominant contribution with respect to $(\mu/M_{\rm SUSY})$, one finds [10]

$$\begin{aligned} \left(\mathcal{M}^2\right)_{12} &= -m_A^2 s_\beta c_\beta - m_Z^2 s_\beta c_\beta \left[1 - \frac{\tan\beta}{8\pi^2}\,\frac{h_t^4}{g^2}\,\frac{\mu A_t^3}{M_{\rm SUSY}^4}\right], \\ \sin(2\alpha) &= 2\,\frac{(\mathcal{M}^2)_{12}}{m_H^2 - m_h^2}\,, \end{aligned} \tag{4}$$

and $\sin(2\alpha)$ may vanish in the physical region. The exact trajectory $\sin(2\alpha) = 0$ in parameter space depends strongly on the approximation made in perturbative expansion; we observe this behavior for large $A_t \gtrsim 3M_{\rm SUSY}$, *i.e.* in part of the non-mSUGRA parameter space. If the observed Higgs sector turns out to be located in this parameter region, the vanishing coupling to $bb, \tau\tau$ would render the total widths small. This can dramatically increase the $h/H \to \gamma\gamma$ branching ratio, even though $\Gamma(h/H \to \gamma\gamma)$ may be suppressed compared to the SM case. This situation is shown in Fig. 2, where the scalar masses and the $\tau\tau$ and $\gamma\gamma$ rates are shown as a function of A_t: the vanishing of the $\tau\tau$ rate is associated with a very large increase of $\sigma B(\gamma\gamma)$. Note that the variation of Higgs masses and decay properties with A_t is quite mild in general, apart from this $\sin(2\alpha) = 0$ effect.

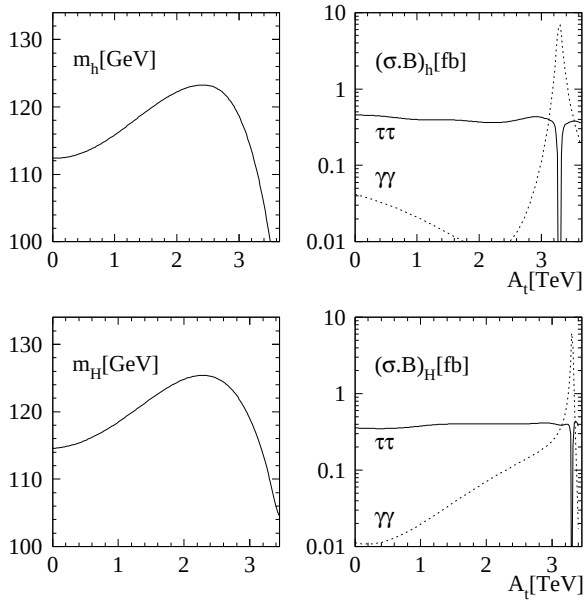

Figure 2. Mass of the CP even Higgs bosons and weak boson fusion rates $\sigma \cdot B(\tau\tau, \gamma\gamma)$ as a function of the trilinear mixing term, A_t. Curves are shown for $M_{\rm SUSY} = 1$ TeV and $\mu = 400$ GeV with $m_A = 130$ GeV, $\tan\beta = 30$ (h: upper row), and $m_A = 105$ GeV, $\tan\beta = 22$ (H: lower row).

III. HIGGS SEARCH IN WEAK BOSON FUSION

Methods for the isolation of a SM Higgs boson signal in the weak boson fusion process ($qq \to qqh, qqH$ and crossing related processes) have been analyzed for the $H \to \gamma\gamma$ channel [6] and for $H \to \tau\tau$ [7]. The analysis for the MSSM is completely analogous: backgrounds are identical to the SM case and the changes for the signal, given by the SUSY factors for production cross sections and decay rates, have been discussed in the previous section.

For the $h, H \to \gamma\gamma$ signal, the backgrounds considered are $\gamma\gamma jj$ production from QCD and electroweak processes, and via double parton scattering [6]. It was found that the backgrounds can be reduced to a level well below that of the signal, by tagging the two forward jets arising from the scattered (anti)quarks in weak boson scattering, and by exploiting the excellent $\gamma\gamma$ invariant mass resolution expected for the LHC detectors [16,17], of order 1 GeV.

For $h, H \to \tau\tau$ decays, only the semileptonic decay channel of the τ leptons, $\tau\tau \to \ell^{\pm} h^{\mp} \not{p}_{\rm T}$ is considered, assuming the τ-identification efficiencies and procedures described by ATLAS for the inclusive $H, A \to \tau\tau$ search [7,17]. According to the ATLAS study, hadronic τ decays, producing a τ jet of $E_{\rm T} > 40$ GeV, can be identified with an acceptance of 26% while rejecting hadronic jets with an efficiency of 99.75%. In weak boson fusion, and with the τ identification requirements of Refs. [7,17] which ask for substantial transverse momenta of the charged τ decay products ($p_{\rm T}(\ell^{\pm}) > 20$ GeV and $p_{\rm T}(h^{\mp}) > 40$ GeV), the Higgs boson is produced at high $p_{\rm T}$. In the collinear τ decay approximation, this allows reconstruction of the $\tau^{\pm}$ momenta from the directions of the decay products and the two measured components of the missing transverse momentum vector [17,18]. Thus, the Higgs boson mass can be reconstructed in the $\tau\tau$ mode, with a mass resolution of order 10%, which provides for substantial background reduction as long as the Higgs resonance is not too close to the $Z \to \tau\tau$ peak.

With these τ-identification criteria, and by using double forward jet tagging cuts similar to the $h, H \to \gamma\gamma$ study, the backgrounds can be reduced below the signal level, for SM Higgs boson masses between 105 to 150 GeV and within a 20 GeV invariant mass bin. Here, irreducible backgrounds from 'Zjj events' with subsequent decay of the (virtual) Z, γ into τ pairs, as well as reducible backgrounds with isolated hard leptons from $Wj + jj$ and $b\bar{b}jj$ events, have been considered. Moreover, it was shown that a further background reduction, to a level of about 10% of the signal, can be achieved by a veto on additional central jets of $E_{\rm T} > 20$ GeV between the two tagging jets. This final cut makes use of the different gluon radiation patterns in the signal, which proceeds via color singlet exchange in the t-channel, and in the QCD backgrounds, which prefer to emit additional partons in the central region [19,20].

Using the SUSY factors of the last section for production cross sections and decay rates, one can directly translate the SM results into a discovery reach for supersymmetric Higgs bosons. The expected signal rates, $\sigma B(h/H \to \tau\tau, \gamma\gamma)$ are shown in Figs. 1,2. They can be compared to SM rates, within cuts, of $\sigma B(H \to \tau\tau) = 0.35$ fb and $\sigma B(H \to \gamma\gamma) = 2$ fb for $m_H = 120$ GeV. Except for the small parameter region where the $\tau\tau$ signal vanishes, and for very large values of m_A (the decoupling limit), the $\gamma\gamma$ channel is not expected to be useful for the MSSM Higgs search in weak boson fusion. The $\tau\tau$ signal, on the other hand, compares favorably with the SM expectation over wide regions of parameter space. The SUSY factors for the production process determine the structure of $\sigma \cdot B(h/H \to \tau\tau)$. Apart from the typical flat behavior in the asymptotic plateau regions they strongly depend on β, in particular in the transition region, where all three neutral Higgs bosons have similar masses and where mixing effects are most pronounced.

Given the background rates determined in Ref. [7], which are of order 0.03 fb in a 20 GeV mass bin, except in the vicinity of the Z-peak, the expected significance of the $h/H \to \tau\tau$ signal can be determined. 5 σ contours for an integrated luminosity of 100 fb^{-1} are shown in Fig. 3, as a function of $\tan\beta$ and m_A.

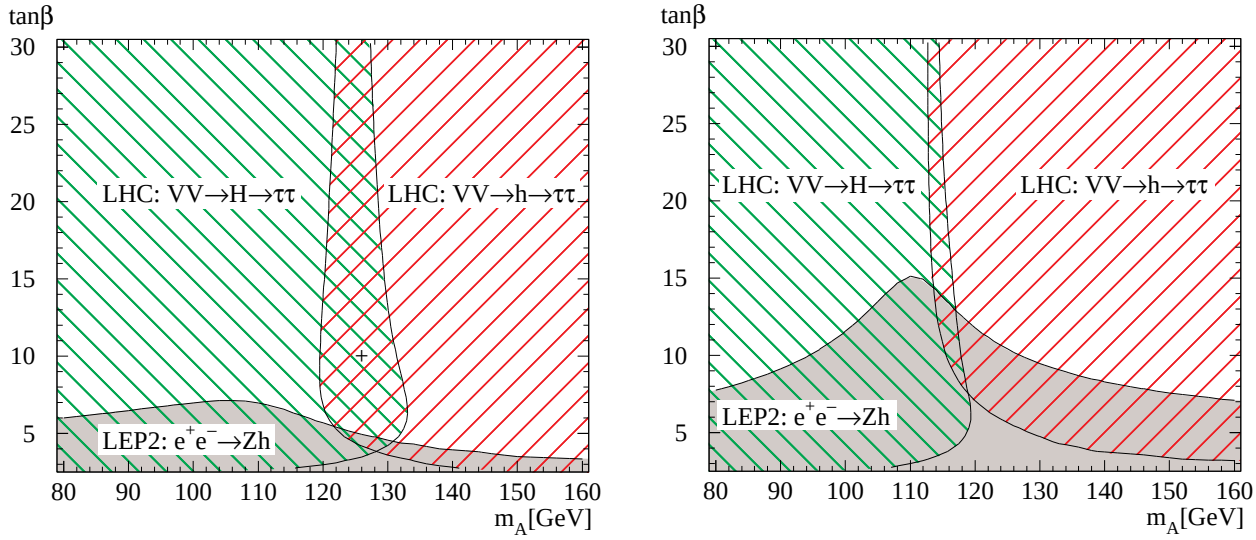

Figure 3. 5σ discovery contours for $h \to \tau\tau$ and $H \to \tau\tau$ in weak boson fusion at the LHC, with 100 fb^{-1}. Also shown are the projected LEP2 exclusion limits (see text). Results are shown for SUSY parameters as in Fig. 1, for maximal mixing (left) and no mixing (right). The marked point is illustrated in Fig. 4.

Here the significances are determined from the Poisson probabilities of background fluctuations [7]. Weak boson fusion, followed by decay to τ-pairs, provides for a highly significant signal of at least one of the CP even Higgs bosons. Even in the low $\tan\beta$ region, where LEP2 would discover the light Higgs boson, the weak boson fusion process at the LHC will give additional information. Most interesting is the transition region, where both h and H may be light enough to be observed via their $\tau\tau$ decay. A possible $\tau\tau$ invariant mass spectrum for this scenario, with backgrounds, is shown in Fig. 4. The observation of a triple peak, corresponding to Z, h and H decays to $\tau\tau$, requires very specific SUSY parameters, of course. Fig. 4 illustrates the cleanness of the weak boson fusion signal, however.

IV. SUMMARY

We have shown that the production of CP even MSSM Higgs bosons in weak boson fusion and subsequent decay to τ pairs gives a significant ($> 5\sigma$) signal at the LHC. This search, with $\lesssim$100 fb^{-1} of integrated luminosity, and supplemented by the search for $h/H \to \gamma\gamma$ in weak boson fusion, should cover the entire MSSM parameter space left after an unsuccessful LEP2 search, with a significant overlap of LEP2 and LHC search regions. The two CERN searches combined provide a no-lose strategy by themselves for seeing a MSSM Higgs boson. At the very least, the weak boson fusion measurements provide valuable additional information on Higgs boson couplings.

Our analysis here and in Ref. [7] should be considered as a proof of principle, not as an estimate of the ultimate sensitivity of the LHC experiments. A variety of possible improvements need to be analyzed further.

– For a Higgs resonance close to the Z peak ($m_h \lesssim 110$ GeV) a shape analysis is needed to estimate the significance of the Higgs contribution. Our sensitivity estimates are solely based on event counting in a 20 GeV invariant mass bin.

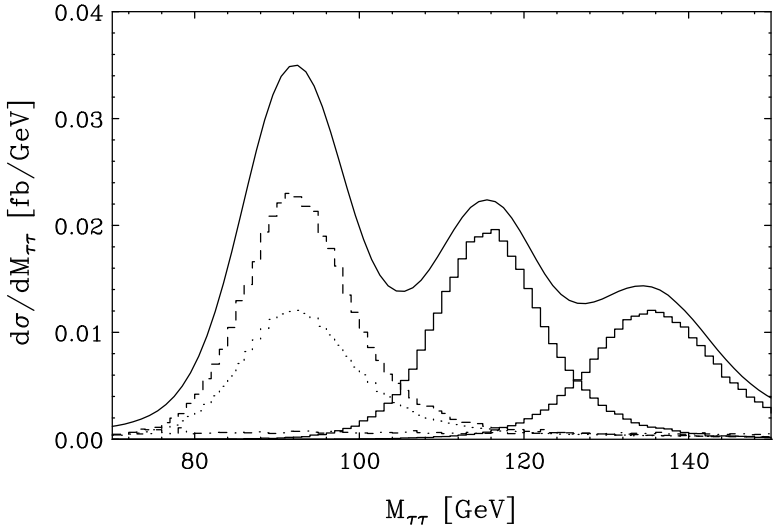

Figure 4. Expected τ pair invariant mass distribution for the signal (solid histograms) and backgrounds for the search described in the text and MSSM parameters marked in Fig. 3. Individual background curves correspond to QCD Zjj (dashed) and electroweak Zjj (dotted) production, and to the combined $Wj + jj$ and $b\bar{b}jj$ reducible backgrounds (dash-dotted). The sum of signal and backgrounds is shown as the solid line. The three peaks correspond to Z, h, and H production.

– A trigger on the forward jets in weak boson fusion events might allow a reduction of the transverse momentum requirement for the τ decay lepton. A lower lepton $p_{\rm T}$ threshold would significantly increase the signal rate.

– The τ identification criteria and the rejection of the $\bar{b}b$ background has been optimized for the inclusive $A/H \to \tau\tau$ search [17], not for the weak boson fusion events considered here. Because of the lower backgrounds to the weak boson fusion process, some of the requirements can be relaxed, leading to a larger signal rate.

– Our analysis is based on parton level simulations. A full parton-shower analysis, including hadronization and detector effects, should be performed to optimize the cuts, and to assess efficiencies.

The present analysis relies only on the typical mixing behavior of the CP even mass eigenstates, and on the observability of a SM Higgs boson, of mass up to $\sim$150 GeV, in weak boson fusion. This suggests that the search discussed here might also cover an extended Higgs sector as well as somewhat higher plateau masses, *e.g.* for very large squark soft-breaking mass parameters. Because decays into τ pairs are tied to the dominant decay channel of the intermediate mass range Higgs boson, $h/H \to \bar{b}b$, the search for a $\tau\tau$ signal in weak boson fusion is robust and expected to give a clear Higgs signal in a wide class of models.

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