Measurement of the $H/A \to \tau\tau$ cross section and possible constraints on $\tan\beta$

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Abstract

The achievable precision of the cross section times branching ratio measurement from the event rates is estimated for the MSSM $H/A \to \tau\tau$ decay in the associated production process $gg \to b\bar{b}H/A$ at large $\tan\beta$ in CMS. This work demonstrates that the above production and decay process exhibit a large sensitivity to $\tan\beta$ and thus add as a significant observable to a global fit of the SUSY parameters. To illustrate this potential an example is given concerning the achievable $\tan\beta$ determination accuracy that could be reached from the event rates and for a given set of SUSY parameters and uncertainties.

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1 Introduction

The Higgs mechanism is a cornerstone of the Standard Model (SM) and its supersymmetric extensions. Therefore, the search for Higgs bosons is one of the top priorities at future high-energy experiments. Since the Minimal Supersymmetric extension of the Standard Model (MSSM) requires the introduction of two Higgs doublets in order to preserve supersymmetry, there are five elementary Higgs particles, two CP-even (h,H), one CP-odd (A) and two charged ones (H^\pm). At lowest order all couplings and masses of the MSSM Higgs sector are determined by two independent input parameters, which are generally chosen as tan\beta = v_2/v_1, the ratio of the vacuum expectation values of the two Higgs doublets, and the pseudoscalar Higgs boson mass m_A. At leading order (LO) the light scalar Higgs boson mass m_h has to be smaller than the Z boson mass m_Z. Nevertheless the upper bound on tan\beta is significantly enhanced by radiative corrections, the leading part of which grows with the fourth power of the top mass m_t and logarithmically with the stop masses. Therefore, the upper bound on m_h is increased to m_h \lesssim 153 GeV/c^2 when one-loop and dominant two-loop corrections are included. The negative direct searches for the Higgsstrahlung processes e^+e^- \rightarrow ZH and the associated production e^+e^- \rightarrow Ah/AH yield lower bounds of m_{h,1H} > 91.0 GeV/c^2 and m_A > 91.9 GeV/c^2. The range 0.5 < tan\beta < 2.4 in the MSSM is excluded for m_t = 174.3 GeV/c^2 by the Higgs searches at the LEP2 experiments.

Thus, one of the most important parameters to be determined in the Minimal Supersymmetric Standard Model as well as in a general type-II Two-Higgs Doublet Model (2HDM) is tan\beta. In the MSSM tan\beta plays a crucial role, since it characterizes the relative fraction of the two Higgs boson doublets contributing to the electroweak symmetry breaking. Consequently, it enters in all sectors of the theory. For small tan\beta, it may be possible to determine the value of tan\beta within the sfermion or neutralino sector. For large tan\beta this method has not been found to be effective. In this regime, however, there are good prospects to measure the value of tan\beta by exploiting the Higgs sector.

At large tan\beta neutral and charged Higgs boson production is dominated by the bremsstrahlung processes gg \rightarrow b\bar{b}H/A and gb \rightarrow th\bar{h}. The dominant parts of the production cross sections are proportional to tan^2\beta. For the heavy scalar MSSM Higgs boson H this behavior is valid within 1% for tan\beta \gtrsim 10, if the pseudoscalar mass m_A is larger than about 200 GeV/c^2, while for m_A > 300 GeV/c^2 it is already satisfied for tan\beta \gtrsim 5. Due to this feature the uncertainty on the tan\beta measurement is only half of the uncertainty on the rate measurement. In the MSSM the supersymmetric loop corrections introduce an additional tan\beta dependence to the cross section, but they can be absorbed in an effective parameter tan\beta_{eff}, since the dominant terms which are enhanced by tan\beta correspond to emission and re-absorption of virtual heavy supersymmetric particles at the bottom Yukawa vertex, which are confined to small space-time regions compared to QCD subprocesses involving massless gluons. The sub-leading terms are small. The dominant terms are universal contributions to the bottom Yukawa coupling. This implies that the method described below determines this effective parameter tan\beta_{eff} in the MSSM (for simplicity, it is denoted everywhere in the rest of the text as tan\beta). The extraction of the fundamental tan\beta parameter requires additional knowledge of the sbottom and gluino masses as well as the Higgs boson mass parameter \mu. These corrections are in general absent in a 2HDM so that in these models the extracted value belongs to the fundamental tan\beta parameter. The H/A → \mu\mu and H/A → \tau\tau decay channels have been identified as the most promising ones for the search of the heavy neutral MSSM Higgs boson H and A at large tan\beta. The final states \ell\ell (\ell = e,\mu), lepton+jet and two-jets have been investigated for the H/A → \tau\tau decay mode. In this study the m_{h_{max}}^\text{min} scenario has been chosen with the following MSSM parameters: SU(2) gaugino mass M_2 = 200 GeV/c^2, \mu = 300 GeV/c^2, gluino mass M_\tilde{g} = 800 GeV/c^2, SUSY breaking mass parameter M_{\text{SUSY}} = 1 TeV/c^2 and stop mixing parameter X_t = v_6 (X_t = A_t - \mu cot\beta). The top mass is set to 175 GeV/c^2. The Higgs boson decays to SUSY particles are allowed.

In this work the Next-to-Leading Order (NLO) cross section and the branching ratio theoretical uncertainty; and the luminosity and statistical uncertainties are taken into account. The precision on the mass measurement in the H/A → \tau\tau channel is estimated and included when trying to determine the precision on the tan\beta measurement. The uncertainty on the background as well as the uncertainty on the signal selection efficiency are included as described in Section 4.

The precision that can be achieved in the measurement of the cross section times branching ratio from the event rate within the MSSM for the H/A → \tau\tau decay channel in the associated production process gg → b\bar{b}H/A at large tan\beta is estimated in this study. The work also demonstrates that the above production and decay process exhibits a large sensitivity to tan\beta becoming a significant observable to be included in a global fit of the SUSY parameters. To illustrate this potential an example is given concerning the achievable tan\beta measurement accuracy that could be reached for the above set of SUSY parameters.

The note is organized as follows: Section 2 describes the event selection and the expected discovery reach. The
measurement uncertainty on the cross section is discussed in Section 3. Section 4 presents the evaluation of the \( \tan\beta \) measurement uncertainty; and in Section 5 the total uncertainty on the \( \tan\beta \) measurement is summarized. Finally, Section 6 is devoted to the conclusions.

2 Event selection and expected discovery reach

This section starts with the comparison between the theoretical NLO cross section and the PYTHIA cross section since PYTHIA has been used for the generation of the hard processes. Then the event selection is discussed, and finally, the expected discovery reach is presented.

2.1 NLO cross section and PYTHIA cross section comparison

Higgs boson production in the \( gg \rightarrow b\bar{b}H/A \) process was obtained with the PYTHIA \[12\] two-to-three processes 181 and 186 and with the PYTHIA6.158 default values for the parton distribution functions and the renormalization and factorization scales. No cut on the transverse momentum of the \( b \) quarks has been applied at the generation level but \( p_T^{b\bar{b}} > 20 \text{ GeV} \) is used for the \( b \)-jet identification in the event analysis. Therefore it is important to know how well PYTHIA describes the \( p_T \) spectrum of the \( b \) quarks compared to the NLO calculations \[13\] in order to estimate how well the efficiency of the event selection can be determined. The comparison was made for the SM process \( gg \rightarrow b\bar{b}h \) (PYTHIA process 121) with a Higgs boson mass of \( 120 \text{ GeV}/c^2 \). The PYTHIA and the NLO cross sections are compared in Table 1 as a function of a cut on the transverse momentum of the \( b \) quark with highest \( p_T \). In PYTHIA as well as in the NLO calculations the \( b \) quark momentum was taken after gluon radiation.

The total PYTHIA cross sections (\( p_T > 0 \)) were normalized to the total NLO cross sections. The agreement between the PYTHIA and the NLO values turns out to be at the level of 5–10%. The statistical uncertainties of the PYTHIA cross sections are shown, too. For completeness the PYTHIA LO cross sections are also compared to the corresponding theoretical LO calculation (the lower two rows in Table 1). In this case the PYTHIA \( b \) quark was taken before gluon radiation. Good agreement within 1–2% has been obtained.

Table 1: Comparison of the NLO and LO cross sections to the PYTHIA cross sections as a function of the cut on the transverse momentum of the \( b \) quark with highest \( p_T \). The total PYTHIA cross sections (\( p_T > 0 \)) are normalized to the corresponding NLO(LO) cross sections.

| \( p_T \) cut \( \text{GeV}/c \) | 0 | 10 | 20 | 30 | 40 | 50 |
|---------------------|----|----|----|----|----|----|
| \( \sigma_{NLO} \) (pb) | 734 | 570 | 294 | 173 | 106 | 68 |
| \( \sigma_{PYTHIA} \) (pb) | 734 | 523 | ± 3 | 275 | ± 3 | 156 | ± 3 | 92 | ± 2 | 60 | ± 2 |
| \( \sigma_{LO} \) (pb) | 528 | 407 | ± 2 | 245 | ± 3 | 154 | ± 2 | 101 | ± 2 | 70 | ± 2 |
| \( \sigma_{PYTHIA} \) (pb) | 528 | 407 | ± 2 | 245 | ± 3 | 154 | ± 2 | 101 | ± 2 | 70 | ± 2 |

2.2 Event selection

The event selection for the two-lepton (\( e\mu \) and \( \ell\ell \), lepton+jet (\( \ell j \)) and two-jet (\( jj \)) final states from \( H/A/h \rightarrow \tau\tau \) are described in detail in Refs. \[8, 9, 10\]. In the region of \( M_A \leq 130 \text{ GeV}/c^2 \) the \( gg \rightarrow b\bar{b}h \) cross section is comparable to the \( gg \rightarrow b\bar{b}A \) production cross section, therefore it has been included in the analysis. The relative fractions of these final states are shown in Table 2. The discovery potential in the \( H/A/h \rightarrow \tau\tau \rightarrow \ell\ell+X \) channel is re-evaluated using the cross sections given by the routine HQQ \[14\] and with updated \( \tau \) selection and \( b \)-tagging efficiencies. Unlike Ref. \[9\], the recent analysis is extended to large Higgs boson masses, and a 5\( \sigma \) reach up to \( m_A \sim 650 \text{ GeV}/c^2 \) at \( \tan\beta \sim 50 \) is obtained. The details will be described in an upcoming note.

Table 2: Relative fractions of \( H/A/h \rightarrow \tau\tau \) final states.

| Final state | branching ratio |
|-------------|-----------------|
| \( H/A/h \rightarrow \tau\tau \rightarrow e\mu+X \) | ~6.3% |
| \( H/A/h \rightarrow \tau\tau \rightarrow \ell\ell+X \) | ~12.5% |
| \( H/A/h \rightarrow \tau\tau \rightarrow \ell j+X \) | ~45.6% |
| \( H/A/h \rightarrow \tau\tau \rightarrow jj+X \) | ~41.5% |
The common backgrounds for all the H/A real and fake the W+jet process is the background for the final states with hadronic both H/A → ττ. The hadronic Tau Trigger for the two-jet final state was studied with full simulation in Ref. [10, 15]. For the eμ, ℓℓ and the f_j final states the trigger was simulated by selecting the kinematic cuts above the trigger thresholds, and taking the trigger efficiencies from Ref. [15]. The used triggers were the Inclusive muon trigger with efficiency 0.9*0.97*0.97 (trigger threshold effect*μ reconstruction efficiency* calorimetric isolation), the Di-electron trigger with efficiency 0.95*0.872*0.77*0.95 (e trigger threshold effect*Level-1 e efficiency*Level-2 e efficiency) and e-τ jet trigger with efficiency 0.95*0.872*0.77*0.95 (e trigger threshold effect*Level-1 e efficiency*HLT e efficiency*τ trigger threshold effect). The backgrounds were suppressed with lepton tracker isolation, τ jet identification, τ tagging with impact parameter, b tagging and jet veto. The τ jet identification [10] selects collimated low multiplicity jets with high pT charged particles. The hadronic jets are suppressed by a factor of ~1000. Tau tagging [15] exploits the short but measurable lifetime of the τ: the decay vertex is displaced from the primary vertex. For b tagging the B hadron lifetime is used to distinguish the associated b jets from c jets and light quark/gluon jets. The Drell-Yan and QCD multi-jet backgrounds are efficiently suppressed with b tagging by a factor of ~100.

Figure 1: Reconstructed ττ invariant mass in the eμ final state for the H/A/h → ττ signal (dark) and for the total background (light) with m_A = 200 GeV/c^2 and tanβ = 20 for 30 fb^-1.

Figure 3: Reconstructed ττ invariant mass in the lepton+jet final state for the H/A/h → ττ signal (dark) and for the total background (light) with m_A = 200 GeV/c^2 and tanβ = 20 for 30 fb^-1.

Figure 2: Reconstructed ττ invariant mass in the ℓℓ final state for the H/A/h → ττ signal (dark) and for the total background (light) with m_A = 200 GeV/c^2 and tanβ = 20 for 30 fb^-1.

Figure 4: Reconstructed ττ invariant mass for H/A → ττ → 2 jets (dark), for the total background (light) and for the multi-jet background (dashed) with m_A = 500 GeV/c^2 and tanβ = 30 for 60 fb^-1.
but it also suppresses the Higgs boson production with no associated b jets. The jet veto is directed against the \( t\bar{t} \) and \( Wt \) backgrounds. The rejection of events with more than one jet (including the b jet and not counting \( \tau \)'s) suppresses the \( t\bar{t} \) background by a factor of \( \sim 5 \) \[10\].

Despite several neutrinos in all the \( H/A \rightarrow \tau\tau \) final states the Higgs boson mass can be reconstructed. The effective \( \tau\tau \) mass was evaluated under the assumption that the neutrinos are emitted along the measured \( \tau \) decay products. The projection of the missing energy vector onto the neutrinos allowed the neutrino energy estimation. Uncertainties in the missing energy measurement can lead to negative neutrino energies. A significant fraction of the signal events is lost when positive neutrino energies are required, but the backgrounds from \( t\bar{t}, Wt \) and QCD multi-jet events are suppressed, since for these backgrounds the neutrinos are generally not emitted along the true or fake \( \tau \)'s. The mass resolution can be improved efficiently with a cut in the \( \Delta \phi \) or angular separation between the two \( \tau \)'s. For the two-jet final state in Ref. \[10\] a mass reconstruction efficiency of 53% has been obtained with the cut \( \Delta \phi < 175^\circ \) and with the requirement of one b jet with \( E_T > 30 \) GeV. The reconstructed Higgs boson mass is shown in Figs. 1 to 4 for the four \( \tau\tau \) final states. The reconstructed mass peak is a superposition of the H and A signals. In the region \( m_A \lesssim 130 \text{ GeV}/c^2 \) the contribution from the lightest Higgs boson h cannot be separated in these channels and is also included in the signal event rates.

### 2.3 Expected discovery reach

The 5\( \sigma \)-discovery potential for the \( H/A/h \rightarrow \tau\tau \) decay channels with the \( e\mu, \ell\ell \) and lepton+jet final states for 30 fb\(^{-1}\) and with the two-jet final state for 60 fb\(^{-1}\) is shown in Figure 5. The 5\( \sigma \)-discovery reach of the \( H/A \rightarrow \mu\mu \) decay channel with 60 fb\(^{-1}\) is also depicted in the figure. The 5\( \sigma \)-discovery reach obtained after the combination of the \( e\mu, \ell\ell \) and two-jet final states from the \( H/A \rightarrow \tau\tau \) decay channel is shown in Fig. 5 for 30 fb\(^{-1}\). The significance was calculated with the Poisson statistics taking into account the number of signal and background events within the Higgs boson mass window. The combined reach is evaluated by adding the number of signal and background events from the three final states in a given \((m_A, \tan\beta)\) point. This method, however, can lead to an unsatisfactory result as the analysis of these final states has been optimized to reach the best possible signal significance which has led to different background levels. For example at low values of \( m_A \) and \( \tan\beta \) the signal for the \( H/A \rightarrow \tau\tau \rightarrow \ell\ell + X \) channel \[8\] suffers from a significantly larger Drell-Yan background than that for the \( H/A \rightarrow \tau\tau \rightarrow \ell\ell + jet \) channel. If the \( \ell\ell \) final state is included, the combined reach is smaller than that from the lepton+jet final state alone.

![Figure 5: The 5\( \sigma \)-discovery potential for the heavy neutral MSSM Higgs bosons as a function of \( m_A \) and \( \tan\beta \) with maximal stop mixing for 30 fb\(^{-1}\). The \( H/A \rightarrow \tau\tau \rightarrow \text{two-jet} \) channel is shown for 60 fb\(^{-1}\).](image-url)
3 Calculation of the cross section measurement uncertainty

The number of signal events after experimental selection is

\[ N_S = \sigma^{\text{prod}} \times L \times \varepsilon_{\text{sel}}, \]

where \( \sigma^{\text{prod}} \) is the cross section times branching ratio, \( L \) is the luminosity and \( \varepsilon_{\text{sel}} \) is the selection efficiency. The measured value of the cross section times branching ratio is given by

\[ \sigma^{\text{prod}} = \sigma^{\text{prod}}_0 \pm \Delta_{\text{stat}} \pm \Delta_{\text{syst}}. \]

The considered systematic uncertainties \( \Delta_{\text{syst}} \) come from the luminosity, the experimental selection and the background uncertainties. The cross section times branching ratio total uncertainty measurement is the quadratic sum of the statistical and systematic uncertainties:

\[ \Delta \sigma^{\text{prod}} / \sigma^{\text{prod}} = \sqrt{\frac{N_S + N_B}{N_S} \Delta L / L + \Delta \varepsilon_{\text{sel}} / \varepsilon_{\text{sel}} + \Delta N_{\text{syst}}^B / N_B}, \]

where \( N_S \) and \( N_B \) are the number of the signal and background events, \( \Delta L \) is the luminosity uncertainty, \( \Delta \varepsilon_{\text{sel}} \) is the experimental selection uncertainty on the signal and \( \Delta N_{\text{syst}}^B \) is the background systematic uncertainty.

3.1 Statistical and luminosity errors

The statistical uncertainty from different H/A/h \( \rightarrow \tau \tau \) final states are combined using the standard weighted least-squares procedure [16]. The measurements are assumed to be uncorrelated and the weighted error is calculated as

\[ \frac{\sigma^{\text{prod}} \pm \Delta_{\text{stat}}}{\sigma^{\text{prod}}} = \frac{\sum_i w_i \sigma^{\text{prod}}_i}{\sum_i w_i} \pm \left( \frac{\sum_i w_i}{\sum_i w_i} \right)^{-1/2}, \]

where

\[ w_i = 1 / (\Delta_{\text{stat}})_i^2. \]

Figure 6 shows the statistical uncertainty on the cross section times branching ratio \( \Delta_{\text{stat}} / \sigma^{\text{prod}} \) for the combined \( e\mu + \ell_j + jj \) and \( \ell \ell + \ell_j + jj \) final states as a function of \( m_A \) for \( \tan \beta = 10, 20, 30 \) and 40, where the signal significance for 30 fb\(^{-1}\) exceeds 5\( \sigma \). The drop in the curves at \( m_A = 300 \text{ GeV}/c^2 \) is due to fully leptonic final states (\( e\mu \) and \( \ell \ell \)) being accessible and included in the \( \tan \beta \) measurement in the region from \( m_A = 100 \text{ GeV}/c^2 \) to \( m_A = 300 \text{ GeV}/c^2 \). Similarly, a small decrease is visible at \( m_A = 200 \text{ GeV}/c^2 \) due to the fully hadronic final state being analyzed only in the region from \( m_A = 200 \text{ GeV}/c^2 \) to \( m_A = 800 \text{ GeV}/c^2 \). The statistical uncertainty ranges from 3% to 25% depending on \( \tan \beta \) and \( m_A \).

The uncertainty on the luminosity measurement is assumed to be 5%.

3.2 Uncertainty on the signal selection

The uncertainty on the signal selection efficiency related to the absolute calorimeter energy scale, \( \tau \) and b-tagging efficiency was taken into account as described in the following.

The calorimeter energy scale introduces an error on the selection efficiency since jets and missing \( E_T \) threshold are required. The full simulation of two tau-jet signal events shows that the assumption of 1% uncertainty on the calorimeter energy scale [15] leads to \( \sim 2.9 \% \) uncertainty on the signal selection efficiency.

The single b-tagging efficiency was evaluated in the following way. Two samples of semileptonic \( t\bar{t} \) events selected for the top quark mass measurement with double b tagging and single b tagging respectively were used. The single b-tagging efficiency is obtained as the ratio of double vs single b-tagged events in the samples, with an additional top mass constraint. Since about 10000 double b-tagged events were obtained after all selections with 30 fb\(^{-1}\) [17], the statistical error of the b-tagging efficiency was \( \sim 1 \% \). Nevertheless, the b-jet purity and the background
Figure 6: The curves show the statistical uncertainty on the cross section times branching ratio measurement as a function of $m_A$ for $\tan \beta = 10, 20, 30$ and $40$ where the statistical significance exceeds $5\sigma$. The uncertainties correspond to $30\text{ fb}^{-1}$.

The uncertainty on the $\tau$ tagging can be evaluated from the measured ratio of $Z \rightarrow \ell\ell \rightarrow \tau\tau \rightarrow \ell\tau\text{jet}$ and $Z \rightarrow \ell\ell$ events. The background contribution to $\mu+\tau$ jet final state from $t\bar{t}$ and $W+\text{jet}$ events is reduced with the cut on muon plus missing $E_T$ transverse mass, $m(\ell, E_{\text{miss}})$, and the $Z$ mass constraint. About 10000 $Z \rightarrow \tau\tau \rightarrow \mu+\tau$ jet events are expected with $30\text{ fb}^{-1}$ after muon and $\tau$-jet selections and a cut on $m(\ell, E_{\text{miss}}) < 30$ GeV/$c^2$. Thus, the statistical uncertainty on the $\tau$-tagging efficiency is about 1% ($Z \rightarrow \ell\ell$ statistical error is negligible). The cut on $m(\ell, E_{\text{miss}})$ introduces however about 1% uncertainty due to the calorimeter energy scale uncertainty. The remaining uncertainty may come from the evaluation of $t\bar{t}$ and $W+\text{jet}$ background under the $Z$ mass peak (about 2500 background events are expected before the $Z$ mass constraint with $30\text{ fb}^{-1}$) and the uncertainty on the muon reconstruction efficiency. Due to these reasons another 2% was added as a conservative, preliminary estimate leading thus to the total uncertainty on the $\tau$-jet identification efficiency of the order of 2.5%.

Therefore, the signal experimental selection uncertainty due to the calorimeter energy scale, $\tau$ and $b$-jet tagging efficiency is 4.3%.

### 3.3 Background uncertainty

The background uncertainty was evaluated for one representative point of the $(m_A, \tan \beta)$ parameter space $m_A = 300$ GeV/$c^2$, $\tan \beta = 20$ and for the $H/A \rightarrow \tau\tau \rightarrow \ell\tau\text{jet}$ channel. The point in the parameter space was chosen close to the $5\sigma$ limit where the number of signal events is lowest, and therefore the error $\Delta N_B/N_S$ is largest.

The background after all cuts within a chosen mass window was estimated by fitting the $m_{\tau\tau}$ distribution of the expected background and signal distributions. The error of the fit gives the background uncertainty. The signal mass distribution was approximated with a Gaussian function. The background, however, consists of several different components with different mass distribution shapes. The Drell-Yan background forms a high peak around the $Z$ mass with a long high mass tail. The $t\bar{t}$ and single top backgrounds form a much wider mass distribution. The $W+j$ and $b\bar{b}$ backgrounds were not taken into account in the fit since their contribution to the total background is negligible ($\leq 5\%$).

The shape of the background mass distributions can be obtained from Monte Carlo or directly from the data by relaxing the cuts chosen to suppress the background. The top background can be enhanced by double $b$ tagging (relaxing the central jet veto) which suppresses the signal and Drell-Yan background. The shape of the $t\bar{t}$ background is best fitted with a Landau distribution. The small change of the shape due to the different event selections was
neglected. The Drell-Yan background shape could be evaluated with the suppression of the b tagging requirement. In that case the signal was very small compared to the background. The shape of the Drell-Yan background was also best fitted with a Landau distribution.

Using the shapes for the signal and background distributions, the mass distribution can be fitted varying the number of signal, Drell-Yan and top events. The fit parameters were then used to evaluate the number of background events and its uncertainty in the signal mass window. For the chosen point \( m_A = 300 \) GeV/c\(^2 \) and \( \tan \beta = 20 \) this procedure gives 80.5 signal events and 25.9 background events with \( \Delta N_B = 8.1 \), which corresponds to a background uncertainty \( \Delta N_B/N_S = 10\% \). This uncertainty is used then as a conservative estimate for the whole \( (m_A, \tan \beta) \) parameter space and for \( \ell \ell \) and two \( \tau \)-jet final states as well.

### 3.4 Total systematic uncertainty

For the chosen point, \( m_A = 300 \) GeV/c\(^2 \) and \( \tan \beta = 20 \), the total systematic uncertainty is \( 12\% \) (the dominating contribution comes from the background uncertainty \( 10\% \)) and is of the same order as the statistical uncertainty. The background uncertainty decreases for higher values of \( \tan \beta \) at a given value of \( m_A \).

### 4 Calculation of the \( \tan \beta \) measurement uncertainty

It is clear that the determination of \( \tan \beta \) alone without any knowledge of the other SUSY parameters is not possible, since the branching ratios develop a significant dependence on \( \mu, M_2, A_t \) and \( M_{\text{SUSY}} \). For example, the gaugino sector is sensitive to the values of \( \mu \) and \( M_2 \), and the stop sector and stop mixing is sensitive to the values of \( \mu \) and \( A_t \). Nevertheless, in order to illustrate the potential of a cross section times branching ratio measurement in the \( \tan \beta \) determination, the SUSY parameters were fixed to the chosen SUSY scenario, but without taking into account the uncertainties, since they are still unknown. Nonetheless, to give an idea of the sensitivity of the signal rate to the SUSY parameters, those were varied by \( 20\% \) around the nominal values, as it will be discussed in Section 4.3.

Ignoring in this approach the uncertainties of the other SUSY parameters, the accuracy of the \( \tan \beta \) measurement is due to the uncertainty on the cross section measurement \( \Delta \sigma_{\text{prod}} \) and the theoretical uncertainty of the cross section calculation.

The branching ratio \( \text{BR}(H/A \rightarrow \tau \tau) \) is approximately constant at large \( \tan \beta \). At large \( \tan \beta \) the total decay width is dominated by Higgs boson decay to heavy down type fermions, \( \tau^+ \tau^- \) and \( b\bar{b} \) pairs, for which the decay widths have similar \( \tan \beta \) dependence. If the SUSY corrections, which are different for the bottom and \( \tau \) Yukawa couplings, are not large, the \( \tan \beta \) dependence cancels out in the ratio \( \Gamma(H/A \rightarrow \tau \tau)/\Gamma_{\text{tot}} \), which becomes approximately constant. The counting of signal events measures the total rate \( \sigma \times \text{BR} \) into the chosen final state, which is therefore approximately proportional to \( \tan^2 \beta \). The total rate for the neutral Higgs boson production as a function of \( \tan \beta \) is shown in Fig. 7 for \( m_A = 300 \) GeV/c\(^2 \).

At large \( \tan \beta \) the production rate can be written as

\[
\sigma_{\text{prod}} = \tan^2 \beta \times X,
\]

where \( X \) is the \( \tan \beta \) independent part of the production rate. The measured value of \( \tan \beta \) is given by

\[
\tan \beta = \tan \beta_0 \pm \frac{1}{2} \Delta \sigma_{\text{prod}} \pm \frac{1}{2} \Delta X
\]

where \( \Delta X \) consist of the theoretical uncertainties of the production cross section and the branching ratio, and the uncertainty on the cross section due to the uncertainty on the Higgs boson mass measurement. The total error of \( \tan \beta \) is taken as the quadratic sum of \( \Delta \sigma_{\text{prod}} \) and \( \Delta X \):

\[
\Delta \tan \beta/\tan \beta = \frac{1}{2} \Delta \sigma_{\text{prod}}/\sigma_{\text{prod}} \oplus \frac{1}{2} \Delta X/X.
\]

### 4.1 Theoretical uncertainty

The uncertainty on the Next-to-Leading Order cross sections for the \( gg \rightarrow b\bar{b}H/A/h \) process has been shown to be \( 20–30\% \) for the total rate \( \text{[13, 18]} \). It depends, however, on the transverse momentum range of the spectator b quarks and reduces to \( 10–15\% \) with the requirement of \( p_{T}^{b, \bar{b}} \geq 20 \) GeV/c \( \text{[13, 19, 20]} \). Therefore, the question about requiring two b jets per event with jet \( E_T > 20 \) GeV arises naturally. Table 3 shows the number of signal
and background events for the H/A → ττ → lepton+jet+X channel with m_A = 200 GeV/c^2 and tanβ = 20 for one b-tagged jet in the event (plus a veto on additional jets) and for events with two b-tagged jets. Although the theoretical uncertainty is smaller for events with two b-tagged jets with jet E_T > 20 GeV, the decrease of the signal statistics due to low reconstruction and b-tagging efficiency of soft b jets increases the measurement uncertainty. Therefore, only one b jet per event should be tagged in this study. The theoretical uncertainty of about 20% is adopted for the production cross section according to Refs. [13–20]. For the branching ratio the uncertainty is 3% and it is related to the uncertainties of the SM input parameters.

Table 3: The uncertainty on the tanβ measurement for the H/A → ττ → lepton+jet+X channel for 30 fb^{-1} with one or two b-tagged jets with jet E_T > 20 GeV.

| m_A = 200 GeV/c^2, tanβ = 20 | N_S | N_B | signif. | √N_S + N_B/N_S | ∆σ/σ | ∆tanβ/tanβ* |
|--------------------------------|-----|-----|---------|-----------------|-------|-------------|
| 1b-tagging+jet veto            | 157 | 70  | 18.8σ   | 9.6%            | 20%   | 17.3%       |
| 2b-tagging                     | 9   | 44  | 1.3σ    | 80.9%           | 10-15%| 48.0-50.5%  |

*) Statistical + theoretical cross section uncertainties only

4.2 Mass measurement uncertainty

Since the value of the cross section depends on the Higgs boson mass, the uncertainty on the mass measurement leads to an uncertainty on the signal rate. The Higgs mass is measured using the different final states, and the cross section uncertainties due to the mass measurement uncertainty are combined using equations 4 and 5 which give smallest weight to the channels with largest uncertainty. The mass resolution is estimated by fitting the reconstructed m_ττ distribution after all selections with a Gaussian function (Fig. 8). The resolution is almost constant as a function of m_A, ~ 24% for the leptonic final state, ~ 17% for the lepton+jet final state and ~ 12% for the hadronic final state as shown in Fig. 9. The fit of the signal plus background distributions (Fig. 10) gives the same Higgs boson mass resolution as the fit of the signal only. The uncertainty on the mass measurement is calculated from the Gaussian fit of the mass peak as σ_Gauss/√N_S, and the error induced to the cross section (Δσ(Δm)) is estimated by varying the cross section for Higgs masses m_0 and m_0 ± σ_Gauss/√N_S. At 5σ limit where the signal statistics is lowest, the uncertainty on the mass measurement brings 5 - 6% uncertainty on the tanβ measurement.

4.3 Dependence on the SUSY parameters

To give an estimation of the sensitivity of the signal rate to the SUSY parameters, those were varied by 20% around the nominal values. The variation of the signal rate within the expected discovery region is at most ~11% which leads to a maximum of 6% uncertainty on the tanβ measurement. At low m_A the uncertainty is even smaller. As
already stated, in reality, it is expected that the cross section measurement will be entered in a global fit together with the other relevant measurements to determine all SUSY parameters simultaneously.

5 Measurement of \( \tan\beta \)

5.1 \( H/A \rightarrow \tau\tau \)

Table 4 shows the statistical uncertainty on the \( \tan\beta \) measurement and the uncertainty on the mass measurement for each individual final state and for the combined final states from \( H/A \rightarrow \tau\tau \) for 30 fb\(^{-1} \). The total estimated uncertainty is shown for the combined final states. As described in the previous section it includes the following uncertainties: statistical, theoretical, luminosity, mass measurement, uncertainty on the experimental signal selection efficiency and background uncertainty. The results are shown for the region of the \((m_A, \tan\beta)\) parameter space where the statistical significance exceeds 5\( \sigma \). Close to the 5\( \sigma \) limit the statistical uncertainty is of the order of 11 - 12%, but it decreases rapidly for increasing \( \tan\beta \).

Table 4: Statistical uncertainty on the \( \tan\beta \) measurement and the uncertainties due to the mass measurement for individual and combined final states in four \((m_A, \tan\beta)\) parameter space points for 30 fb\(^{-1} \) with better than 5\( \sigma \) significance. The total uncertainty \( \Delta \tan\beta/\tan\beta \) in the Table includes the following uncertainties: statistics, mass measurement, cross section and branching ratio theoretical uncertainties, luminosity, experimental selection efficiency and background uncertainties.

| 30 fb\(^{-1} \) | \( m_A = 200 \text{ GeV/c}^2 \) | \( m_A = 200 \text{ GeV/c}^2 \) | \( m_A = 500 \text{ GeV/c}^2 \) | \( m_A = 500 \text{ GeV/c}^2 \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \tan\beta = 20 \) | \( \Delta \sigma (\Delta m) \) | \( \Delta \sigma (\Delta m) \) | \( \Delta \sigma (\Delta m) \) | \( \Delta \sigma (\Delta m) \) |
| H/A→\( \tau\tau \→e\mu \) | 8.95% | 4.82% | 4.85% | 3.27% | - | - | - | - |
| H/A→\( \tau\tau \→\ell\ell \) | 7.96% | 3.50% | 4.08% | 2.37% | - | - | - | - |
| H/A→\( \tau\tau \→l\jmath \) | 4.81% | 2.46% | 2.84% | 1.65% | - | - | 8.40% | 4.82% |
| H/A→\( \tau\tau \→j\jmath \) | 13.7% | 4.73% | 8.25% | 3.21% | 12.4% | 5.82% | 8.45% | 4.44% |
| Combined e\( \mu \)+j\jmath | 4.05% | 1.99% | 2.35% | 1.34% | 9.09% | 4.28% | 5.96% | 3.26% |
| Combined \( \ell\ell \)+j\jmath | 3.94% | 1.85% | 2.24% | 1.25% | 9.09% | 4.28% | 5.96% | 3.26% |

As shown in the table, the highest statistical accuracy of about 5\% for \( m_A = 200 \text{ GeV/c}^2 \) and \( \tan\beta = 20 \), is
obtained with the lepton+jet final state. Combining other channels with the lepton+jet channel in this mass range improves the precision only slightly. The difference between the fully leptonic channels ($e\mu$ and $\ell\ell$) is small: the statistical uncertainty is slightly smaller for the $e\mu$ channel, if $m_A$ is close to the Z peak, but already at $m_A = 200$ GeV/c$^2$ the final state with any two leptons yields better statistics and lower uncertainties. The combined $\ell\ell+\ell j+jj$ channel yields a slightly smaller statistical error at $\tan\beta = 20$ than the combined $e\mu+\ell j+jj$ channel despite the larger backgrounds in the $\ell\ell$ final state.

Figure 11 shows the statistical uncertainty and the statistical plus systematic uncertainties on $\tan\beta$ for the combined $e\mu+\ell j+jj$ and $\ell\ell+\ell j+jj$ final states as a function of $m_A$ for $\tan\beta = 20$, 30 and 40, and for 30 fb$^{-1}$. The total uncertainty ranges from 12% to 19% depending on $\tan\beta$ and $M_A$.

5.2 $H/A \rightarrow \mu\mu$

In the region $m_A \lesssim 300$ GeV/c$^2$, the value of $\tan\beta$ could also be measured in the $H/A \rightarrow \mu\mu$ channel using event rates. In this channel, the Higgs mass resolution is about 2%. Therefore the total width of the Higgs boson could be measured with good precision from the Higgs boson mass peak. The variation of the natural width as a function of $\tan\beta$, from less than 1 GeV/c$^2$ to about 20 GeV/c$^2$ in the expected $\tan\beta$ range, could be used to determine the value of $\tan\beta$. This method, based on the direct width measurement, would therefore be complementary to the method explained in this note.

6 Conclusion

The precision of the cross section times branching ratio, $\sigma^{\text{prod}}$, measurement and the derived $\tan\beta$ value was estimated in the $H/A \rightarrow \tau\tau$ decay channel with two-lepton, lepton+jet and two-jet final states for 30 fb$^{-1}$. The
Figure 12: The uncertainty on the $\tan \beta$ measurement shown as error bars. The small error bars and gray area show the statistical errors only. The large error bars show the total uncertainty evaluated as described in the text. The solid curve corresponds to the $5\sigma$-discovery contour of Fig. 5. Those results correspond to 30 fb$^{-1}$ of integrated luminosity.

Figure 13: The same as in Fig. 12 but with 60 fb$^{-1}$ taken at low luminosity.
statistical precision on $\sigma_{\text{prod}}$ is expected to be 3–25% and the associated systematic error $\leq$ 12% both depending on the signal significance.

In the region of large $\tan\beta$, the $\tan^2\beta$ dependence of the associated production processes $gg \rightarrow b\bar{b}H/A$ has been exploited to obtain a statistical uncertainty being a factor of two smaller than that of the event rates. Due to the presence of potentially large radiative corrections to the bottom Yukawa coupling, the results obtained in this analysis correspond to an effective parameter $\tan\beta_{\text{eff}}$ which absorbs the leading universal part of these corrections. A theoretical error of 20% (cross section) and 3% (branching ratio) and a luminosity uncertainty of 5% have been assumed. If two $b$ jets with $E_T > 20$ GeV are tagged, the theoretical uncertainty on the cross section reduces to 10-15%, but the event rates have been found to decrease significantly leading to a worse accuracy of the $\tan\beta$ measurement. With one tagged $b$ jet in the event the total uncertainty on $\tan\beta$ estimated with the $H/A \rightarrow \tau\tau$ decay channels ranges from 12% to 19% within the $5\sigma$-discovery reach depending on $\tan\beta$ and $M_A$ after collecting $30 \text{ fb}^{-1}$. The combination of the $e\mu$, $e+\text{jet}$ and two-jet or $\ell\ell$, $\ell+\text{jet}$ and two-jet final states gives 4% better statistical accuracy than the best individual final state. Close to the $5\sigma$-discovery limit the statistical uncertainty ranges in the same order as the theoretical one, but for $\tan\beta$ regions where the signal significance exceeds $5\sigma$ significantly the theoretical error dominates.

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References

[1] M. Carena and H.E. Haber, hep-ph/0208209 and references therein.
[2] LEP Higgs Working Group for Higgs boson searches, Proceedings International Europhysics Conference on High Energy Physics (HEP 2001), Budapest, Hungary, 12-18 Jul 2001, hep-ex/0107029 and hep-ex/0107030.
[3] H. Baer, C. Chen, M. Drees, F. Paige, X. Tata, Phys. Rev. D 59 (1999) 055014.
[4] D. Denegri, W. Majerotto and L. Rurua, Phys. Rev D 60 (1999) 035008.
[5] J.F. Gunion, L. Poggioli, R. Van Kooten, C. Kao and P. Rowson, hep-ph/9703330.
[6] L. J. Hall, R. Rattazzi and U. Sarid, Phys. Rev. D 50 (1994) 7048; M. Carena, M. Olechowski, S. Pokorski and C. E. Wagner, Nucl. Phys. B 426 (1994) 269; M. Carena, D. Garcia, U. Nierste and C. E. Wagner, Nucl Phys. B 577 (2000) 88; J. Guasch, P. Häfliger and M. Spira, hep-ph/0305101.
[7] R. Kinunnen and I.K. Furic, CMS Note 1998/039; L. Bellucci, MSSM Neutral Higgs Boson searches at CMS in the $\mu\mu$ channel, Dissertation, Universita degli studi di Firenze, December, 2001.
[8] S. Lehti, Prospects for the Detection of the MSSM Higgs Bosons Decaying into Tau Leptons in the CMS Detector, Dissertation, University of Helsinki, Report Series in Physics, HU-P-D93, 2001.
S. Lehti, CMS NOTE 2002/035.
[9] R. Kinunnen and A. Nikitenko, CMS NOTE 1997/106.
[10] R. Kinunnen and A. Nikitenko, CMS NOTE 2003/006.
[11] M. Carena, S. Heynemeyer, C.E.M. Wagner and G. Weiglein, hep-ph/0202167.
[12] T. Sjöstrand, P. Eden, Ch. Friberg, L. Lönnblad, C. Mius, S. Mrenna and E. Norrbin, Comput. Phys. Commun. 135 (2001) 238.
[13] S. Dittmaier, M. Spira and M. Krämer, hep-ph/0309204.
[14] M. Spira, Fortschr. Phys. 46 (1998) 203.
[15] CERN/LHCC 2002-26, CMS TDR 6.2.

[16] K. Hagiwara et. al., Phys. Rev. D 66 (2002) 010001.

[17] L. Sonnenschein, CMS NOTE 2001/001.

[18] T. Plehn, Phys. Rev. D67 (2003) 014018, hep-ph/0206121. E. Boos and T. Plehn, hep-ph/0304034.

[19] J. Campbell et. al., hep-ph/0204093.

[20] S. Dawson, C.B. Jackson, L. Reina and D. Wackeroth, hep-ph/0311067.

[21] S. Lehti, CMS NOTE 2001/019.