SM Higgs searches: CMS

Javier Cuevas (U. Oviedo) on behalf of the CMS Collaboration
Outline

• Observation of a new state with mass of $125.3^{+0.6}_{-0.6}$ GeV
  – $5.0 \sigma$ excess observed, $5.8 \sigma$ expected.
  – Consistent with SM prediction
    • More data and more studies needed to draw final conclusions

• The CMS experiment at LHC and data taking in 2012

• **SM Higgs boson search**
  – Decay modes with high mass resolution
  – Decay modes with low mass resolution

• Results and combination of the searches

• Conclusions
CMS: a simple and elegant concept

Fast detectors: 25-50ns bunch crossing
High granularity: 20-40 overlapping complex events
High radiation resistance: >10 years of operation

$\sigma(p_T)/p_T \sim 15\%$ at 1TeV

Neutrinos measured through missing transverse energy ($E_T^{\text{miss}}$) in calorimeters.

$\sigma(E)/E \sim 3\%/\sqrt{E} \text{ [GeV]} \oplus 0.3\%$

$\sigma(E_T)/E_T \sim 100\%/\sqrt{E_T} \text{ [GeV]} \oplus 5\%$

$\sigma(p_T)/p_T \sim 1\%$ at 100GeV
$\sigma(p_T)/p_T \sim 10\%$ at 1 TeV
The CMS Detector

Total weight: 14000 t
Overall diameter: 15 m
Overall length: 28.7 m

**ECAL**
- 76k scintillating PbWO₄ crystals
- Scintillator/brass Interleaved ~7k ch

**HCAL**
- Pixels (100x150 $\mu m^2$) ~1 m² ~66M ch
- Si Strips (80-180 $\mu m$) ~200 m² ~9.6M ch

**Solenoid**
- 3.8T Solenoid

**Tracker**
- Pixels & Tracker

**Muon Barrel**
- 250 Drift Tubes (DT) and 480 Resistive Plate Chambers (RPC)

**Iron Yoke**
- 473 Cathode Strip Chambers (CSC)
- 432 Resistive Plate Chambers (RPC)

**Preshower**
- Si Strips ~16 m² ~137k ch

**Forward Cal**
- Steel + quartz Fibers ~2k ch

**Endcaps**
- 473 Cathode Strip Chambers (CSC)
- 432 Resistive Plate Chambers (RPC)
The CMS detector

3.8T Superconducting Solenoid

Hermetic (|\eta|<5.2) Hadron Calorimeter (HCAL) [scintillators & brass]

Lead tungstate E/M Calorimeter (ECAL)

All silicon tracker (Pixels- Microstrips)

Redundant Muon System (RPCs, Drift Tubes, Cathode Strip Chambers)
41 Countries and 179 institutes ~3000 Authors including ~2200 PhD’s and ~800 PhD students
Detector operations in 2010-11-12

Excellent performance over the three years. Data taking efficiency always higher than 91%.

- **2010**: $\varepsilon > 92\%$
- **2011**: $\varepsilon > 91\%$
- **2012**: $\varepsilon > 93.5\%$

Record efficiency achieved in 2012 despite the most challenging condition: Instantaneous luminosity higher than $7.5 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$.

Typical yields of physics quality data: 90-95% of the recorded data.
LHC: going strong

CMS Integrated Luminosity, pp, 2012, $\sqrt{s} = 8$ TeV
Data included from 2012-04-04 22:37 to 2012-10-23 17:21 UTC

- LHC Delivered: 17.90 fb$^{-1}$
- CMS Recorded: 16.68 fb$^{-1}$

CMS Peak Luminosity Per Day, pp, 2012, $\sqrt{s} = 8$ TeV
Data included from 2012-04-04 22:37 to 2012-10-23 06:27 UTC

Max. inst. lumi.: 7.54 Hz/nb
Record lumi: 7.5 Hz/cm$^2$
The challenge of 2012: 8 TeV and high pile-up.

Event from special high pu run: 78 reconstructed vertices and 2 muons...
The challenge of 2012: 8 TeV and high pile-up.
Particle Flow (global event description)

• Rely on high granularity of CMS detector to identify and reconstruct each individual particle in the event in an optimal way.

• Allows tagging of charged particles from pile-up: minimize impact of PU on jet reconstruction, and lepton or photon isolation.
  – Charged particles well separated in large tracker volume and 3.8 T magnetic field
  – Excellent tracking, able to go down to very low momenta (~100 MeV)
  – Granular electromagnetic calorimeter with excellent energy resolution
  – In multi-jet events, only 10% of the energy goes to neutral (stable) hadrons (~60% charged, ~30% neutral electromagnetic)
Electron/photon reconstruction and identification

- **Cluster reconstruction in ECAL** Common for both electrons & photons. Designed to collect bremsstrahlung and conversions in an extended phi region. Energy spread in $\phi$ due to brems ($E_T>4$ GeV)

- **Dedicated track reconstruction for electrons** Gaussian Sum Filter allows for tracks with large curvature due to brems and enables hit collection up to ECAL; ECAL-seeded reconstruction complemented by a tracker-seeded reconstruction to gain efficiency at low $p_T$

- **Energy scale and resolution**
  - Extensive control at the $Z$ peak (and at the $J/\psi \rightarrow ee$ for low $p_T$ electrons)
Electron reconstruction and identification

- Multivariate electron identification in 2012
  - ECAL, tracker, ECAL-tracker-HCAL matching and impact parameter (IP) observables
- Background from data samples
  - W+jet for training
  - Z+jet for testing
- Performance
  - 30% efficiency improvement in H- >ZZ- >4e wrt cut based ID
- Efficiencies
  - Via tag-and-probe at the Z- >ee peak
Photon Energy Corrections, Scale and Resolution

- ECAL cluster energies corrected using a MC trained multivariate regression
  - Improves resolution and restores flat response of energy scale versus pileup
  - Inputs: Raw cluster energies and positions, lateral and longitudinal shower shape variables, local shower positions w.r.t. crystal geometry, pileup estimators
- Regression also used to provide a per photon energy resolution estimate
- **Energy Scale and resolution:** use $Z \rightarrow e^+e^-$

![Graph 1: Non converted photons in the barrel $|\eta|<1$](image1.png)

![Graph 2: Effect of the regression on the $Z \rightarrow e^+e^-$ peak](image2.png)

PPC 2012 - KIAS - Nov 5th

Javier Cuevas, University of Oviedo
Progress in ECAL calibration

For the golden categories, both photons in the barrel and no conversions:
FWHM/2.35=1.04 GeV (0.87%) approaching the nominal value.
Still room for improvement.
Muon reconstruction and identification

- PF Muon Identification in 2012
  - Exploit information from all subdetectors
- High efficiency >96% for $p_T=5$ GeV; >99% for $p_T=10$ GeV;
  - Exploit also tracker-based muon ID
  - Important for $H\rightarrow ZZ\rightarrow 4l$
  - Efficiency controlled in data with $J/\Psi$ and $Z$ T&P

Tighter quality criteria applied in some analyses to further suppress reducible backgrounds
Particle-based isolation

- Created by summing energy deposits from individual particles in DR=0.4 cone around the lepton
  - Avoids double counting of the energy deposit in the calorimeters from charged particles
- Pile-up contribution:
  - Negligible for charged hadrons from vertex
  - Neutral contribution corrected using the average energy density, $\rho$ from the pile-up and underlying event.

Isolation Efficiency is stable in high PU environment (important for higher lumi runs in the future!)

Det Based vs PF Based
Jet Identification

Typical regular jet

Typical Pileup jet

Important in VBF searches.

- Pileup jets structure differs wrt regular jets:
  - Pileup jets originate from several overlapping jets which merge together
  - Likelihood grows rapidly with high pileup
  - Discriminant exploits shape and tracking variables
    - Discrimination both inside and outside tracker acceptance

Validation on data: jet counting in $Z \rightarrow \mu\mu$ events vs vertex multiplicity.
Stable to <1% for jet $p_T > 20$ GeV
Jet Energy Correction Uncertainties

- The contribution of different uncertainty sources depends on $p_T$ and $\eta$.
- Total uncertainty of the jet energy scale is close to 1% for $|\eta| < 2.4$. 
- MET resolution for different $N_{PV}$ is fitted with:

$$\sigma_{\text{tot}} = \sqrt{c^2 + \frac{N_{PV}}{0.7} \cdot \sigma_{PU}}$$

- the fit yields:
  - $c$: average resolution without PU
  - $\sigma_{PU}$: degradation in resolution caused by PU

- improved resolution in 2012 for fixed $N_{PV}$
  - improved ECAL/HCAL energy reconstruction
    - reduces out-of-time pileup effects
  - MET pile-up corrections applied
- pile-up introduces an additional smearing of $\sim 3$ GeV on MET resolution $\sigma_{PU}$ (in quadrature)
**Tau Identification**

- **Tau identification:**
  - Searches for major $\tau$ decay modes within PF jets. Mainly $\tau$ decaying to 1 or 3 charged hadrons.
  - Photons/Electrons clustered in strips to reconstruct $\pi^0$
  - Discriminating variables computed on reconstructed $\tau$ object.

- **Tau isolation:** Multivariate discriminator using sum of energy deposits in dR rings around the $\tau$.

70% efficiency with 5% fake!

$\tau$'s in CMS have become “normal” leptons.
Top mass

CMS average: 172.6 ± 0.4 ± 1.2 GeV

Lepton+jets:
CMS-PAS-TOP-11-015

Dilepton:
CMS-PAS-TOP-11-016

μ+Jets analysis
CMS-PAS-TOP-11-015

~1.3 (syst) GeV including color reconnection
Effect of the underlying event expected to be small
Excellent agreement with NLO (or approx. NNLO) predictions.

Key ingredients for Higgs hunting:

$$\sigma(pp) \rightarrow H+X$$ (for m_H = 125 GeV) = 17.5 pb

same order of magnitude of the diboson (WW, WZ, ZZ production).
Standard Model rare processes.

4-fermion $Z \rightarrow llll$ decays observed at a hadron collider! (BR = 4.4 $\cdot$ 10^{-6}), $\sigma \approx 125 \pm 26$ fb

$Z \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

800 $WW \rightarrow llll$ events observed in 2011, $\pm 10\%$ xsec precision. It constrains Higgs backgrounds and anomalous trilinear couplings.

CMS-PAS-SMP-12-009

CMS-PAS-SMP-12-005
Search for the SM Higgs Boson
Higgs Boson Production

- Dominant production mode: gluon-gluon fusion followed by Vector Boson Fusion (VBF)
- All production modes exploited (gg, VBF, VH, ttH)
  - Latter 3 have smaller $\sigma$ but better S/B in many cases

$\sqrt{s} = 8$ TeV

~25-30% higher $\sigma$ than at 7 TeV at low $m_H$
Higgs Decays

- Five important decay modes:
  - High mass: \(WW, ZZ\)
  - Low mass \(bb, \tau\tau, WW, ZZ, \gamma\gamma\)

- Low mass region really reach and challenging:
  - Main identifiable decay modes, \(bb\) and \(\tau\tau\) hard to identify in a huge background

- Two high resolution mass (~1%) decay modes: \(H \rightarrow \gamma\gamma\) and \(H \rightarrow ZZ \rightarrow 4l\)

- \(H \rightarrow ZZ \rightarrow 4l\) has in addition very low background

Many other channels also analyzed
## Search for the SM Higgs Boson

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110-150</td>
<td>5.1</td>
<td>5.3</td>
<td>incl. + VBF</td>
<td>☮</td>
<td>☮</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow tt$</td>
<td>110-145</td>
<td>4.9</td>
<td>5.0</td>
<td>0/1 jet + VBF + WH + ZH</td>
<td>☮</td>
<td>☮</td>
<td>☮</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>110-135</td>
<td>5.0</td>
<td>5.0</td>
<td>WH + ZH + ttH</td>
<td>-</td>
<td>-</td>
<td>☮</td>
<td>☮</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>110-600</td>
<td>5.1</td>
<td>5.3</td>
<td>inclusive</td>
<td>☮</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow 2l2\nu$</td>
<td>110-600</td>
<td>4.9</td>
<td>5.3</td>
<td>0/1 jet + VBF + WH + ZH</td>
<td>☮</td>
<td>☮</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 2l2\nu$</td>
<td>200-600</td>
<td>5.0</td>
<td>5.0</td>
<td>0/1 jet + VBF</td>
<td>☮</td>
<td>☮</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 2l2q$</td>
<td>130-600</td>
<td>4.9</td>
<td>-</td>
<td>0/1/2 b-tags</td>
<td>☮</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow lvqq$</td>
<td>240-600</td>
<td>4.9</td>
<td>5.1</td>
<td>inclusive</td>
<td>☮</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Javier Cuevas, University of Oviedo*
High mass resolution decay mode

\[ H \rightarrow \gamma\gamma \]

5 fb/1 at 7 TeV (2011) + 5 fb/1 at 8 TeV (2012)

\[
\begin{align*}
\text{p}_{T\gamma} &= 89.8 \text{ GeV} \\
\text{m}_{\gamma\gamma} &= 125.9 \text{ GeV}
\end{align*}
\]

\[ H \rightarrow \gamma\gamma \text{ candidate} \]
Search for a narrow peak in the diphoton mass spectrum with two isolated high ET photons on a smoothly falling background

- In barrel resolution ~ 1%

Analysis optimized categorizing events according to purity and mass resolution.

- Specific di-jet tag categories targeting VBF production mode.

Several complementary analysis:
Main analysis optimized using a MultiVariate technique to identify and classify events, cross-checked with (independent) cut based and mass sideband background MVA model
$H \rightarrow \gamma\gamma$

- **Analysis selection (MultiVariate Analysis MVA)**
  - Vertex ID
    - Input variables: $\Sigma p_T^2$ (tracks), $p_T$ balance wrt $\gamma\gamma$, conversions information
    - ID photons $p_{T1} > m_{\gamma\gamma}/3 \ p_{T2} > m_{\gamma\gamma}/4$
  - MVA Diphoton discriminant categories
    - High score
      - signal-like events
      - good $m_{\gamma\gamma}$ resolution
    - Designed to be $m_{\gamma\gamma}$ independent
    - Trained on signal and background MC
    - Input variables:
      - Kinematic variables: $p_T/ m_{\gamma\gamma}$, $\eta$, $\cos(\varphi_1 - \varphi_2)$
      - Photon ID MVA output for each photon
      - Per-event mass resolutions for the correct and incorrect choice of vertex
H → γγ: what’s new in 2012

• 2011 data reprocessed with new energy calibrations in ECAL to further improve the mass resolution.

• 2012 prompt reco. data: calibration stable vs time thanks to live light monitoring corrections.

E/p scale stable to 0.2%

Laser calibration: Automated 48-hour calib. loop.
H → γγ: what’s new in 2012

• 2011 data reprocessed with new energy calibrations in ECAL to further improve the mass resolution.
• 2012 prompt reco. data: calibration stable vs time thanks to live light monitoring corrections.
• Re-optimized photon selection using isolation based on Particle Flow reconstruction
• Split di-jet tag events in two categories with different purity (15% better sensitivity)
H → γγ: mass distributions

7 TeV (5 categories)

8 TeV (6 categories)

Di-Jet

loose
tight
**S/(S+B) weighted mass distribution**

- **S** and **B** are the number of signal and background events calculated from the simultaneous fit to all categories.
- Summed plot for illustration, results obtained with simultaneous ML fit to all categories.

H → γγ results

Excess of events observed for diphoton masses around 125 GeV, consistently in 7 and 8 TeV data

Local significance 4.1σ. Signal strength $1.6 \pm 0.4 \times \sigma_{\text{SMH}}$

Evidence for a new state
High mass resolution decay mode

$H \rightarrow ZZ \rightarrow 4l$

5 fb/1 at 7 TeV (2011) + 5 fb/1 at 8 TeV (2012)
$H \rightarrow ZZ \rightarrow 4l$

- **Golden channel**: clean experimental signature
  - Narrow resonance
  - Four (potentially low $p_T$) tightly identified and isolated leptons

- **Low level of background**: irreducible $ZZ^*$, reducible $Z$+jets, $t\bar{t}$bar with two leptons from b or light jets, $WZ$, estimated from data - 50% uncertainty: fake rate method applied from signal-free control samples, validation (data wrong flavours and charges)

- A great performing channel in the whole mass range, but extremely demanding in terms of selection efficiency down to the lowest $p_T\epsilon^4$
H → ZZ → 4l

**Improvements in 2012:**
- New lepton selection
- Recovery of photons from final state radiation
- Exploit angular information to discriminate signal from irreducible ZZ background
- ~20% gain in sensitivity with respect to the 2011 analysis
- Optimization done without looking at the data in the signal region.
Matrix Element Likelihood Analysis

2D analysis using $m_{4l}$ and MELA

$$MELA = \left[ 1 + \frac{P_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4l})}{P_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4l})} \right]^{-1}$$

PRD81,075022(2010), arXiv:1001.5300
H → ZZ → 4l results

- Localized excess of events observed around 126 GeV

![Diagram showing ZZ candidates with per-event mass uncertainties](image)
H $\rightarrow$ ZZ $\rightarrow$ 4l results

- Localized excess of events observed around 126 GeV and at signal-like values of the angular discriminator
H → ZZ → 4l results

- Localized excess of events observed around 126 GeV and at signal-like values of the angular discriminator
- Local significance $3.2\sigma$ (expected from SM H: $3.8\sigma$)

CMS Preliminary

- $\sqrt{s} = 7$ TeV, $L =$ 5.05 fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L =$ 5.26 fb$^{-1}$

Javier Cuevas, University of Oviedo
H → WW (2l 2ν, lν jj)

5 fb/1 at 7 TeV (2011) + 5 fb/1 at 8 TeV (2012)
H → WW

- **Dileptonic channel:**
  - 2011 analysis unchanged.
  - 2012 analysis with improvements in objects and methods to deal with the increase in pile-up.
  - Cut-based analysis for ICHEP.
  - Shape analysis in eμ

- **Semi-leptonic channel,** new after Moriond’12, for Higgs boson masses above 170 GeV.
H → WW → 2l 2ν

- Excess of events with two leptons of opposite sign, and missing transverse energy.
  - Irreducible background:
    - qq→WW + gg→WW
  - Data driven estimates
    - W+jets: Fake rate measured in QCD enriched data sample
    - Z/γ*: Normalized in Z mass
    - Top: b-tagging efficiency from top control region in data
- Split in categories with different S/B and B composition:
  - 0/1 jet and VBF
  - Final state lepton flavors (ee, μμ, eμ)

Spin correlation, scalar boson decay to Vector bosons, and V-A structure of the W interaction
Expect small di-lepton Δφ and mass if SM Higgs
**H → WW → 2l 2ν : kinematics at final selection**

Trigger 1 or 2 leptons > 97%
\[ p_T > 20,10 \text{ GeV}, \text{iso, ID, from PV} \]
Projected mET > 20 GeV

- Anti-top + \( p_T^{\parallel} > 45 \text{ GeV} \)
- 3rd lepton veto
- \( Z \) veto and mE\(_T\) cuts
- Mass dependant: \( p_T, m_{ll}, \Delta \phi_{ll}, m_T \)

**Final selection (8 TeV dataset):** Observed number of events in data, estimates of the background and signal predictions for \( m_H = 125 \text{ GeV} \)

---

<table>
<thead>
<tr>
<th>Category:</th>
<th>0-jet ( e\mu )</th>
<th>0-jet ( \ell\ell )</th>
<th>1-jet ( e\mu )</th>
<th>1-jet ( \ell\ell )</th>
<th>2-jet ( e\mu )</th>
<th>2-jet ( \ell\ell )</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>87.6 ± 9.5</td>
<td>60.4 ± 6.7</td>
<td>19.5 ± 3.7</td>
<td>97 ± 1.9</td>
<td>0.4 ± 0.1</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>WZ + ZZ + Z(\gamma)</td>
<td>2.2 ± 0.2</td>
<td>37.7 ± 12.5</td>
<td>2.4 ± 0.3</td>
<td>87 ± 4.9</td>
<td>0.1 ± 0.0</td>
<td>3.1 ± 1.8</td>
</tr>
<tr>
<td>Top</td>
<td>9.3 ± 2.7</td>
<td>1.9 ± 0.5</td>
<td>22.3 ± 2.0</td>
<td>9.5 ± 1.1</td>
<td>3.4 ± 1.9</td>
<td>2.0 ± 1.2</td>
</tr>
<tr>
<td>W + jets</td>
<td>19.1 ± 7.2</td>
<td>10.8 ± 4.3</td>
<td>11.7 ± 4.6</td>
<td>3.9 ± 1.7</td>
<td>0.3 ± 0.3</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>W(\gamma)(*)</td>
<td>6.0 ± 2.3</td>
<td>4.6 ± 2.5</td>
<td>5.9 ± 3.2</td>
<td>1.3 ± 1.2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>All backgrounds</td>
<td>124.2 ± 12.4</td>
<td>115.5 ± 15.0</td>
<td>61.7 ± 7.0</td>
<td>33.1 ± 5.7</td>
<td>4.1 ± 1.9</td>
<td>5.4 ± 2.2</td>
</tr>
<tr>
<td>Signal ((m_H = 125 \text{ GeV}))</td>
<td>23.9 ± 5.2</td>
<td>14.9 ± 3.3</td>
<td>10.3 ± 3.0</td>
<td>4.4 ± 1.3</td>
<td>1.5 ± 0.2</td>
<td>0.8 ± 0.1</td>
</tr>
<tr>
<td>Data</td>
<td>158</td>
<td>123</td>
<td>54</td>
<td>43</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>
H → WW → 2l 2ν : ICHEP results

- Broad excess of about 1.6 σ observed (2.4 σ expected) in the low mass range. Compatible with the expectations from a SM Higgs signal at 125 GeV, given the low mass resolution.

Exclusion Range

**Observed:** 129 - 520 GeV

**Expected:** 123 - 450 GeV

Results in WW topologies are compatible within uncertainties
H → WW → 2l 2ν : post-ICHEP results

MultiVariate shape analysis in the $e\mu$ final state in the 0 and 1 jet categories: Cut-based variables + $\Delta R_{ll}$, $m_T^{(1,2)}$, $\Delta\phi(ll, MET)$, $\Delta\phi(ll, jet1)$

@ $m_H = 125$ GeV
Exp. significance 2.5 $\sigma$
Obs. significance 2.2 $\sigma$

Signal strength: $0.82 \pm 0.38$
H→WW→lνqq, Analysis

- Most sensitive for Higgs boson mass around 350 GeV
- Selection differences to lνlν channel
  - One electron (muon) with pT > 35 (25) GeV and MET > 25 (30) GeV (leptonic W decay)
  - Two jets with 65 < Mjj < 95 (hadronic W decay)
- Main background: W+jets
  - Suppressed using angular likelihood discriminant for each mass hypothesis
- Signal extraction
  - Kinematic fit allows full reconstruction of Higgs boson mass
  - Search for mass peak against continuum background from W+jets events
H→WW→lνqq, Results

8 TeV Analysis

- The 8 TeV data analysis excludes [260, 390] GeV at 95% CL
- In combination with the 7 TeV data [240, 450] GeV is excluded at 95% CL

Combined 7 + 8 TeV
**W/Z + H, H → bb**

The largest BR for $m_H < 130$ GeV, but $\sigma_{bb}(\text{QCD}) \sim 10^7 \times \sigma_H \times \text{BR}(H \to bb)$

Search in associated production with W or Z, leading to final states with leptons, MET and b-jets.

**• General strategy:**
  - High boosted vector boson and dijet
  - 2 b-tagged jets
  - Back to back V and H
  - Reconstruct $mbb$

**• Main backgrounds, V+jets and top anti top, estimated from data in control regions.**

$$M_{bb} = 128 \text{ GeV}, \ p_T(bb) = 181 \text{ GeV}$$

**5 channels:** $Z(\ell\ell)H(bb), Z(\nu\nu)H(bb), W(l\nu)H(bb)$

Reducible Backgrounds: QCD, top, W/Z+ light jets
Less reducible: V+bb, ZZ(bb), WZ(bb)

Key piece of the observation puzzle
Tests specific production & decay couplings
\[ W/Z + H, \ H \to bb \]

Many improvements:

- Jet energy reconstruction using BDT regression (15-20% improvement)

Extensively validated in data using \( Z(\ell\ell) + bb, tt\bar{b} \) and single top events
W/Z + H, H → bb

Many improvements:

- Jet energy reconstruction using BDT regression (15-20% improvement)
- Categorize events in medium and high boost
W/Z + H, H → bb

Many improvements:
• Jet energy reconstruction using BDT regression (15-20% improvement)
• Categorize events in medium and high boost
• Use full shape of final MVA discriminator
Gain in sensitivity ~50% already on 2011 dataset!
W/Z + H, H → bb: results

- Some excess compared to background predictions (significance ~1σ)
- Compatible both with a $1\times\sigma_{\text{SMH}}$ signal and with just background.
ttH, H $\rightarrow$ bb

Important to probe the coupling:
same couplings as the dominant part of $\sigma(gg \rightarrow H)$ production cross section but at tree level
(no loopholes for BSM particles to contribute...)
ttH, H → bb

**Strategy:**

- Separate events by top decay mode (di-lep., lep+jets), and by number of jets and b-tags
- MVA shape analysis in each event category
- Categories with low S/B used to constrain the background in higher S/B ones.
ttH, H → bb: results

• Only 2011 data analyzed at the moment. No evidence of excess, but not yet sensitive to a $1 \times \sigma_{SMH}$ signal anyway.
• ttH cross section grows very quickly with $\sqrt{s}$.
  $(x1.5$ from 7 to 8 TeV, $x5$ from 8 to 14 TeV!)
• If scaling as $\sqrt{(\sigma \times L)}$ could have $\Delta \sigma / \sigma_{SMH} \sim 1$ already with $L \sim 20$ fb$^{-1}$ at 8 TeV.
H → ττ

- Combination of three production mechanisms
- Search is performed in eτh, μτh, eμ, μμ decay modes

Characteristics:
- High σ x BR at low mass
- Sensitive to all production modes
- Probes coupling to leptons
- Enhanced σx BR in MSSM
- Challenging large backgrounds:
  - DY→ττ, W+Jets, QCD

Analysis Strategy

Jets p_T > 30 GeV

Analysis divided into 5 categories mass resolution, S/B

All categories are fit simultaneously

VBF
2 jets, no jets in rapidity gap MVA based selection

0 Jet, High pT
Lepton p_T spectrum harder from H

1 Jet, Low p_T
Enhancement from p_T and jet requirement

0 Jet, Low p_T
High background

1 Jet, Low p_T
Enhancement from jet requirement
Analysis re-optimized:

- Improved lepton and $\tau_{\text{had}}$ identification criteria

MVA-based tau isolation algorithm
Analysis re-optimized:
• Improved lepton and $\tau_{\text{had}}$ identification criteria
• New mass reconstruction (20% better resolution)
$H \rightarrow \tau\tau$

Analysis re-optimized:

- Improved lepton and $\tau_{\text{had}}$ identification criteria
- New mass reconstruction (20% better resolution)
- New event categorization: lower jet $p_T$ thresholds, rely also on $p_T$ of the tau.
$H \rightarrow \tau\tau$

Analysis re-optimized:

- Improved lepton and $\tau_{\text{had}}$ identification criteria
- New mass reconstruction (20% better resolution)
- New event categorization: lower jet $p_T$ thresholds, rely also on $p_T$ of the tau.
- MVA selection for VBF tag
H → ττ: results

- Sensitivity of new analysis very close to $1 \times \sigma_{\text{SMH}}$
- No excess seen. Just bad luck or non-SM Higgs?
Vector boson fusion

• **VBF signature**
  - $\gamma \gamma$, $t\bar{t}$, $WW$ channels deploy VBF signature
  - $ZZ(4l)$ has very low signal yield
  - $bb$ is challenging and work in progress

• increases sensitivity and allows coupling measurement

• three analysis deploy quite different strategies

<table>
<thead>
<tr>
<th>Channel</th>
<th>Technique</th>
<th>Variable</th>
<th>Jet kinematic</th>
<th>Pile-up</th>
<th>gluon fusion cont. at 125 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>cuts, 2 categories</td>
<td>$m(jj), \Delta\eta(jj), \Delta\phi(H,jj), \text{Zep.}$</td>
<td>$p_T &gt; 20$ (30) GeV, $</td>
<td>\eta</td>
<td>&lt; 4.7$</td>
</tr>
<tr>
<td>$H \rightarrow t\bar{t}$</td>
<td>MVA</td>
<td>$m(jj), \Delta\eta(jj), \Delta\eta(H,j), \Delta\phi(jj), p_T(t\bar{t}), p_T(jj)$</td>
<td>$p_T &gt; 30$ GeV, $</td>
<td>\eta</td>
<td>&lt; 5.0$</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>cuts</td>
<td>$m(jj), \Delta\eta(jj)$</td>
<td>$p_T &gt; 30$ GeV, $</td>
<td>\eta</td>
<td>&lt; 4.7$</td>
</tr>
</tbody>
</table>

• diversity result of independent development and optimization, but needs investigation!
Combined Results
Combined results

- Most analyses using 5+5 fb\(^{-1}\), many improved w.r.t. 2011
- Biggest combination done so far at CMS: 95 individual final states contributing at 125 GeV mass hypothesis!
Combined results

- Most analyses using 5+5 fb\(^{-1}\), many improved w.r.t. 2011
- Biggest combination done so far at CMS: 95 individual final states contributing at 125 GeV mass hypothesis!
**Combined results: ZZ+ γγ**

In high mass resolution channels, observe an excess with local significance of 5.0σ (expected from SM H: 4.7σ)
Combined results: all channels

Local significance of excess: \(4.9 \sigma\)
Expected for SM Higgs signal: \(5.8 \sigma\)

Global significance > 4\(\sigma\)

We interpret this excess as the observation of a new boson with mass around 125 GeV.
Combined results: all channels

Best fit signal strength at mass 125 GeV:
\[(0.87 \pm 0.23) \times \sigma_{\text{SMH}}\]

Compatible with the expectations from a SM Higgs boson signal!
Mass of the observed particle

• Likelihood scan for mass and signal strength in three high mass resolution channels:
  – ZZ 4l
  – $\gamma\gamma$ untagged
  – $\gamma\gamma$ with di-jet tag

• Results are compatible within the uncertainties
Mass measurement

- Perform a fit of the mass with freely floating signal strength for the three final states, to minimize model dependence.

\[ M = 125.3 \pm 0.6 \]

- Ultimate precision:

\[ \sigma_m < 100 \text{ MeV} \]
Mass measurement

- Systematical uncertainty on the mass driven by energy scale uncertainty in $\gamma\gamma$: now conservative estimate $\sim 0.5\%$, will improve in the future.

\[ M = 125.3 \pm 0.4 \text{ (stat.)} \pm 0.5 \text{ (syst.)} = 125.3 \pm 0.6 \text{ GeV} \]
Is it a SM Higgs boson?

- Observed signal strength in the analyzed decay modes and production topologies compatible with a SM Higgs
- However, with the present data sample only few modes have sensitivity to a signal of SM strength.
Is it a SM Higgs boson?

- Slightly better sensitivity when combining channels by decay mode or production topology.
- Compatible with SM Higgs within uncertainties.
Is it a SM Higgs boson?

- Test of custodial symmetry: compare the signal strength observed in WW and ZZ modes.
- Fit the ZZ and WW (0/1 jet) data assuming:
  \[ \sigma \times \text{BR}_{H \to ZZ} = \mu_{ZZ} \times [ \sigma \times \text{BR}_{H \to ZZ} ]_{\text{SM Higgs}} \]
  \[ \sigma \times \text{BR}_{H \to WW} = R_{W/Z} \times \mu_{ZZ} \times [ \sigma \times \text{BR}_{H \to WW} ]_{\text{SM}} \]
- Result compatible with SM within the large uncertainties

\[ R_{W/Z} = 0.9^{+1.1}_{-0.6} \]
Is it a SM Higgs boson?

- Test compatibility w.r.t SM predictions by introducing two parameters \((c_V, c_F)\) modifying the expected signal yields in each mode through simple LO expressions

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>LO SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH</td>
<td>(H \rightarrow bb)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2}) (\sim C_V^2)</td>
</tr>
<tr>
<td>ttH</td>
<td>(H \rightarrow bb)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2}) (\sim C_V^2)</td>
</tr>
<tr>
<td>VBF</td>
<td>(H \rightarrow \tau\tau)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2}) (\sim C_V^2)</td>
</tr>
<tr>
<td>ggH</td>
<td>(H \rightarrow \tau\tau)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2}) (\sim C_V^2)</td>
</tr>
<tr>
<td>ggH</td>
<td>(H \rightarrow ZZ)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2}) (\sim C_V^2)</td>
</tr>
<tr>
<td>ggH</td>
<td>(H \rightarrow WW)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2}) (\sim C_V^2)</td>
</tr>
<tr>
<td>VBF</td>
<td>(H \rightarrow WW)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2}) (\sim C_V^2)</td>
</tr>
<tr>
<td>ggH</td>
<td>(H \rightarrow \gamma\gamma)</td>
<td>(\sim \frac{C_V^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}) (\sim C_V^2)</td>
</tr>
<tr>
<td>VBF</td>
<td>(H \rightarrow \gamma\gamma)</td>
<td>(\sim \frac{C_V^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}) (\sim C_V^2)</td>
</tr>
</tbody>
</table>
Is it a SM Higgs boson?

- Test compatibility w.r.t SM predictions by introducing two parameters \((c_V, c_F)\) modifying the expected signal yields in each mode through simple LO expressions, modifying only coupling strength, not the tensor structure.

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>LO SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH</td>
<td>(H \rightarrow bb)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2} \sim C_V^2)</td>
</tr>
<tr>
<td>ttH</td>
<td>(H \rightarrow bb)</td>
<td>(\sim \frac{C_F^2 \times C_V^2}{C_F^2} \sim C_F^2)</td>
</tr>
<tr>
<td>VBF</td>
<td>(H \rightarrow \tau\tau)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2} \sim C_V^2)</td>
</tr>
<tr>
<td>ggH</td>
<td>(H \rightarrow \tau\tau)</td>
<td>(\sim \frac{C_F^2 \times C_V^2}{C_F^2} \sim C_F^2)</td>
</tr>
<tr>
<td>ggH</td>
<td>(H \rightarrow ZZ)</td>
<td>(\sim \frac{C_F^2 \times C_V^2}{C_F^2} \sim C_V^2)</td>
</tr>
<tr>
<td>ggH</td>
<td>(H \rightarrow WW)</td>
<td>(\sim \frac{C_F^2 \times C_V^2}{C_F^2} \sim C_V^2)</td>
</tr>
<tr>
<td>VBF</td>
<td>(H \rightarrow WW)</td>
<td>(\sim \frac{C_V^2 \times C_F^2}{C_F^2} \sim \frac{C_V^4}{C_F^2})</td>
</tr>
<tr>
<td>ggH</td>
<td>(H \rightarrow \gamma\gamma)</td>
<td>(\sim \frac{C_F^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2} \sim C_V^2)</td>
</tr>
<tr>
<td>VBF</td>
<td>(H \rightarrow \gamma\gamma)</td>
<td>(\sim \frac{C_F^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2} \sim \frac{C_V^4}{C_F^2})</td>
</tr>
</tbody>
</table>
Is it a SM Higgs boson?

- Test compatibility w.r.t SM predictions by introducing two parameters \( (c_V, c_F) \) modifying the expected signal yields in each mode through simple LO expressions.

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>LO SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH</td>
<td>( H \rightarrow bb )</td>
<td>( \sim \frac{c_V^2}{c_F^2} )</td>
</tr>
<tr>
<td>ttH</td>
<td>( H \rightarrow bb )</td>
<td>( \sim \frac{c_F^2}{c_V^2} )</td>
</tr>
<tr>
<td>VBF</td>
<td>( H \rightarrow \tau\tau )</td>
<td>( \sim \frac{c_V^2}{c_F^2} )</td>
</tr>
<tr>
<td>ggH</td>
<td>( H \rightarrow \tau\tau )</td>
<td>( \sim \frac{c_F^2}{c_V^2} )</td>
</tr>
<tr>
<td>ggH</td>
<td>( H \rightarrow ZZ )</td>
<td>( \sim \frac{c_V^2}{c_F^2} )</td>
</tr>
<tr>
<td>ggH</td>
<td>( H \rightarrow WW )</td>
<td>( \sim \frac{c_F^2}{c_V^2} )</td>
</tr>
<tr>
<td>VBF</td>
<td>( H \rightarrow WW )</td>
<td>( \sim \frac{c_V^2}{c_F^2} )</td>
</tr>
<tr>
<td>ggH</td>
<td>( H \rightarrow \gamma\gamma )</td>
<td>( \sim \frac{c_F^2}{c_V^2} \times (8.6c_V - 1.8c_F)^2/c_F^2 )</td>
</tr>
<tr>
<td>VBF</td>
<td>( H \rightarrow \gamma\gamma )</td>
<td>( \sim \frac{c_V^2}{c_F^2} \times (8.6c_V - 1.8c_F)^2/c_F^2 )</td>
</tr>
</tbody>
</table>
Is it a SM Higgs boson?

- Test compatibility w.r.t SM predictions by introducing two parameters ($c_V, c_F$) modifying the expected signal yields in each mode through

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>LO SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH</td>
<td>$H \rightarrow bb$</td>
<td>$\sim \frac{c_V^2 \times c_F^2}{c_F^2}$ $\sim c_V^2$</td>
</tr>
<tr>
<td>ttH</td>
<td>$H \rightarrow bb$</td>
<td>$\sim \frac{c_F^2 \times c_V^2}{c_F^2}$ $\sim c_F^2$</td>
</tr>
<tr>
<td>VBF</td>
<td>$H \rightarrow \tau\tau$</td>
<td>$\sim \frac{c_F^2 \times c_V^2}{c_F^2}$ $\sim c_V^2$</td>
</tr>
<tr>
<td>ggH</td>
<td>$H \rightarrow \tau\tau$</td>
<td>$\sim \frac{c_F^2 \times c_V^2}{c_F^2}$ $\sim c_F^2$</td>
</tr>
<tr>
<td>ggH</td>
<td>$H \rightarrow ZZ$</td>
<td>$\sim \frac{c_F^2 \times c_V^2}{c_F^2}$ $\sim c_V^2$</td>
</tr>
<tr>
<td>ggH</td>
<td>$H \rightarrow WW$</td>
<td>$\sim \frac{c_F^2 \times c_V^2}{c_F^2}$ $\sim c_V^2$</td>
</tr>
<tr>
<td>VBF</td>
<td>$H \rightarrow WW$</td>
<td>$\sim \frac{c_F^2 \times c_V^2}{c_F^2}$ $\sim \frac{c_V^4}{c_F^2}$</td>
</tr>
<tr>
<td>ggH</td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\sim \frac{c_F^2 \times (8.6c_V - 1.8c_F)^2}{c_F^2}$ $\sim c_V^2$</td>
</tr>
<tr>
<td>VBF</td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\sim \frac{c_F^2 \times (8.6c_V - 1.8c_F)^2}{c_F^2}$ $\sim \frac{c_V^4}{c_F^2}$</td>
</tr>
</tbody>
</table>
Is it a SM Higgs boson?

• **CMS data compatible with SM prediction at 95% C.L.**

• Best fit $c_F$ driven to low values by VBF $\gamma\gamma$ excess and $\tau\tau$ deficit.

• **More data needed to draw any definite conclusion.**

• LHC Cross Section WG also converging on an improved models for these kinds of fits.
Anything elsewhere?

- Stringent exclusion limits for any heavy Higgs-like boson decaying into WW and ZZ bosons:
  - e.g. $\sigma \sim 0.3 \times \sigma_{\text{SMH}}$ is excluded in most of the 140-500 GeV range.
What next?

• \textit{Reassert} the observation with the full 2011+2012 dataset, using 12 fb\textsuperscript{-1} already collected, and then the final Run 1 dataset, \textbf{5 fb-1 at 7 TeV and O(20 fb-1) at 8 TeV}.

• \textbf{Measurement of spin and parity} using angular distributions in ZZ, WW, \gamma\gamma.

• \textbf{Search for deviations from the SM in the couplings} by progressively introducing new degrees of freedom in the fit to the data, in collaboration with LHC Higgs XS WG.

• \textbf{Improve the mass measurement}.
Projections for $J^{PC}$ measurements

$H \rightarrow ZZ \rightarrow 4l$

CMS Simulation $L = 30 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

Expect $\sim 3\sigma$ separation between scalar and pseudoscalar in 2012

$H \rightarrow WW \rightarrow 2l2\nu$

JHU Generator level $L = 10 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

Expect $\sim 3\sigma$ separation between spin 0, 2 with 10 fb$^{-1}$ but assuming no systematics and WW as only background

http://indico.cern.ch/contributionDisplay.py?c ontribId=473&sessionId=53&confId=181298
Conclusion

• LHC, ATLAS, CMS performing extremely well in their 3\textsuperscript{rd} year of first run, with a major battle with pile-up.

• In the searches for a SM Higgs boson at CMS, a new state with mass $125.3 \pm 0.6$ GeV has been observed, dominantly in the $\gamma\gamma$ and $4l$ modes.

• Within the limited precision of the current data, the observation is compatible with the predictions for a SM Higgs boson signal, despite the larger excess in $\gamma\gamma$ and the deficit in $\tau\tau$, $bb$ modes.

• More data is needed to draw any firm conclusions on this second point.
  • Moriond will have almost $3\times$ the statistics of July 4\textsuperscript{th}.
For further information:

• CMS Higgs results twikipage
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

• 4th July seminar at CERN:
  https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=6125

• CMS talks on Higgs searches at ICHEP 2012:
  https://indico.cern.ch/conferenceProgram.py?confId=181298
  (too many to list them all individually)

• CMS long paper in preparation, and new results using 12 fb⁻¹ at 8 TeV.