Higgs results from ATLAS and CMS

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Higgs boson discovery

- In winter conferences, ATLAS & CMS updated Higgs search results with full dataset.
- New boson declared to be a Higgs boson on 14th March 2013.
- This talk: measurement of properties.
Contents

• Properties with high sensitivity channels
  $H \rightarrow ZZ \rightarrow 4\ell, H \rightarrow \gamma\gamma, H \rightarrow WW$
  – Mass
  – Signal strength
  – Couplings
  – Spin

• More properties
  – Fermionic final states
  – Rare decays
  – High mass analyses
Confirmation of the discovery

- Channels updated with full 7 + 8 TeV data set
- Clear evidence for a new particle
Combined significance

- **ATLAS:** 4.6-4.8 fb^{-1} (13-20.7 fb^{-1}) of 7 TeV (8 TeV) data
- Combined significance almost at 10\sigma.
- No doubt about discovery of a new particle. But is it the SM Higgs boson?

- Use H→ZZ, H→γγ, H→WW, H→ττ, H→bb in the figure.

**Observed (expected) significance for different channels:**

<table>
<thead>
<tr>
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<th>ATLAS</th>
<th>CMS</th>
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</thead>
<tbody>
<tr>
<td>H→γγ</td>
<td>7.4(4.2)</td>
<td>3.9(4.2)</td>
</tr>
<tr>
<td>H→ZZ</td>
<td>6.6(4.4)</td>
<td>6.7(6.7)</td>
</tr>
<tr>
<td>H→WW</td>
<td>3.8(3)</td>
<td>4.0(5.1)</td>
</tr>
<tr>
<td>H→ττ</td>
<td>1.1(1.7)</td>
<td>2.9(2.6)</td>
</tr>
<tr>
<td>H→bb</td>
<td>2.1(2.1)</td>
<td></td>
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</tbody>
</table>
Mass measurement

- Accurate mass from ZZ and $\gamma\gamma$ channels.

$m_H = 125.5 \pm 0.2 \text{ (stat)} ^{+0.5}_{-0.6} \text{ (sys)} \text{ GeV}$

- Separation between $\gamma\gamma$ and ZZ at the level of $2.4\sigma$ in ATLAS.

$m_H = 125.7 \pm 0.3 \text{ (stat)} \pm 0.3 \text{ (sys)} \text{ GeV}$
Signal strengths

- Signal strength $\mu = \sigma/\sigma_{SM}$, assuming fix value of $m_H$.

$\mu = 1.33 \pm 0.18$

- No large deviation from SM prediction.
- Compatibility of combined $\mu$ value and SM $\mu=1$. 
SM Higgs production

- Gluon-gluon fusion (ggF) dominant
- Several measurements of vector-boson fusion (VBF)
- Data not yet very sensitive to VH and ttH.
Production modes

- Combine VBF and VH (both scale with V-H coupling).
- Combine ggF and ttH (both scale with t-H coupling).

\[ \mu_{\text{VBF+VH}}/ \mu_{\text{ggF+ttH}} = 1.4^{+0.7}_{-0.5} \]

- 3.3σ significance of non-vanishing VBF.

- Individual channels consistent with SM prediction.
Fermion and vector couplings

• Coupling scale factors to vector and fermions (K_V, K_F, respectively) are the ratio between the measured and the SM expected value.
• K_V measured directly and indirectly in many channels
• K_F measured:
  – directly in H→bb and H→ττ – not well measured yet
  – indirectly via loop in gg→H

• Fermion and vector couplings non-zero and consistent with SM.
Measurement of spin

- SM prediction for Higgs is $J^P=0^+$
- $J=1$ strongly disfavoured after $H \rightarrow \gamma\gamma$ observation (Landau-Yang theorem)

- Use $H \rightarrow ZZ$ to study $J=0^-$
- Use $H \rightarrow WW$, $H \rightarrow ZZ$ to study $J=1^{+,-}$
- Use $H \rightarrow WW$, $H \rightarrow ZZ$, $H \rightarrow \gamma\gamma$ to study $J=2^+$
- For $2^+$, results analysed in a graviton inspired model which has an unknown production mechanism – fraction of $qq$ to $gg$

- Variables:
  - $\cos \theta^*$: variable in Higgs rest frame for $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ (left figure)
  - Other decay final state variables for $H \rightarrow WW$
Spin from $H \rightarrow \gamma \gamma$

- Reconstruct decay angle from photons
- Sensitive to spin but not parity
- Fit background and signal in bins of $\cos \theta^*$. 

Spin 0$^+$

Spin 2$^+$

Spin 0 favoured.
Spin from $H \to WW$

- Combine several variables in a multivariate discriminant
- Variables used: $m_\ell$, $P_T^\ell$, $\Delta\phi_\ell$, $m_T$.

Spin 0$^+$

Spin 2$^+$

Spin 0$^+$

Spin 2$^+$

- Spin 0 favoured.
Spin from $H \rightarrow ZZ$

- Combine several variables in a multivariate discriminant
- Variables used: $\phi$, $\theta_1$, $\theta_2$, $m_{12}$, $m_{34}$, $\theta^*$, $\phi_1$

- Spin $0^+$ favoured.
Spin summary (1)

- Test $2^+ \text{ versus } 0^+$ spin-parity hypotheses

- 3 channels combined exclude $2^+$ at 99.9% CL independent of production mode.

- $H \rightarrow ZZ$ and $H \rightarrow WW$ combined excludes $2^+$ hypothesis with 99.4% CL.
Spin summary (2)

- \(H \to ZZ\) excludes 0\(^-\) with 97.8% CL.
- \(H \to WW, H \to ZZ\) exclude 1\(^+\) (1\(^-\)) with more than 99.9% (99.6%) CL.
- \(H \to WW, H \to ZZ, H \to \gamma \gamma\) exclude 2\(^+\) at 99.9%
Fermionic decays – search for $H \rightarrow \tau\tau$

- Final states of tau decays
  - $H \rightarrow \tau\tau \rightarrow 2\ell + 4\nu$ (lep-lep): $Br=12.4\%$
  - $H \rightarrow \tau\tau \rightarrow \ell + \tau_{\text{had}} + 3\nu$ (lep-had): $Br=45.6\%$
  - $H \rightarrow \tau\tau \rightarrow 2\tau_{\text{had}} + 2\nu$ (had-had): $Br=42\%$

- ATLAS event topologies
  - VBF: 2 forward jets with rapidity separation in central region.
  - Boosted: !VBF and $\tau\tau$ system produced with a boost by recoiling against an addtional high-$p_T$ jet.
  - 2-jet VH: Not in previous category && associated jets from V.
  - 1-jet: Fail previous categories && activity due to additional jet.
  - 0-jet: inclusive category, no jet with $p_T>25(30)$ GeV.

VH events in CMS analysis
- $W(\ell +\nu) + H(\ell \tau_{\text{had}} + 2\tau_{\text{had}})$
- $Z(2\ell) + H(2\ell)$
- $VH \rightarrow VWW^*$ are treated as part of the signal
Results for $H \rightarrow \tau \tau$

- **ATLAS**: 17.6 fb$^{-1}$ of 7 + 8 TeV data
- Local significance at 125 GeV: $1.1 \sigma$ ($1.7 \sigma$) observed (expected)

- **CMS**: 24.3 fb$^{-1}$ of 7 + 8 TeV data
- Local significance at 125 GeV: $2.85 \sigma$ ($2.62 \sigma$) observed (expected)

- Both results consistent with the presence of SM $H \rightarrow \tau \tau$ signal.
Fermionic decays – search for VH with H→bb

- **ZH→ll+bb**
  - **Signature**: two opposite sign leptons with 2 b-tagged jets
  - **Major backgrounds**: Z+ heavy flavor jets

- **ZH→νν + bb**
  - **Signature**: large MET and 2 b-tagged jets
  - **Major backgrounds**: top, Z/W+ heavy flavor jets

- **WH→lν + bb**
  - **Signature**: one lepton, MET and 2 b-tagged jets
  - **Major backgrounds**: W+ heavy flavor jets, top

- **ATLAS**
  - Cut-based analysis uses $M_{bb}$ to extract signal

- **CMS**
  - Multivariate analysis
Results for VH with H→bb

- ATLAS: 17.7 fb⁻¹ of 7 + 8 TeV data
  - 95% CL limit on $\sigma/\sigma_{SM}$ at 125 GeV: $1.8 \times$ SM ($1.9 \times$ SM) observed (expected)

- CMS: 24.0 fb⁻¹ of 7 + 8 TeV data
  - 95% CL limit on $\sigma/\sigma_{SM}$ at 125 GeV: $1.89 \times$ SM ($0.95 \times$ SM) observed (expected)
  - Local significance at 125 GeV: $2.1 \sigma$
Fermionic decays- search for $ttH(\rightarrow bb)$

• $ttH$ production is directly sensitive to $ttH$ coupling

• Dominant background is top quark pair production

• ATLAS: $\ell \nu +$ jets final state; cut-based analysis; event categories based on $N_{jets}$ and $N_{b-tag}$

• CMS: $\ell \nu +$ jets and $2\ell 2\nu+$jets final state; MVA analysis; event categories based on $N_{leptons}$, $N_{jets}$ and $N_{b-tag}$

Examples of final discriminants used in fits for signal

ATLAS-CONF-2012-135
arXiv:1303.0763
Results for $tt(H \rightarrow bb)$

- **ATLAS**: 4.7 fb-1 of 7 TeV data
  - 95% CL limit on $\sigma/\sigma_{SM}$ at 125 GeV: 13.1 x SM (10.5 x SM) observed (expected)

- **CMS**: 10.1 fb-1 of 7 + 8 TeV data
  - 95% CL limit on $\sigma/\sigma_{SM}$ at 125 GeV: 5.8 x SM (5.1 x SM) observed (expected)
Fermionic decays-search for VBF $H(\rightarrow bb)$

- Fully hadronic final state
- Use mass of b-jets to extract signal
  - Categorize events using neural network (no b-jet info)

CMS: 19.0 fb-1 of 8 TeV data
- 95% CL limit on $\sigma/\sigma_{SM}$ at 125 GeV: 3.6 x SM (3.0 x SM) observed (expected)
Rare decays – search for $H \rightarrow Z\gamma$

- Reconstruct $Z \rightarrow ll$ and photon
- Take difference between $m_{ll\gamma}$ and $m_{ll}$ ($= \Delta m$).

**ATLAS**

- Observed (expected) limit at $m_H = 125$ GeV is $18.2 (13.5) \times \sigma_{SM}$ at 95% CL.
Rare decays – search for $H \rightarrow \mu\mu$

- Look for a peak in $\mu\mu$ mass spectrum

- Observed (expected) limit at $m_H = 125$ GeV is $9.8 \ (8.2) \times \sigma_{SM}$ at 95% CL.
Rare decays – search $H \rightarrow \text{invisible}$

- $4.7 \text{ fb}^{-1} + 13.0 \text{ fb}^{-1}$ at 7 TeV + 8 TeV
- Assuming SM ZH production rate ($m_H = 125 \text{ GeV}$)
- $H \rightarrow \text{invisible BF} < 65\%$ observed (84% expected) at 95% CL.
High mass search

- In discovery papers a narrow resonance was excluded at 95% CL for regions 111–122 GeV and 131–559 GeV.
- Want to extend search up to 1 TeV
- $H \to ZZ \to ll\nu\nu$ range: $200 < m_H < 1000$ GeV
- $H \to WW \to l\nu(j)$ range: $600 < m_H < 1000$ GeV
High mass search H→ZZ→llνν

- Search range 200 < m_\(H\) < 1000 GeV
- Divide analysis into VBF and ggF categories
- VBF: |\(\Delta \eta_{jj}\)| > 4, m_\(jj\) > 500 GeV, central jet veto, leptons in central region
- ggF: !VBF event with either 0 or 1+ jets
- Data driven background i.e. Z+jets from \(\gamma\)+jets
- Cut based and shape analysis – baseline results from shape-based
Results for $H \rightarrow ZZ \rightarrow ll\nu\nu$

- Exclusion 248-930 GeV observed (254-898 GeV expected)
High mass search $H\rightarrow WW\rightarrow l\nu(j)$

- Search range $600 < m_H < 1000$ GeV
- Boosted system: both $W\rightarrow \ell \nu$ & $W\rightarrow j$ with very high $p_T$ (>200 GeV)
  - for the latter, decay jets merge into a single fat jet
- Cambridge/Aachen ($\Delta R= 0.8$), employ substructure techniques
- Increase decay products separation 10% (42%) at 600 GeV (1 TeV)
- Use jet pruning to recover $W$ mass peak

- $N$-subjettiness $\tau_N$: to increase $S/B$, $\tau_2/\tau_1$ for instance
Results for $H \rightarrow WW \rightarrow l\nu(j)$

- Mass distribution in the analysis for electron channel.
- Observed limits approaching theory line for low mass.
Conclusions

• New particle confirmed with whole LHC dataset.
• Mass measurements:
  – ATLAS -> \( m_H = 125.5 \pm 0.2 \) (stat) \( +0.5 \) \( -0.6 \) (sys) GeV
  – CMS -> \( m_H = 125.7 \pm 0.3 \) (stat) \( \pm 0.3 \) (sys) GeV
• Signal strengths in different decay modes compatible with SM.
• >3\( \sigma \) observation of VBF production mode
• Couplings consistent with SM
• Non-SM spin/parity disfavoured

New particle looks very much like the SM Higgs.
Backup
H → γγ
H → WW
Run Number: 209109, Event Number: 86250372
Date: 2012-08-24 07:59:04 UTC

$H \rightarrow \tau \tau$
H → bb
Non-SM contributions from H→γγ and gg→H loops, while allowing for potential extra contributions to the total width:

a) branching fraction \( B_{i,u} = BR_{\text{inv.,undet.}} \) to invisible or undetectable decay modes (\( \kappa_\gamma \) and \( \kappa_g \) are profiled);

b) coupling scale factor \( \kappa_\gamma \) (\( \kappa_g \) and \( BR_{\text{inv.,undet.}} \) are profiled);

c) coupling scale factor \( \kappa_g \) (\( \kappa_\gamma \) and \( BR_{\text{inv.,undet.}} \) are profiled). The dashed curves show the SM expectation.
**ATLAS VBF H(→γγ)**

- Observed local $p_0^{VBF}$ value for VBF $H\rightarrow\gamma\gamma$ production as a function of $m_H$ for the combination of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data (solid black).
- The corresponding expected local $p_0^{VBF}$ value for the SM Higgs boson signal plus background hypothesis are shown by the dashed curve.
- A vertical line is drawn at the best-fit mass $m_H = 126.8$ GeV.
CMS ttH($\rightarrow\gamma\gamma$)

- On the right, 95% CL upper limit on ttbarH, H→$\gamma\gamma$ production combining the results of the leptonic and hadronic channel, divided by the SM production cross section times branching ratio.
Couplings – Custodial symmetry

- Measure HWW/HZZ couplings (=\(\lambda_{WZ}\)) will tell us if the object produced is Higgs like.

- \(\lambda_{WZ} = 0.80 \pm 0.15\)

- \([0.73, 1.00]\) at 68% CL
LHC and ATLAS/CMS

• proton-proton collisions at 7 TeV (2011) and 8 TeV (2012).

• The peak instantaneous luminosity at 8 TeV was $7.7 \times 10^{33}$ cm$^{-2}$ s$^{-1}$.
Higgs decays

- $\Gamma_H = 4$ MeV not directly measurable at LHC.
- Best experimental mass resolution for $\gamma \gamma$ and 4l decays.
- Tree level couplings $\rightarrow$ decay $\tau \tau / bb$ (fermions) $WW/ZZ$ (bosons)
- Loops couplings $\gamma \gamma \rightarrow$ sensitive to BSM
The great challenge in 2012: PILE-UP

Design value, expected to be achieved with $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$!

Event $Z \rightarrow \mu \mu$ from 2012 data, 25 reconstructed vertices.

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$ATLAS$ Online Luminosity

$\sqrt{s} = 7 \text{ TeV}$

$\sqrt{s} = 8 \text{ TeV}$

Peak interactions per crossing

Jan, Apr, Jul, Oct

Month in 2010, Month in 2011, Month in 2012
Standard Model: $Z \rightarrow 4\ell$

- Single resonant $Z$ decays selected by a looser selection compared to $H \rightarrow ZZ$ analysis

- Total cross-section in measurement phase space ($M_{ZZ} > 4$ GeV, $76 < M_{4\ell} < 106$)
  - $114 \pm 27 \pm 7 \pm 2$ fb @ 7 TeV
  - $150 \pm 13 \pm 7 \pm 5$ fb @ 8 TeV

- Branching fraction $= (4.2 \pm 0.4) \times 10^{-6}$

- All consistent with SM expectations
Standard Model: \( Z \rightarrow 4\ell \)

- Fit of reconstructed mass in 4 channels compared with MC

- Looser selection to improve statistics, \( M_{Z2}>1 \) GeV

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<thead>
<tr>
<th>( M_{4\ell} ) fit MC</th>
<th>( M_{4\ell} ) fit Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>4e</td>
<td>89.86±0.08</td>
</tr>
<tr>
<td>2( \mu )2e</td>
<td>90.82±0.07</td>
</tr>
<tr>
<td>2e2( \mu )</td>
<td>90.21±0.04</td>
</tr>
<tr>
<td>4( \mu )</td>
<td>91.04±0.03</td>
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</table>
Photon energy calibration

• MC based calibration at cluster level tuned in testbeam
• Need accurate material description for e-$\rightarrow$$\gamma$ extrapolation (cross checked with EM shower shapes, photon conversions, hadronic interactions and E/p,…)
• Energy scale corrections from Z decay to electrons. Cross checked at the lower energy spectrum with radiative Z decays

Material description for e-$\rightarrow$$\gamma$ conversion

Stability of EM calorimeter response vs time