Searches for extended Higgs sectors with the CMS experiment

Luca Pernié

On behalf of the CMS Collaboration

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Outline

❖ A 125 GeV Higgs-like boson has been discovered:
  → End or beginning of new discoveries?
  → Extending the Higgs-sector:
    → MSSM, NMSSM, 2HDM…

❖ The Compact Muon Solenoid (CMS)

❖ CMS searches on the extended-Higgs sector (just a glimpse of few CMS results):
  → Heavy Higgs searches
  → Light Higgs searches

❖ Outlooks

Extended H-sector ?
SM-like H
Extending the Higgs sector

- Higgs-like particle has been observed:
  - \( m_H = 125.09 \pm 0.21 \text{(stat)} \pm 0.11 \text{(syst)} \)
  - \( \Gamma_H < 26 \text{ MeV (for } f_{\Lambda Q}=0 \text{ at the } 95\% \text{ CL.)} \)
  - \( J^{PC} = 0^{++} \)
  - \( \text{(https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG)} \)

- No SUSY has been discovered so far, but:
  - Still good to focus in naturalness
  - General interest on sparticles with influence on quadratic term in Higgs potential
  - See if newly found resonance is part of an extended Higgs sector is of primary importance!

- Higgs sector could result extended in many ways:
  - MSSM (tension with current 125 GeV Higgs)
  - NMSSM (add. superfield S singlet under the SM gauge)
  - 2HDM (particularly simple extension of the SM)
The Large Hadron Collider

- Run 2 is officially started!
  → About 3 fb\(^{-1}\) collected in 2015
  → 30 fb\(^{-1}\) by the end of 2016

- Comparison with 8 TeV:
  - 160% larger collision energy → \(\sqrt{s}=13\) TeV
  - 200% larger number of bunches → 2800 bunches
  - 200% larger pileup → 40 interactions/crossing
  - 33% smaller \(\beta^*\) → 40 cm
  - 170-220% larger peak Lumi. → (13-17)\(\times10^{33}\) cm\(^{-2}\)s\(^{-1}\)

- Comparison with 8 TeV:
  - Recorded @ 3.8 T = 2.8 fb\(^{-1}\)
    - Good for all: 2.2 fb\(^{-1}\)
    - Good for many*: 2.6 fb\(^{-1}\)
    - Good for muons: 2.7 fb\(^{-1}\)

  * \(|\eta| < 3.0\) for jets and MET

Preliminary luminosity uncertainty:
4.8% @ 50 ns
4.6% @ 25 ns

Data included from 2015-06-03 08:41 to 2015-11-03 06:25 UTC
The Compact Muon Solenoid

- **Total weight**: 14000 t
- **Diameter**: 15 m
- **Length**: 28.7 m

**Pixels & Tracker**
- Pixels (100x150 μm²)
  - ~1 m² ~66M ch
- Si Strips (80-180 μm)
  - ~200 m² ~9.6M ch

**MUON BARREL**
- 250 Drift Tubes (DT)
- 480 Resistive Plate Chambers (RPC)

**ECAL**
- 76k scintillating PbWO₄ crystals

**HCAL**

**MUON ENDCAPS**
- 473 Cathode Strip Chambers (CSC)
- 432 Resistive Plate Chambers (RPC)

**IRON YOKE**

**Preshower (Si Strips)**

η = ln(tg(θ/2))

X-axis (LHC center)

Y-axis

Z-axis (beam)

φ (trans. plane)
Heavy Higgs searches
Heavy Higgs searches in Run 1

❖ Several analysis considered:
  → $H \rightarrow WW/ZZ$ (145$<m<1000$ GeV), 55 event categories in $WW(2l2\nu)$, $WW(2l2q)$, $ZZ(4l)$, $ZZ(2l2\nu)$, $ZZ(2l2q)$.
  → $A/H/h \rightarrow \tau\tau$ (90$<m<1000$ GeV), sensitive variable is $m_{\tau\tau}$.
  $(\tau\mu\tau\mu, \tau\tau\tau\tau, \tau\tau\tau\tau, \tau\tau\tau\tau, \tau\tau\tau\tau)$ and $\rightarrow \mu\mu$ (115$<m<300$ GeV).
  → $H^{\pm} \rightarrow \tau\nu$-$tb$ ($\tau\nu$ dominates sensitivity). Divided in low and high mass region.
  → $A/H \rightarrow bb$ (100$<m<900$ GeV). Prod. in assoc. with b-jets.
    Discr. variable: invariant mass of the 2 leading b-jets.
  → $A \rightarrow ZH$ (140$<m<1000$ GeV). Z goes into leptons, H into b-quarks or $\tau$.

❖ Two ways to obtain limits:
  → Templates for the full signal prediction for each value in the exclusion plane of the considered scenario.
    ($m_A$-$\tan\beta$ for MSSM; $m_H$-$\tan\beta$ for 2HDM)
  → 95% CL limits on $\sigma \cdot Br$ of a single, narrow-width resonance (except for $H \rightarrow WW/ZZ$ analysis).
    Limits translated into the exclusion plane.

**Signal:**
- \( H \to ZZ \to 4l \) (\( l = e, \mu \))
  - Analysis measures both SM-H and limits on additional resonances
  - Significance for SM-H: 2.5σ

**Backgrounds:**
- \( ZZ \) (irreducible): estimated by simulation
- \( Z+\)jets, \( tt, Z\gamma +\)jets, \( WW+\)jets, \( WZ +\)jets (reducible): estimated by two independent control regions

**SM-H and bkg. treated as one process in gg-fusion:**
- \( P(m_{4l}, m_X, \Gamma_X, \sigma_X) \) for the \( gg \to bkg + H(125)^* + X(m_X) \to 4l \)
  - Allows inclusion of interference, including off-shell tail of \( H(125) \)
  - Limits at the 95% CL on \( \sigma \cdot Br \) for several values of \( \Gamma_X \)

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Low mass $H \rightarrow \gamma\gamma$

- **Signal:**
  - A new resonance decaying into two photons in 80-100 GeV range (in NMSSM or 2HDM a lighter Higgs is expected, if $h_2$ is the observed one)

- **Selection:** $p_{T1}/m(\gamma\gamma) > 28/80$; $p_{T2}/m(\gamma\gamma) > 20/80$

- **Main background:**
  - Irreducible direct di-photon production
  - Reducible $\gamma/Z +$ jets

- **4 classes depending on $\eta$ and $R_9$ variables**

- **Results:**
  - No excess has been found in the 80-110 GeV mass range.
  - 95% C.L. upper limit has been set on the $\sigma \cdot B.R.$


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Light Higgs searches
H(125) → aa → μμbb

- **Signal:**
  - SM Higgs decaying to 2 light bosons a (foreseen by in NMSSM or 2HDM)
  - Only the gluon fusion production mechanism considered
  - Here: m(a) ~ [25,65] GeV

- **Selection:**
  - 2 muons with $p_T > 24$ and 9 GeV
  - 2 jets with $p_T > 15$ GeV (b-tagged)
  - $|m(μμbb)-125| < 25$ GeV

- **Main background:**
  - Z + jets, tt

- **Sensitivity extracted using a fit to m(μμ) distribution:**
  - Limits on the production rate times B.R.

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**Signal:**
- SM Higgs decaying to 2 light pseudoscalar bosons (foreseen by 2HDM or 2HDM+S)
- $m(a) \sim [20, 63]$ GeV
- Considering: $\mu\mu\tau_\mu\tau_h$, $\mu\mu\tau_\mu\tau_e$, $\mu\mu\tau_e\tau_e$, $\mu\mu\tau_h\tau_h$ ($\mu\mu\tau_\mu\tau_\mu$: ambiguities in pairing muons)

**Selection:**
- Two $\mu$ with $p_T > 18/9$ GeV
- $p_T > 5, 7, 15$ GeV for $\tau_\mu$, $\tau_e$ and $\tau_h$
- $|m(\mu\mu\tau\tau) - 125| < 25$ GeV
- $|m(\mu\mu) - m(\tau\tau)| < 0.8 m(\mu\mu)$

**Main background:**
- Irreducible ZZ production
- Reducible processes with at least one jet misidentified (Z+jets and WZ+jets).

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**Figure 4:** Background and signal ($m(a) = 40$ GeV) models, scaled to their expected yields, in the $\mu\mu\tau\tau$ (top left), $\mu\mu\tau_\mu\tau_\mu$ (top right), $\mu\mu\tau_\mu\tau_e$ (center left), $\mu\mu\tau_\mu\tau_h$ (center right), and $\mu\mu\tau_\mu\tau_h$ (bottom left) final states, and their combination (bottom right). The two components that form the background model, ZZ and reducible processes, are drawn. Every observed event in the individual decay channels is represented by an arrow, together with its measured $m(\mu\mu)$ value; while in the combined mass plot data are binned in a histogram. The signal samples are scaled with $B(h \rightarrow a a) = 10\%$ and considering decays of the pseudoscalar $a$ boson to leptons only. The results are shown after a simultaneous maximum likelihood fit that takes into account the systematic uncertainties described in Chapter 6.
Upper limits on $h \rightarrow aa$ production relative to the SM $h$ production, scaled by $B(a \rightarrow \tau \tau)^2$

- Data comparable with background-only hypothesis (No excess exceed $2\sigma$ glob. significance)
- Set 95% C.L. upper limits on signal event rate
- Limits in the context of 2 HDM+S models

$$\frac{\Gamma(a \rightarrow \mu \mu)}{\Gamma(a \rightarrow \tau \tau)} = \frac{m_\mu^2 \sqrt{1 - (2m_\mu/m_a)^2}}{m_\tau^2 \sqrt{1 - (2m_\tau/m_a)^2}}$$
$H(125) \rightarrow aa \rightarrow \tau\tau\tau\tau$

- **Signal:**
  - SM-Higgs decaying into 2 light bosons $\Phi_1 (=a_1,h_1)$ (foreseen by NMSSM)
  - SM-H corresponds to:
    - $h_2$ and decays into $h_2 \rightarrow 2h_1$
    - $h_2$ and decays into $h_2 \rightarrow 2a_1$ ($2m_\tau < m(a_1) < 2m_b$)
    - $h_1$ and decays into $h_1 \rightarrow 2a_1$

- **Selection:**
  - One $\tau$ goes to $\mu$ and other to one-prong mode
  - Two same sign $\mu$ with $p_\tau > 17/10$ GeV and $|\eta| < 2.1$
  - One opp. sign track with $p_\tau > 2.5$ GeV and $|\eta| < 2.4$

- **Main background:** QCD multijet events

- **95% C.L. upper limit set on the production rate of signal events**

Search for $H \rightarrow aa \rightarrow \mu\mu\mu\mu$

- **Signal:**
  - Pair production of new light bosons, each decaying into a pair of muons

- **Selection:**
  - $P_{T1} > 17$ GeV; $|\eta_1| < 0.9$; $P_{T2,3,4} > 8$ GeV
  - $|z_{1\mu\mu} - z_{2\mu\mu}| < 1$ mm

- **Main background:**
  - $b\bar{b}$, double J/$\Psi$ (SPS and DPS)

- **Excess searched on the diagonal:**
  - $|m_{1\mu\mu} - m_{2\mu\mu}| < 0.13$ GeV + $0.065(m_{1\mu\mu} + m_{2\mu\mu})/2$
  - Model independent search,
  - benchmark model is NMSSM
  - Assume SM-like production $\sigma$ for $h_{1,2}$
    to simplify interpretation

Search for $H \rightarrow aa \rightarrow \mu\mu\mu\mu$

- Additional Benchmark: Dark SUSY
  \[ h \rightarrow n_1n_1 \rightarrow n_Dn_D\gamma_D\gamma_D + X \]
  - Dark photons could have an appreciable life-time before decay
  - Dark photons are generated with $m(\gamma)$ in the range 0.25–2.0 GeV and a decay length in the range of 0–20 mm

- 95% CL limit on H boson production $\sigma \cdot B.R.$
  - The limit set in the [$m(\gamma_D),\varepsilon$] plane.
  - Implies model dependence when comparing to low energy results
  - Nice complementarity with ATLAS analysis searching for decays far from the interaction point

Conclusions

- Studies on the Higgs sector are moving towards the era of precision measurements:
  - Kinematic
  - Properties
  - Production cross-sections

- So far the 13 TeV data are consistent with 7 and 8 TeV data

- Just few examples of searches for extended Higgs sector have been presented:
  - Combination is in progress

- Exciting news foreseen during this year:
  - Expected 30 fb\(^{-1}\) by the end of the 2016
Backup
The Compact Muon Solenoid

Key:
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

Transverse slice through CMS

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers
Heavy Higgs searches in Run 1

2HDM Type II, $\cos(\beta-\alpha)=0.1$, $m_A = m_H = 100$ GeV

- Observed exclusion 95% CL
- Expected exclusion 95% CL
- $h(125)$ (HIG-15-002)
- $H \rightarrow WW/ZZ$ (arXiv:1504.00936)
- $A/H \rightarrow \tau\tau$ (HIG-14-029)
- $A \rightarrow ZH \rightarrow \ell\ell\tau\tau$ (arXiv:1603.02991)
- $A \rightarrow ZH \rightarrow llbb$ (arXiv:1603.02991)
- Non-perturbative region

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