Higgs Properties and Tests of the Standard Model @ CMS

A. Zghiche

CEA/IRFU - Saclay

On behalf of the CMS collaboration
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Higgs Properties

• Post Higgs discovery question: Is it the SM Higgs boson?
  – What is expected for the SM Higgs boson?
    * Spin Zero
    * Charge Zero
    * Parity Plus
    * Couplings to fermions and bosons fixed by SM
    * Mass not predicted by SM
    * Once the mass is measured, everything else can be well predicted: Width, Production Cross-sections and Decay Branching Fractions

• Progress on the measurement of all these properties and SM test.
The SM Higgs Production Cross Sections and Decays

by LHCHXSWG, and arXiv:1307.1347

Production Cross sections are calculated in the SM where QCD corrections are important

Higgs Production Processes

Cross Sections and Br. are very sensitive:
- to the production process,
- and to the Higgs mass value.

Where to look? which mass? which decay?

The choice of reconstructed decay channels made according to the detectors’ resolutions, and to signal over background ratios:
\[ \Rightarrow H \rightarrow \gamma\gamma \text{ and } H \rightarrow ZZ \]
The Higgs Mass (CMS)

Need to look for narrow resonances over smooth backgrounds in the invariant mass distributions.

Two channels with very good mass resolution are used to determine the Higgs boson mass: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$

$$m_H = 124.70 \pm 0.31{}^{(\text{stat})} \pm 0.15{}^{(\text{syst})} \text{ GeV}$$

$\rightarrow$ 0.28% uncertainty

$H \rightarrow ZZ \rightarrow 4l(4\mu, 2e2\mu, 4e)$

- Full kinematics info. used to reduce bkgs.
- Isolated leptons, $p_T^{\ell} > 7 \text{ GeV}$, $p_T^{\mu} > 5 \text{ GeV}$
- 3D Likelihood used for mass measurement
- Signal and background modeled by MC+data

$$m_H = 125.6 \pm 0.4{}^{(\text{stat})} \pm 0.2{}^{(\text{syst})} \text{ GeV}$$

$\rightarrow$ 0.36% uncertainty

Amina Zghiche
CEA/IRFU-Saclay(FR)
The mass measurements with $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ data, are combined assuming a single state. The $m_H$ is extracted from the test statistic scan, where the production and decay ratios are left free.

\[ m_H = 125.02^{+0.26}_{-0.27} \text{(stat)}^{+0.14}_{-0.15} \text{(syst.)} \text{ GeV} \to 0.25\% \text{ uncertainty} \]
Combined Measurement of the Mass (CMS+ATLAS)

Combination of ATLAS and CMS mass measurements with $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ data. The results are obtained from a simultaneous fit to the reconstructed invariant mass peaks in both channels and for both experiments. 


$m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst.}) \text{ GeV} \rightarrow 0.19\% \text{ uncertainty}$
The Higgs Width Limit (CMS)

The Higgs width limit measurements with $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ data. The results are obtained from a scan of a profile likelihood to set an upper limit on $\Gamma_H$.

**Direct measurement with:**

$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ data

- $\Gamma_{H_{SM}} \sim 4.07\text{MeV}$
- $\Gamma_{H}^Z \rightarrow 4l \leq 3.4\text{GeV}$
- $\Gamma_{H}^H \gamma \leq 2.4\text{GeV}$
- $\Gamma_{H_{Combined}} \leq 1.7\text{GeV}$

Upper limits far from SM pred.

**Off-shell measurement with:**

$H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow ZZ \rightarrow 212
$

$\Gamma_{H} < 22\text{MeV}@95\%CL(<5.4\text{SM})$

**Dominant Bkgs. for $H \rightarrow ZZ$**

- $q \rightarrow qZ$
- $q \rightarrow qZ$
- $q \rightarrow qZ$

**Off-shell+anomalous couplings in $H \rightarrow ZZ \rightarrow 4l$**

- Limits depend on $f_{\Lambda Q}$
- $f_{\Lambda Q}=0., \Gamma_{H} < 26.\text{MeV}@95\%CL$
- $f_{\Lambda Q}=\text{unc.}, \Gamma_{H} < 46.\text{MeV}@95\%CL$
- $\tau_{H} < 1.9 \times 10^{-13}s@95\%CL$

$\sim 10^6 SM_{pred.}$
Inclusive and differential fiducial cross sections of $H \to 4l$

- Inclusive NNLL+NNLO $H \to 4l$ fiducial theory cross section compared to data
- $gg \to H$ contribution is modeled at the parton level using HRes, corrected using POWHEG+JHUgen and Pythia 6.4
- Differential $H \to 4l$ fiducial cross section
  - for Higgs transverse momentum $p_T^H$
  - for Rapidity $|Y^H|$
  - for Jet transverse momentum $p_T^{Jet}$

$$\sigma^{Fid.}_{7\text{GeV}} = 0.562^{+0.67}_{-0.44}(\text{stat})^{+0.21}_{-0.06}(\text{syst.}) \text{ fb}$$

$$\sigma^{Fid.}_{8\text{GeV}} = 1.11^{+0.41}_{-0.35}(\text{stat})^{+0.14}_{-0.10}(\text{syst.}) \text{ fb}$$

Amina Zghiche
CEA/IRFU-Saclay (FR)
The Signal Strength $\mu = \sigma / \sigma_{SM}$

$\mu = 1.00 \pm 0.09^{\text{stat}} \pm 0.08^{\text{theory}} \pm 0.07^{\text{syst}}$

Amina Zghiche
CEA/IRFU-Saclay (FR)
Boson, Fermion Mediated Production Processes

$$\frac{\mu_{VBF, VH}}{\mu_{ggH, ttH}} = 1.25^{+0.62}_{-0.44}$$
Custodial Symmetry: $\kappa_Z = \kappa_W$ test

Scaling factors $\kappa_i$ are defined to test deviations from the SM: $\kappa^2_{PC} = \frac{\sigma_{PC}}{\sigma_{SM}}$, $\kappa^2_{DC} = \frac{\Gamma_{DC}}{\Gamma_{SM}}$, PC and DC are production and decay channel, respectively.

$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.94^{+0.22}_{-0.18}$ assuming the SM couplings to fermions $\kappa_f = 1$.

$\lambda_{WZ} = 0.92^{+0.14}_{-0.12}$ profiling the coupling to fermions.
Higgs Coupling Tests

Vector boson/fermion couplings

\[ \kappa_V = \kappa_W = \kappa_Z \]

\[ \kappa_f = \kappa_t = \kappa_b = \kappa_\tau \]

Asymmetries of fermion couplings

\[ \lambda_{du} = \frac{\kappa_d}{\kappa_u} \]

\[ \lambda_{lq} = \frac{\kappa_l}{\kappa_q} \]
Higgs Coupling Tests

\[ \kappa_f = v \frac{m_f}{M^{1+\epsilon}} \]

\[ \kappa_V = v \frac{m_V^{2+\epsilon}}{M^{1+2\epsilon}} \]

\[ \lambda_f = \kappa_f \frac{m_f}{v} \]

\[ g_V = \kappa_V \frac{2m_V^2}{v} \]

\[ v = 246.2 \text{ GeV} \]
Spin-Parity

Search for correlations in the kinematic distributions of production and decay, indication of a non-zero spin, using $H \rightarrow WW, ZZ, \gamma\gamma$ for spin-parity study

- $H \rightarrow ZZ \rightarrow 4l$
  - the 4l system is fully reconstructed (8 obs.)
  - use of the Matrix Element Likelihood Approach

- $H \rightarrow WW \rightarrow l\nu l\nu$
  - Two observables sensitive to $J^P$: $M_{ll}, M_T$

- $H \rightarrow \gamma\gamma$
  - $J=1$ forbidden
  - $\cos\theta^*$ is the only variable sensitive to $J^P \ @LO$

Amina Zghiche
CEA/IRFU-Saclay(FR)
Higgs Spin-Parity

\[ q = -2 \ln \frac{L(data|J^P+bkg)}{L(data|H+bkg)} \]

- Pure \( J^P = 0^-, 1^+, 1^- \) exclu.\@99.9%CL
- Ten \( J^P = 2 \) models exclu.\@99.9%CL
- Data compatible with 0\(^+\) within 1\(\sigma\)
- \((0^-,0^+)\) mixing to be constrained
Rare Higgs Decays

Search for the $H \rightarrow \mu\mu$ and $H \rightarrow ee$ fermionic decays in the $[120, 150]$ GeV mass range

$H \rightarrow \mu\mu$

- $B_{SM}(H \rightarrow \mu\mu) = 2.2 \times 10^{-4}$
- $\sigma \times B_{SM}(H \rightarrow \mu\mu) < 0.033 pb$
- $B(H \rightarrow \mu\mu) < 0.0016$
- $B(H \rightarrow \mu\mu) < 7.40(6.5^{+2.8}_{-1.9})_{\text{exp.}} \times B_{SM}$
- $\mu = 0.8^{+3.5}_{-3.4}$

$H \rightarrow ee$

- $B_{SM}(H \rightarrow ee) = 5.0 \times 10^{-9}$
- $\sigma \times B_{SM}(H \rightarrow ee) < 0.041 pb$
- $B(H \rightarrow ee) < 0.0019 \sim 3.7 \times 10^{5} B_{SM}$

Amina Zghiche
CEA/IRFU-Saclay(FR)
Rare Higgs Decays

**Search for the** $H \rightarrow \gamma^* \gamma \rightarrow ll\gamma$ **in the** $[120,150]$ **GeV mass range**

- $m_{ll\gamma}$ distributions for $ee$ and $\mu\mu$
- $m_{ll} < 20$GeV
- no excess $120 < m_{ll\gamma} < 150$GeV
- $B(H \rightarrow \gamma^* \gamma \rightarrow ll\gamma) < 7.7(6.4^{+3.1}_{-2.0}) \times B_{SM}$
- $B(H \rightarrow J/\Psi \gamma \rightarrow ll\gamma) < 1.5 \times 10^{-3}$
- $B(H \rightarrow J/\Psi \gamma \rightarrow ll\gamma) < 540 \times SM_{pred.}$ with $2.9 < m_{ll} < 3.3$GeV
Direct search for the \( H \rightarrow \mu \tau_e \) and \( H \rightarrow \mu \tau_h \) in the [100,150] GeV mass range

- combined distribution of \( M(\mu \tau)_{col} \) showing a 2.4\( \sigma \) excess
- \( p_{value} = 0.010 @ 125 \text{ GeV} \)
- \( B_{BestFit}(H \rightarrow \mu \tau) = 0.84^{+0.39}_{-0.37}\% \)
- \( B(H \rightarrow \mu \tau) < 1.51(0.75 \pm 0.38)_{exp.}\% \)

- improved the limit on the Yukawa couplings by an order of magnitude, compared to indirect searches, excluding the light blue area
- \( Y_{\mu \tau} < 3.6 \times 10^{-3} \)
The Higgs Invisible Decays

EPJ C74(2014)2980, and Preliminary CMS-PAS-HIG-14-038

Combination of VBF and ZH with $H \rightarrow invisible$ and search for $H \rightarrow \gamma + invisible$

- Combined limits for VBF and ZH with $H \rightarrow invisible$ and $Z \rightarrow ll$ and $Z \rightarrow bb$
  - VBF: 57% (exp. 40%) (new – prel.)
  - VBF + ZH: 47% (exp. 35%) (new – prel.)

Possible re-interpretation in terms of limit on a DM candidate

- Search for $H \rightarrow \gamma + invisible$
  - Measurement consistent with BKG only hypothesis in the low-scale SUSY models

Amina Zghiche
CEA/IRFU-Saclay (FR)

arXiv:1507.00359
Summary

- All performed measurements confirm the H(125) boson as the SM Higgs particle.
- First LHC Higgs combined measurement: the Higgs mass
  \[ m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst.}) \text{ GeV} \rightarrow 0.19\% \text{ uncertainty} \]
  - precision dominated by statistical uncertainty.
- Width upper limit from Off-shell combined 4l and 2l2\nu: \[ \Gamma < 5.4 \times \Gamma_H^{SM} @95\%CL. \]
- 20 – 30\% uncertainties on signal strengths, but consistent with SM.
- No deviation from SM observed in fiducial \( H \rightarrow 4l \) cross sections.
- Pure alternative to \( 0^+, J^P \) spin parity hypotheses excluded at 99.9\%CL. \( (0^-,0^+) \) mixing subjet to further study.
- Established limits for Higgs rare decays.
- Most intriguing excess is in LFV decay (\( H \rightarrow \mu\tau \)) but not significant yet (2.4\sigma).
  Improved limit of the Yukawa coupling \( Y_{\mu\tau} \).
- No sign of invisible decay, but new limits for the DM candidate.
- No sign of low-scale SUSY particles in the \( H \rightarrow \gamma + \text{invisible} \) process.
- Searches for small deviations from the SM will continue @ LHC-RUNII.
**Backup**

**JHEP 01(2014)096**

$H \rightarrow WW$

$m_H = 125.5^{+3.6}_{-3.8}\, GeV$

**JHEP 05(2014)104**

$H \rightarrow \tau\tau$

$m_H = 122 \pm 7 GeV$
Scenario 1: systematic uncert. left unchanged
Scenario 2: theory uncert./2 and other syst. scaled by $\sqrt{\text{int.lumi}}$.  

ArXiv:1307.7135
New Combination results for RunI

![Graph showing combined results of ATLAS and CMS for RunI, with shaded regions for SM, CMS, and combined ATLAS+CMS, along with 68% and 95% confidence levels.](image)