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Search for H/A $\rightarrow \mu\mu$ and $\tau\mu$ at the LHC

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Abstract. The expected experimental sensitivity to the heavy neutral Higgs boson decays H/A $\rightarrow \mu\mu$ and H/A $\rightarrow \tau\mu$ at the LHC is discussed in the framework of the MSSM and of two type-III Two-Higgs-Doublet Models allowing for lepton flavour violation (LFV), respectively. Despite a small branching fraction, the H/A $\rightarrow \mu\mu$ decay allows for a precise measurement of the Higgs boson mass and for an evaluation of the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. The search for the lepton flavour violating decay H/A $\rightarrow \tau\mu$ allows stringent constraints to be set on the LFV coupling parameter $\lambda_{\tau\mu}$.

1 Introduction

The Large Hadron Collider (LHC), which will deliver p-p collisions at a centre-of-mass energy of 14 TeV, is expected to start operation in 2007 at an initial luminosity of $2\ \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$. The two general purpose detectors ATLAS [1] and CMS [2], presently under construction, are equipped with high-precision tracking systems, high resolution and hermetic calorimetry and large acceptance muon spectrometers. Their design ensures efficient b tagging and τ identification, good jet and Missing E_T resolution, and precise and efficient muon reconstruction.

The understanding of the electroweak symmetry breaking mechanism is one of the major goals of the LHC physics programme. The search for and the measurement of the properties of the Higgs boson(s) are therefore a key issue in this process.

In particular, in the Minimal Supersymmetric extension of the Standard Model (MSSM) as well as in any Two-Higgs-Doublet Models, the lighter neutral scalar h is accompanied by a heavier scalar state H and a pseudoscalar state A. The coupling of these heavier two states to down-type fermions generally scales with $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. As a consequence, the cross section of the associated production gg $\rightarrow$ b$\bar{\text{b}}$H/A is larger than the Standard Model cross section by a factor $\tan^2\beta$. This large cross section, as well as the distinct signature with two b-quark jets, makes this process one of the most promising handles for the discovery of the heavy Higgs bosons, H and A, at the LHC. For the same reason as above, H and A predominantly decay into down-type fermion pairs at large $\tan\beta$. Because the b$\bar{\text{b}}$ decay mode yields an experimentally challenging b$\bar{\text{b}}$b$\bar{\text{b}}$ final state, the decay H/A $\rightarrow \tau\tau$ (BR$\approx$10%), is currently considered as the "golden" channel. Other rare or non-standard decays, however, are also quite interesting in terms of their discovery potential, in measuring the Higgs boson parameters and in the search for effects of new physics. In this report, the physics sensitivity of the LHC experiments to the H/A $\rightarrow \mu\mu$ and the lepton flavour violating H/A $\rightarrow \tau\mu$ decays is discussed. In ATLAS and CMS, the efficient and precise muon reconstruction is particularly well suited for the two studies. The H/A $\rightarrow \mu\mu$ channel, in spite of a low branching fraction (BR$\approx 3 \cdot 10^{-4}$), provides a clean signature and allows for a precise measurement of the Higgs boson masses. The search for the decay mode H/A $\rightarrow \tau\mu$ gives the opportunity to detect lepton flavour violating effects.

2 Search for H/A $\rightarrow \mu\mu$

Several feasibility studies have been done by both ATLAS [3] and CMS [4] to quantify their discovery potential for the heavy neutral MSSM Higgs bosons in the H/A $\rightarrow \mu\mu$ channel. In this report, a study performed by CMS is presented [5]. The study is based on the detection of the H/A $\rightarrow \mu\mu$ decay in the b$\bar{\text{b}}$H/A associated production channel, and assumes the luminosity conditions expected in the first phase of the LHC operation. Both the signal and the background samples were generated with PYTHIA [6], passed through the GEANT-based full detector simulation CMSIM [7] and the CMS Oject-Oriented reconstruction and analysis program, ORCA [8].

The analysis strategy is based on the detection of two high-tranverse-momentum and isolated muons, and on the tagging of the b quarks. The main backgrounds are expected from Drell-Yan production $Z/\gamma^* \rightarrow \mu\mu$, representing the dominant contamination, and from t$\bar{\text{t}}$ $\rightarrow$ WbWb events, with both W bosons decaying into a muon and a neutrino. Other potential backgrounds from b$\bar{\text{b}}$, c$\bar{\text{c}}$ QCD production and WW, ZZ events were found to be negligible. The b tagging is the main handle against the background coming from Drell-Yan events, in which only about

2% of the events contain b quarks (originating from the production mechanism $\mathrm{b\bar{b}Z/\gamma^*}$). As the b jets from the signal are, in general, soft and emitted in the forward region, no attempt is done to tag them separately. An event b-tagging algorithm is used instead, which relies on a combination of different variables carrying lifetime information, like the number of secondary vertices in the event and the multiplicity of charged particle tracks with large impact parameters. The b-tagging requirement yields a factor ≈ 10 rejection on the background from $\mathrm{Z}/\gamma^* \to \mu\mu$, with a relatively high ($\approx 40\%$) efficiency for the signal. The background from $\mathrm{t\bar{t}}$ events, which contain two hard b jets and cannot be rejected by means of b tagging, is suppressed by applying a central jet veto and by requiring the missing energy in the event to be small.

In Fig. 1 the invariant mass of the di-muon system for a 150 GeV/c^2 Higgs boson is shown, together with the distribution expected from the Drell-Yan and $\mathrm{t\bar{t}}$ backgrounds, for an integrated luminosity of 20 fb^{-1}. In CMS the invariant mass of the muon pair can be reconstructed with an experimental resolution of about 1.5%. The peak corresponds to the integral signal from the A and H bosons, fully degenerate for this choice of the MSSM parameters. With an integrated luminosity of 60 fb^{-1} this channel allows for a measurement of the A/H mass with a relative precision of 0.2%. Moreover, for large values of tanβ, where the natural width of the Higgs bosons is larger than the experimental resolution, it allows $\Gamma_{\mathrm{H,A}}$ to be measured directly and tanβ to be constrained independently of the total cross section.

The 5σ $\mathrm{H/A} \to \mu\mu$ discovery contour lines as a function of $\mathrm{M_A}$ and tanβ are shown in Fig. 2, with the hypothesis of two different integrated luminosities, 20 and 60 fb^{-1}. The rise of the discovery contours at large $\mathrm{M_A}$ reflects the decrease of the production cross section. With 60 fb^{-1}, roughly corresponding to three years of LHC at low luminosity, the sensitivity extends down to $\tan\beta \approx 15$ if $\mathrm{M_A} < 200$ GeV/c^2.

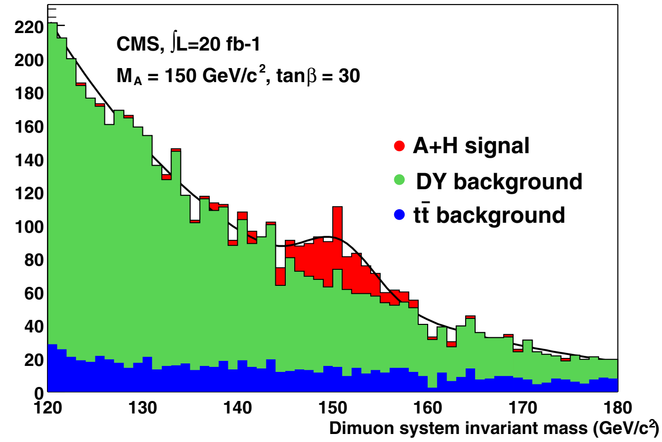

Fig. 1. Invariant mass of the di-muon system at the end of the selection, for a 150 GeV/c^2 Higgs boson with tan$\beta = 30$ (*red histogram*) and the Drell-Yan (*green histogram*) and $\mathrm{t\bar{t}}$ (*blue histogram*) background, assuming $\int \mathrm{L} = 20$ fb^{-1}. The solid line shows the results of a fit to the distribution using a Gaussian for the signal and an exponential for the background. The fitted peak and width of the Gaussian are respectively 150.8±0.6 GeV/c^2 and 3.7±0.7 GeV/c^2

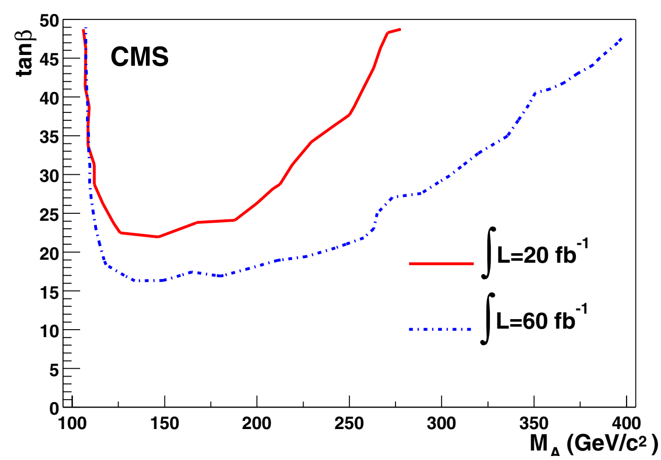

Fig. 2. The 5-σ contours as a function of $\mathrm{M_A}$ and $\tan\beta$ for the discovery of the MSSM heavy neutral Higgs bosons in the $\mathrm{b\bar{b}H/A, H/A} \to \mu\mu$ channel with CMS, assuming an integrated luminosity of 20 fb^{-1} (*solid line*) and 60 fb^{-1} (*dash-dotted line*). The wiggly nature of the line is of statistical origin

3 Search for $\mathrm{H/A} \to \tau\mu$

If Lepton Flavour Violation (LFV) exists, as suggested by the experimental evidence for ν_μ/ν_τ oscillations with maximal mixing [9], it could be observed at the LHC through different signatures, like in the decays $\tau \to \mu\gamma$, $\tau \to 3\mu$ and $\tilde{\chi}^o_2 \to \tilde{\chi}^o_1\mu\tau$. The possibility to detect evidence for LFV in the decay of the neutral heavy Higgs states $\mathrm{H/A} \to \tau\mu$ has been investigated by ATLAS [10], within the framework of two different (type a,b) 2HDM-III models [11,12,13]. In these models, the branching fraction of the Higgs bosons into a muon and a tau can be parametrized in terms of the coupling $\mathrm{k}_{\tau\mu}$ and the branching ratio of the Standard Model Higgs in $\tau\tau$ as

$$\mathrm{BR(H/A} \to \tau\mu) = \mathrm{k}^2_{\tau\mu} \cdot \frac{2\mathrm{m}_\mu}{\mathrm{m}_\tau} \cdot \mathrm{BR(H^0_{SM}} \to \tau\tau), \quad (1)$$

where the coupling $\mathrm{k}_{\tau\mu}$ depends on the LFV coupling $\lambda_{\tau\mu}$, the mixing angle of the CP-even neutral Higgs sector α, the ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta$, and on the total width of the Higgs boson in the 2HDM-III Model (a,b) and in the Standard Model.

The search is performed on the final states where the τ decays into hadrons or into electrons. The study is restricted to the Higgs boson mass region 120-160 GeV/c^2, primarily because the branching fraction $\mathrm{BR(H/A} \to \tau\mu)$ drops for Higgs boson masses above the the WW production threshold. The main contamination is expected from the process $\mathrm{Z}/\gamma^* \to \tau\tau$ and, in the hadronic channel, from W+jets events, which are however efficiently rejected by requiring a central jet veto and by selecting one-prong decays of the τ. Less important background come from $t\bar{t}$, WW and WZ events.

The isolation of the signal relies on the presence of a high-transverse-momentum, isolated muon and of an energetic tau. The τ energy and momentum is reconstructed from the hadron (electron) and the missing transverse energy measured in the event, assuming the neutrino to be emitted collinearly to the visible tau decay product. The background is then further suppressed by requiring the $\tau\mu$ system to be consistent with a two-body decay of the Higgs boson. The muon track is required to have a large opening angle in the transverse plane with respect to the visible τ decay product, and to be more energetic than the visible τ decay product due to the presence of the neutrino(s) in the τ decay. These requirements allows for both a strong rejection against the Standard Model background from $Z/\gamma^* \to \tau\tau$ and an efficient separation of the $H/A \to \tau\mu$ signal from the MSSM decay $H/A \to \tau\tau$.

The 5σ constraints on the LFV coupling $\lambda_{\tau\mu}$ which can be achieved with 100 fb^{-1}, assuming combined ATLAS and CMS data, are shown in Fig. 3 as a function of the Higgs boson mass. Depending on the type of 2HDM-III model and on $\tan\beta$, the bounds on $\lambda_{\tau\mu}$ range from $\approx 10^{-3}$ to ≈ 10, yielding in most cases a significantly better reach than the current limits derived from the measurements of the muon anomalous magnetic moment g-2 [14].

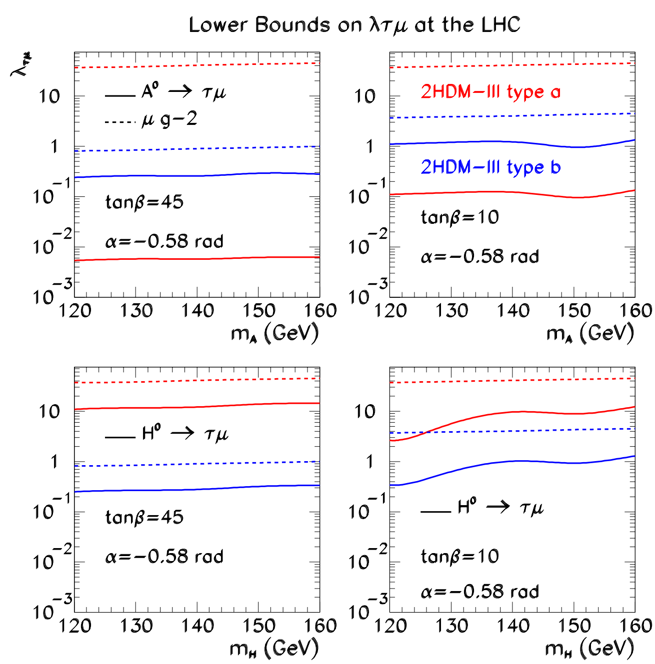

Fig. 3. Expected 5σ sensitivity on the LFV coupling $\lambda_{\tau\mu}$ as a function of the Higgs mass (*solid lines*), achievable with 100 fb^{-1} at the LHC assuming combined ATLAS and CMS data. The dashed lines correspond to the constraints coming from g-2 data [14]. For contraints from the muon g-2 data and the $H \to \tau\mu$ decay, the curves at higher $\lambda_{\tau\mu}$ correspond to the 2HDM-III type a model, while the lower curves to the 2HDM-III type b. The trend is reversed for $A \to \tau\mu$

4 Conclusions

In this report, a study of the physics potential of the CMS experiment for the discovery of the heavy neutral MSSM Higgs bosons A,H in the $H/A \to \mu\mu$ decay channel has been discussed. Although characterized by a low branching ratio, this channel provides a clean final state and complements the principal search channel $H/A \to \tau\tau$ in the small Higgs boson mass region. Moreover, it gives the opportunity to measure the Higgs boson mass with high precision, and the unique possibility to measure directly the Higgs boson natural width. The di-muon mass resolution expected for both the ATLAS and CMS experiments may even allow the signals from the neutral Higgs bosons h,A,H to be separated in regions of the MSSM parameter space where they are non-degenerate, as in the "Intensive Coupling Regime" scenario discussed in [15].

The detection of the heavy neutral Higgs boson decay $H/A \to \tau\mu$ provides an evidence for Lepton Flavour Violating effects involving the second and third generation. In particular, a study performed by the ATLAS collaboration shows that, within the framework of two different 2HDM models which predict LFV, the sensitivity to leptor flavour violating couplings $\lambda_{\tau\mu}$ could be extended significantly beyond the current constraints from muon g-2 data.

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