Search for Heavy Higgs Bosons in Fermionic Decay Channels with CMS

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Latest results of searches for heavy Higgs bosons in fermionic final states are presented using the CMS detector at the LHC. Results are based on pp collision data collected at centre-of-mass energies of 8 and 13 TeV which have been interpreted according to different extensions of the Standard Model such as MSSM, 2HDM, and NMSSM. These searches look for evidence of other scalar or pseudoscalar bosons, in addition to the observed SM-like 125 GeV Higgs boson, and set 95% confidence level upper limits in fermionic final states and benchmark models explored. The talk reviews briefly the major results obtained by the CMS Collaboration during Run I, and presents the most recent searches performed during Run II.

Keywords: CMS; Heavy Higgs Bosons; Fermionic Decay; MSSM; 2HDM; NMSSM.

1. Introduction: Heavy Higgs Boson Searches at CMS

The Minimal Supersymmetric Standard Model (MSSM) was originally proposed around the eighties of the last century^{1,2,3}. Within the MSSM theory, two Higgs doublet states are allowed, resulting in five Higgs boson final states which include two spin even neutral Higgs bosons (h/H), one spin odd neutral Higgs boson (A) and two charged Higgs bosons ($H^\pm$). After the discovery of the standard model like Higgs boson, the MSSM model has become one of the benchmark scenarios for additional Higgs boson searches at the CMS⁴ experiment. A recent summary of MSSM Higgs boson production cross sections can be found in the LHC Higgs boson Cross Section Working Group (HXS WG) report⁵. The progress of MSSM Higgs boson searches also triggers prospective Higgs boson like resonance searches in other phenomenological models, including the Two Higgs Doublet model (2HDM)⁶, Graviton models⁷ etc.

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Fig. 1. Neutral heavy Higgs decay modes being explored with the CMS experiment.

Since 2011, the CMS Collaboration has written publications specifically targeting MSSM Higgs boson searches taken at three center-of-mass energies. As illustrated in Fig. 1, neutral Higgs bosons have been searched via three fermionic final states $\tau\tau$ ^{8,9,10,11}, $b\bar{b}$ ^{13,14}, and $\mu\mu$ ¹⁵. There are additional neutral Higgs boson or resonance searches via double bosonic decays like ZH , HH , ZZ and WW , with results partially re-interpreted within the framework of MSSM scenarios¹⁸. The charged Higgs boson searches have been performed via final states of $\tau\nu$ and $t\bar{b}$ ¹⁶, which could be very important for further constraints of the MSSM parameter space.

2. Neutral MSSM Higgs Boson search via $\tau\tau$

For the neutral MSSM Higgs boson production, the cross section is quite low. However, when a Higgs boson is produced associated with a b quark, the cross section could be enhanced proportional to $\tan^2\beta$. There are three di-fermion decay modes that have been discussed in this session, namely $\tau\tau$, $b\bar{b}$, and $\mu\mu$. In Fig. 2, three principal tree level production subprocesses are depicted.

The search for neutral MSSM Higgs bosons via $\tau\tau$ decays has been performed by the CMS experiment^{8,9} with 7 TeV and 8 TeV data. The decay mode has been re-investigated with around 2.3 fb^{-1} data collected in 2015¹⁰ and then with 12.9 fb^{-1} data collected in 2016¹¹. Four decay modes of $\tau\tau$ pairs have been studied, $\mu\tau_h$, $e\tau_h$, $e\mu$ and $\tau_h\tau_h$. The final transverse invariant mass distribution of $\mu\tau_h$ has been shown in Fig. 3 as an example. The combination results have reached the region beyond 1 TeV and there are no obvious new phenomena that have been seen in the

Fig. 2. Feynman diagrams of neutral Higgs boson production in the MSSM framework. Left: leading order MSSM Higgs boson production with the gluon fusion process. Middle: leading order MSSM b-associated Higgs boson production. Right: additional leading order MSSM Higgs boson production with the five-flavor scheme^{8,9,10,11}.

Fig. 3. MSSM $H \rightarrow \tau\tau$ search with 12.9 fb^{-1} 13 TeV data. Post-fit plots of the $\tau\tau$ transverse mass distribution in the $\mu\tau_h$ channel. The left plot is without the b-tag category and the right plot is with the b-tag category¹¹.

$\tau\tau$ spectrum. A model independent limit has been provided, along with the MSSM m_h^{mod+} and hMSSM scenarios in a CMS Physics Analysis Summary¹¹. With all data collected in 2016, the parameter spaces of M_A and $\tan\beta$ have been further constrained¹².

3. Neutral MSSM Higgs Boson search via $b\bar{b}$

The $b\bar{b}$ final state has been considered as a very important decay mode for Higgs boson searches due to the relative large branching ratio of the Higgs boson decay to $b\bar{b}$. The large QCD multi-jet background made this channel very challenging to measure. For 7 TeV and 8 TeV center-of-mass energies, two results have been released by the CMS Collaboration^{13,14}. 95% confidence level upper limits of MSSM Higgs bosons produced in association of at least one b quark and decaying to $b\bar{b}$ have been set. The physics results have been discussed for several MSSM benchmark scenarios and an upper limit of the Higgs boson cross section has been provided combining the 7 TeV and 8 TeV CMS data. Until now, the CMS results are the only results for the search of the MSSM Higgs boson to $b\bar{b}$ in LHC experiments.

4. Neutral MSSM Higgs Boson search via $\mu\mu$

The MSSM Higgs boson to $\mu\mu$ decay mode has been presented with relatively low systematic uncertainties¹⁵. Fig. 5 shows the invariant spectrum of $\mu\mu$ without or with b-tag. The combined 7 and 8 TeV results have been presented together with the m_h^{mod+} MSSM scenario in Ref.¹⁵. Due to the fact that the cross section is around 10^{-3} lower compared to $\tau\tau$ decays, the discovery region beyond 1 TeV has not yet been accessible with currently available results. With data accumulated in Run II,

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Fig. 4. MSSM $H \rightarrow b\bar{b}$ search with 19.6 fb⁻¹ 8 TeV data. Left: the invariant mass spectrum of the two leading b jets. Right: upper limits of the MSSM Higgs boson cross section in m_A and $\tan\beta$ parameter spaces¹⁴.

Fig. 5. MSSM $H \rightarrow \mu\mu$ search with 19.6 fb⁻¹ 8 TeV data. Invariant mass spectrum of $\mu\mu$ without or with additional b-tag¹⁵.

this decay mode could be very attractive given the excellent muon reconstruction performance of the CMS experiment.

5. Charged MSSM Higgs Boson search

The MSSM model allows for the existence of two charged Higgs bosons. When $m_{H^\pm} < (m_t - m_b)$, a large fraction of charged Higgs bosons are expected to decay via $\tau\nu$; when $m_{H^\pm}$ is above the $(m_t - m_b)$ threshold, $H^\pm \rightarrow tb$ is expected to provide the dominated production. CMS has performed the charged Higgs boson search through two decay modes $H^\pm \rightarrow \tau\nu$ and $H^\pm \rightarrow tb$ ^{16,17}. With 19.7 fb⁻¹ 8 TeV Run I data, the upper limits of the cross section for $m_{H^\pm} = 80 - 160 \text{ GeV}$ have been set to be $\sigma(pp \rightarrow t(b)H^\pm)B(H^\pm \rightarrow \tau\nu_\tau) = 0.38$ to 0.025 pb . Assuming $B(H^\pm \rightarrow tb) = 1$, upper limits on the cross section ($\sigma(pp \rightarrow t(b)H^\pm)$ for $m(H^\pm) = 180 - 600$

Fig. 6. Combined m_h^{mod+} MSSM results with CMS 7 and 8 TeV data¹⁸.

GeV are set to be 2.0 to 0.13 pb¹⁶. With 12.9 fb⁻¹ data accumulated at Run II, the upper limits on charged Higgs bosons times branching ratio are set for Higgs bosons with 180 GeV < $m(H^\pm)$ < 3 TeV¹⁷.

6. Summary and outlook

An overview of the CMS Run I additional heavy Higgs boson searches has been given in a CMS Physics Analysis Summary¹⁸, including the discussion within MSSM benchmark scenarios. Fig. 6 shows results for one of the MSSM scenarios m_h^{mod+} as an example. Di-fermion processes are currently sensible to high $\tan\beta$ regions and di-boson processes are sensible to low $\tan\beta$ regions.

Searches for heavy Higgs bosons motivated by the predictions of a few models beyond the SM, have become a focus of the CMS experiment in Run II of the LHC after the discovery of the SM-like Higgs boson. New results of fermionic decay modes with around 12.9 fb⁻¹ data accumulated in 2016 have been shown along with the Run I reviews. With the current data sample, no hint for new physics has appeared yet. More decay modes both for additional neutral Higgs bosons and charged Higgs bosons are expected to be explored with 2016 and 2017 data.

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