MSSM Higgs searches with CMS and corresponding SM candle studies

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On behalf of the CMS Collaboration
The CMS experiment

- General purpose detector designed to optimize the discovery potential of LHC.
- Good muon system.
- A 4 Tesla magnetic field allows a good resolution in the measure of energetic muons.
- Angular coverage:
  - Tracker: $|\eta| < 2.5$
  - Calorimeters: $|\eta| < 5.3$
  - Muons: $|\eta| < 2.4$
The CMS experiment

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Introduction

- Higgs boson discovery is one of the main goals of the CMS detector.

- In the MSSM there are 5 Higgs bosons:
  - 3 neutral (H and h with CP even; A with CP odd).
  - 2 charged (H±).

- At the tree level, the Higgs sector is defined by $\tan\beta$ and $M_A$.
  - The other MSSM parameters are important for the calculation of the radiative corrections.

- For the analysis described here the $M_{h_{\text{max}}}$ benchmark scenario is taken:
  - $M_{\text{SUSY}} = 1$ TeV; $\mu = 200$ GeV; $M_2 = 200$ GeV; $X_t = \sqrt{6} M_{\text{SUSY}}$
Production

- Production of neutral MSSM Higgs at LHC:
  - Gluon fusion: \( pp \rightarrow gg \rightarrow h,H,A \)
  - Vector-boson fusion: \( pp \rightarrow qq \rightarrow qq + WW/ZZ \rightarrow qq + h/H \)
  - Higgs-strahlung: \( pp \rightarrow qq \rightarrow Z^*/W^* \rightarrow h/H + Z/W \)
  - Associated production with b quarks: \( pp \rightarrow qq/gg \rightarrow h/H/A + bb \)

- Production of charged MSSM Higgs at LHC:
  - Associated production with heavy quarks: \( pp \rightarrow qq/gg \rightarrow H^\pm + tb \)
  - Drell-Yan type process: \( pp \rightarrow qq \rightarrow H^+H^- \)
  - gg initial state: \( pp \rightarrow gg \rightarrow H^+H^- \)
  - Associated production with W bosons: \( pp \rightarrow gg \rightarrow HW \)
Search for neutral Higgs Bosons

- $\tan\beta > 15$:
  - $H/A \rightarrow \mu\mu$
  - $H/A \rightarrow \tau\tau \rightarrow e + \text{jet} + X$
  - $H/A \rightarrow \tau\tau \rightarrow \mu + \text{jet} + X$
  - $H/A \rightarrow \tau\tau \rightarrow \text{jet} + \text{jet} + X$
  - $H/A \rightarrow \tau\tau \rightarrow e + \mu + X$
  - $H/A \rightarrow bb$

- $\tan\beta < 15$:
  - $A \rightarrow Zh \rightarrow ll bb$
  - $H/A \rightarrow \chi^0_2 \chi^0_2 \rightarrow 4l + \text{Miss } E_T$
Search for charged Higgs Bosons

- $M_H < M_{\text{top}}$:
  - $H^\pm \rightarrow \tau \nu$

- $M_H > M_{\text{top}}$:
  - $H^\pm \rightarrow \tau \nu$
  - $H^\pm \rightarrow t b$
Neutral Higgs: $bb\Phi \rightarrow b\bar{b}\mu\bar{\mu}$

- The Branching ratio in two muons is very small ($3\cdot10^{-4}$), but the final state is very clean.
- The Higgs masses and widths can be reconstructed very precisely:
  $\Delta M_A \approx 0.5 \text{ GeV}/c^2$
  $\Delta \Gamma_A \approx 1.5 \text{ GeV}/c^2$
- Main background from $Z/\gamma^* \rightarrow \mu^+\mu^-$, tt pairs, $Z/\gamma^*bb \rightarrow \mu^+\mu^-bb$.
- The number of background and signal events are entirely determined by data (no need of Monte Carlo to calculate the significance).
Neutral Higgs: $bb\Phi \rightarrow bb\mu\mu$

- To calculate the significance a binned likelihood fit method is applied in the signal+background hypothesis ($L_{S+B}$) and in the only background hypothesis ($L_B$).

- Discovery contour plot for 30 fb$^{-1}$:
  - For $M_A$ near 100 GeV/c$^2$ we are too close to the Z peak.
  - For $M_A$ near 130 GeV/c$^2$ the three Higgs bosons contribute and the peak is smeared.

- From theory we have that $\Gamma_A \propto \tan^2\beta$:
  - It is possible to exploit the good precision in the Higgs boson width determination ($\Delta \Gamma_A \approx 1.5$ GeV/c$^2$) to measure $\tan\beta$. 
Neutral Higgs: \( bb\Phi \rightarrow bb\tau\tau \)

- The BR(\( \Phi \rightarrow \tau\tau \)) is about 10%.
- The Higgs mass is reconstructed with the neutrinos-charged lepton collinear approximation method.
- Main background comes from \( Z/\gamma^* \rightarrow \tau^+\tau^- \), tt pairs and \( Z/\gamma^*bb \rightarrow \tau^+\tau^-bb \).
- Four analysis have been developed depending by the \( \tau \) decay.

**Final state e + jet:**
- Main selection cuts based on the identification of an isolated electron and \( \tau \)-jet, and on the b-tag.
Neutral Higgs: $bb\Phi \rightarrow bb\tau\tau$

- **Final state $\mu + jet$:**
  - Main selection cuts based on the identification of an isolated muon and $\tau$-jet, and on the b-tag.

- **Final state two jet:**
  - With respect to the previous analysis, the huge QCD multi-jet background is dominant.

- **Final state $e + \mu$:**
  - Compared with hadronic final state the BR for this channel is small (6.3%), but clean signal.

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Zbb as a benchmark for Hbb

- Can we trust about Monte Carlo?
- Zbb events have almost the same production mechanism of MSSM Hbb:
  - Zbb measured from data can be used to verify the theoretical prediction for the cross section, and Z boson and b quark transverse momentum distribution.
  - $Z \rightarrow \tau\tau$ can be used to verify $H \rightarrow \tau\tau$ mass reconstruction with the collinear approximation method.
- A study on $Z \rightarrow \tau\tau \rightarrow \mu +$ hadrons has been performed to measure $\tau$ tag efficiency from data.
Neutral Higgs: $bb\Phi \rightarrow bbbb$

- The QCD multi-jet background is huge:
  - The channel is studied with the CMS fast simulation (the signal is also studied with the full simulation to validate the fast simulation).
- This channel can be considered as a cross-check for the discovery (it is required the knowledge of the Higgs boson mass).
- The selection is based on the request of at least four high energetic jets, with at least three of these tagged as b-jet.
- Result are strongly dependent by the knowledge of the background from data.
Neutral Higgs: $A \rightarrow Zh$

- In this study $Z \rightarrow \ell^+\ell^-$ and $h \rightarrow bb$.
- Low $\tan\beta$ and $m_Z + m_h \leq m_A \leq 2m_{top}$.
- Strongly dependent by the MSSM parameters $\mu$ and $M_2$ (the decay $A \rightarrow \chi\chi$ can become dominant). Better results are obtained for large values of $\mu$ and $M_2$.
- The main background comes from $tt$ pairs and $Zbb$.
- The main selection cuts require two opposite sign high $p_T$ isolated leptons and two high $E_T$ tagged $b$-jets.

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Neutral Higgs: $\Phi \rightarrow \chi\chi \rightarrow 4\ell + E_T^{\text{miss}}$

- The study is performed in three mSUGRA benchmark points in the low and intermediate region of $\tan\beta$.
- Very clean final state.
- SM background comes from ZZ, Zbb and tt. SUSY background comes from decay of squarks and gluinos in charginos and neutralinos, and from production of slepton and gaugino pairs.
- The study is done with the CMS fast simulation.
Charged Higgs: $H^\pm \rightarrow \tau^\pm \nu_\tau$ ($m_H < m_t$)

- The channel is $t\bar{t} \rightarrow H^\pm Wb\bar{b}$.
- The $BR(H^\pm \rightarrow \tau^\pm \nu_\tau)$ is 98%.
- The leptonic decay of the $W$ is chosen, while the $\tau$ decay to hadrons.
- The main background comes from $t\bar{t}$, $W^\pm + 3$ jets and $Wt$ events.

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Charged Higgs: $H^\pm \rightarrow \tau^\pm \nu_\tau \ (m_H > m_t)$

- Produced with $gg \rightarrow tbH^\pm$.
- The final state is quite clean and almost background free.
- The tau helicity correlations favouring the $H^\pm \rightarrow \tau^\pm \nu_\tau$ decay over the $W^\pm \rightarrow \tau^\pm \nu_\tau$ decay.
- The main background comes from $tt$, $Wt$, $W+3$jets and QCD multi-jet events.
- After the selection cuts the transverse mass $(\tau$-jet; $E_T^{miss})$ is reconstructed:

$$m_T = \sqrt{2 \times E_T^{jet} \times E_T^{miss} \times (1 - \Delta \phi(\tau jet, E_T^{miss}))}$$

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Charged Higgs: $H^\pm \rightarrow tb$ ($m_H > m_t$)

- For $m_H > m_t$ the BR($H^\pm \rightarrow tb$) becomes dominant.
- Two channels:
  - $gb \rightarrow tH^\pm \rightarrow ttb \rightarrow W^+W^- bbb \rightarrow qq'\mu\nu\mu bbb$ (Fast simulation)
  - $gg \rightarrow tH^+b \rightarrow ttbb \rightarrow W^+W^- bbbb \rightarrow qq'\mu\nu\mu bbbb$ (Full simulation)
- Presence of an isolated muon and high branching fraction (~30%).
- Main background comes from $tt +$ jets production.
- Large background remains after all selection cuts:
  - The effect of systematic uncertainty on the knowledge of the background is important
- No visibility for this channel during the low luminosity phase at LHC.

![Graphs showing $\tan \beta$ vs. $m_A$ for $gb \rightarrow tH^\pm$ and $gg \rightarrow tH^+b$.](image)
Summary of discovery contour plot

CMS, 30 fb$^{-1}$

pp → tbH$^\pm$, H$^\pm$ → τν,$\nu$

m$_t$ = 175 GeV/c$^2$

CMS, 30 fb$^{-1}$

pp → bb$\phi$, $\phi$ = h,H,A

m$_h^{\text{max}}$ scenario

M$_{\text{SUSY}}$ = 1 TeV/c$^2$

M$_2$ = 200 GeV/c$^2$

μ = 200 GeV/c$^2$

m$_{\text{gluino}}$ = 800 GeV/c$^2$

Stop mix: $X_t = 2 M_{\text{SUSY}}$

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Summary of discovery contour plot

- Discovery plot for MSSM h Higgs bosons from rescaling of SM Higgs boson study in the channels $h \rightarrow \gamma\gamma$ and $qqh$. 

![Summary of discovery contour plot](image)
Conclusions

Many channels have been studied to estimate the discovery potential of MSSM Higgs bosons at CMS.

Neutral Higgs bosons:
- $H \rightarrow \tau\tau$: 4 analysis studied. Good discovery region in the $M_A$-tan$\beta$ plane.
- $H \rightarrow \mu\mu$: it is possible to measure MSSM parameters.
- $H \rightarrow bb$: cross-check for the Higgs discovery.
- $A \rightarrow Zh$: low tan$\beta$ study.
- $H \rightarrow \chi\chi$: mSUGRA study.

Charged Higgs bosons:
- $H^\pm \rightarrow \tau^\pm\nu_\tau$: two different studies depending on $m_{H^\pm}$. Good discovery region in the $M_A$-tan$\beta$ plane.
- $H^\pm \rightarrow tb$: no visibility for this channel during the low luminosity fase at LHC.

Studies have been performed on SM processes to better understand MSSM processes.
Backup slides
$\Phi \rightarrow \tau \tau \rightarrow e + \text{jet}: \text{systematics}$

- 3% error on jet energy scale.
- 10% error on MET scale.
- 5% b-tag efficiency (from tt events).
- 2% electron identification.
- 5.6% of theoretical uncertainty of tt background.
- 1% of theoretical uncertainty of $Z/\gamma^*$ background.
- 14.2% of theoretical uncertainty of $Z/\gamma^*bb$ background.
- 3% luminosity uncertainty.
LEP limits
**Tevatron limits**

- MSSM H-$\rightarrow$ττ Search.
- CDF Run II 310 fb$^{-1}$, preliminary

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