Dedication

To the great minds who made a theoretical breakthrough half-a-century ago, which took so long to confirm experimentally, and Ad Memoriam Robert Brout (1928-2011)

François Englert

Robert Brout

Peter Higgs

Gerald Guralnik

Carl Hagen

Tom Kibble
The Higgs boson playground
Happy birthday, Mr. Higgs!
Higgs boson production and decay
Experimental results:
- Lucid Higgs boson
- Visible Higgs boson
- Not-yet-visible Higgs boson
- Invisible Higgs boson
- Invincible Higgs boson
Conclusions
The Higgs Playground
High-Quality, Plentiful Data

- Excellent machine and detector performance resulted in large amount of data with very high quality: ~95% of delivered data are recorded, and ~90% of those are certified and used in physics publications!
  - We publish based on ~85% of all the bunch collisions that took place at the LHC!
Successful Pileup Mitigation

LHC already reached nominal pileup rate; experiments cope well!

<\text{N}_{\text{PU}}>=21

\begin{figure}
\centering
\includegraphics[width=\textwidth]{pileup_mitigation.png}
\caption{LHC pileup mitigation results.}
\end{figure}
4th of July Fireworks
The significance of the excess is mildly sensitive to uncertainties in the energy resolutions and energy scale systematic uncertainties on the background-only expectation. The observed (solid) local significance for the 9.2. Observation of an excess of events and 131–559 GeV. Three mass regions are excluded at 99% CL, 582 GeV. The observed 95% CL exclusion regions are 111–122 GeV.

Fig. 7. Using the asymptotic approximation, are shown as a function of the SM Higgs boson mass. The dashed line shows the expected local significance, respectively, for a Higgs boson mass of approximately 125.5 GeV for the various combinations of channels. The consistency of the observed excess with the background-only hypothesis may be judged from the global combination as a function of the SM Higgs boson mass. The dashed line shows the expected local significance (4.9 -value for decay modes with high mass-resolution, allowing good localization of the invariant mass.

For the 2012 data alone, the maximum local significance reaches 5.8. These results confirm the very low probability of a statistical fluctuation of the background. The excess corresponding to 4.7 -value for the five decay modes and the overall combination as a function of the hypothesised Higgs boson mass. The dashed curves show the expected local significance from a statistical fluctuation of the background. The excess constitutes a 5.1 sigma discovery at 95% CL, which is enhanced to 6.0 sigma when added to the 5.0 sigma for the low mass-resolution data.

For further analysis, see the tables and figures in the accompanying paper.
Moriond 2013 - What a Week!

New results indicate that new particle is a Higgs boson

Higgs boson and new pope confirmed

Is the Higgs boson the key that will unlock the secrets of the universe?

Through the Wormhole
March 20th at 9pm
Only on Science

Click To See More Pics From The Vatican

White smoke rises from the chimney on the roof of the Sistine Chapel, indicating the election of a new pope on March 13, 2013.
Happy Birthday, Mr. Higgs

- It’s been a great year for the Higgses (both Peter and the Boson)!
- Long journey in one year:
  - Established the existence of new particle beyond any doubts (LHC+Tevatron)
  - Mass measured to 0.50% precision, i.e. better than top (or any other) quark mass! (ATLAS+CMS)
  - It is a $0^{++}$ boson responsible for EWSB, as evident from its relative couplings to W/Z vs. $\gamma$ (ATLAS+CMS)
  - Established couplings to the third-generation fermions (CMS+Tevatron)
  - Nearly excluded negative couplings to fermions (CMS)
  - Big 5 → big 6: thanks to $ttH$ ($bb$, $\gamma\gamma$, and $\tau\tau$)
- See more in Fabio Cerutti’s talk (next)

<table>
<thead>
<tr>
<th>Combination</th>
<th>Expected (pre-fit)</th>
<th>Expected (post-fit)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H\to ZZ$</td>
<td>7.1 $\sigma$</td>
<td>7.1 $\sigma$</td>
<td>6.7 $\sigma$</td>
</tr>
<tr>
<td>$H\to \gamma\gamma$</td>
<td>4.2 $\sigma$</td>
<td>3.9 $\sigma$</td>
<td>3.2 $\sigma$</td>
</tr>
<tr>
<td>$H\to WW$</td>
<td>5.6 $\sigma$</td>
<td>5.3 $\sigma$</td>
<td>3.9 $\sigma$</td>
</tr>
<tr>
<td>$H\to bb$</td>
<td>2.1 $\sigma$</td>
<td>2.2 $\sigma$</td>
<td>2.0 $\sigma$</td>
</tr>
<tr>
<td>$H\to tt$</td>
<td>2.7 $\sigma$</td>
<td>2.6 $\sigma$</td>
<td>2.8 $\sigma$</td>
</tr>
<tr>
<td>$H\to tt$ and $H\to bb$</td>
<td>3.5 $\sigma$</td>
<td>3.4 $\sigma$</td>
<td>3.4 $\sigma$</td>
</tr>
</tbody>
</table>
The following four mechanisms can be tested at the LHC and the Tevatron:

- (a) gluon fusion (19 pb @ 8 TeV)
- (b) VBF (WW or ZZ fusion)
- (c) Associated production (VH)
- (d) ttH production
The Nature has chosen the Higgs boson mass (~125.5 GeV) maximally rich, but quite challenging experimentally.

The “big five”:
- H(bb) - 57%
- H(WW) - 22%
- H(ττ) - 6.2%
- H(ZZ) - 2.8%
- H(γγ) - 0.23%
Lucid Higgs
Most sensitive, high-resolution channel for a 125 GeV Higgs!

- ATLAS: Cut-in-categories, FSR accounting, untagged + VBF+ VH
- CMS: MELA (angular analysis), FSR recovery, untagged + VBF

**ATLAS Collaboration, arXiv:1307.1427**

**CMS PAS HIG-13-002**

ATLAS Collaboration, arXiv:1307.1427

CMS preliminary

6.6σ (4.4σ exp.)

m =

6.7σ (7.2σ exp.)
H(ZZ→4l) Results

**ATLAS Collaboration, arXiv:1307.1427**

**ATLAS**

\[ m_H = 125.5 \text{ GeV} \]

<table>
<thead>
<tr>
<th>Final State</th>
<th>Total Uncertainty</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to ZZ^* \to 4l )</td>
<td>( \sigma_{\text{(stat)}} )</td>
<td>( +0.33 )</td>
</tr>
<tr>
<td></td>
<td>( \sigma_{\text{(sys)}} )</td>
<td>(-0.17 )</td>
</tr>
<tr>
<td></td>
<td>( \sigma_{\text{(theo)}} )</td>
<td>(-0.14 )</td>
</tr>
</tbody>
</table>

\[ \bar{s} = 7 \text{ TeV} \int L dt = 4.6-4.8 \text{ fb}^{-1} \]

\[ \bar{s} = 8 \text{ TeV} \int L dt = 20.7 \text{ fb}^{-1} \]

**CMS Preliminary**

\[ m_H = 125.8 \text{ GeV} \]

\[ \mu = 0.91^{+0.30}_{-0.24} \]

**ATLAS**

\[ m_H = 125.5 \text{ GeV} \]

<table>
<thead>
<tr>
<th>Final State</th>
<th>Total Uncertainty</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to ZZ^* \to 4l )</td>
<td>( \frac{h_{\text{VBF+VH}}}{\sigma_{\text{ggF+tH}}} )</td>
<td>( +0.6 \pm 0.4 )</td>
</tr>
</tbody>
</table>

\[ \bar{s} = 7 \text{ TeV} \int L dt = 4.6-4.8 \text{ fb}^{-1} \]

\[ \bar{s} = 8 \text{ TeV} \int L dt = 20.7 \text{ fb}^{-1} \]

**CMS Preliminary**

\[ m_H = 125.8 \pm 0.5 \pm 0.2 \text{ GeV} \]
Seeing Light Higgs w/ Light

✦ One of the most challenging and sensitive channels:
  ✷ Small branching fraction (0.23%), compensated by large cross section
  ✷ Large QCD background from direct diphotons, and direct photons with \( j \rightarrow \gamma \)
    ✷ Thorough optimization; background estimated from sidebands
  ✷ Ambiguity with primary vertex selection
    ✷ ATLAS - photon pointing
    ✷ CMS - dedicated MVA technique
  ✷ Analysis is done in categories:
    ✷ ATLAS: untagged (9 sub-categories), lepton-tag (WH/ZH), \( ME_T \) tag (\( Z(\nu\nu)H \), 8 TeV only), VBF (1 or 2 categories)
    ✷ CMS: untagged (4 sub-categories), lepton-tag, \( ME_T \) tag, VBF (1 or 2 categories); also a cut-in-categories cross-check analysis
  ✷ Takes advantage of higher boost of the Higgs boson with respect to background (gluons radiate more than quarks!)
**ATLAS Collaboration, arXiv:1307.1427**

**ATLAS**

\[ m_H = 126.8 \pm 0.2 \pm 0.7 \ \text{GeV} \]

<table>
<thead>
<tr>
<th>Category</th>
<th>( N_D )</th>
<th>( N_B )</th>
<th>( N_S )</th>
<th>ggF</th>
<th>VBF ( m_H = 125 \ \text{GeV} )</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untagged</td>
<td>14248</td>
<td>13582</td>
<td>350</td>
<td>320</td>
<td>19</td>
<td>7</td>
<td>4.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Loose high-mass two-jet</td>
<td>41</td>
<td>28</td>
<td>5.0</td>
<td>2.3</td>
<td>2.7 &lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>Tight high-mass two-jet</td>
<td>23</td>
<td>13</td>
<td>7.7</td>
<td>1.8</td>
<td>5.9 &lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>Low-mass two-jet</td>
<td>19</td>
<td>21</td>
<td>3.1</td>
<td>1.5</td>
<td>&lt; 0.1</td>
<td>0.92</td>
<td>0.54</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>( E_T^{\text{miss}} ) significance</td>
<td>8</td>
<td>4</td>
<td>1.2</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>0.43</td>
<td>0.57</td>
<td>0.14</td>
</tr>
<tr>
<td>Lepton</td>
<td>20</td>
<td>12</td>
<td>2.7</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>1.7</td>
<td>0.41</td>
<td>0.50</td>
</tr>
<tr>
<td>All categories (inclusive)</td>
<td>13931</td>
<td>13205</td>
<td>370</td>
<td>330</td>
<td>27</td>
<td>10</td>
<td>5.8</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**ATLAS**

\[ m_H = 125.5 \ \text{GeV} \]

Signal significance:
- Observed: 7.4\( \sigma \)
- Expected: 4.3\( \sigma \)

**ATLAS**

\[ m_H = 126.5 \ \text{GeV} \]
“One event - discovery; two events - differential cross sections; three events - partial-wave analysis”

- Given a strong signal, ATLAS proceeded with determining differential distributions for $H(\gamma\gamma)$
  - Similar selection, detector unfolding
  - Observed somewhat harder $p_T$ spectrum than predicted at NLO (POWHEG, MINLO) or NNLO +NNLL (HRes)
  - No deviations seen in the leading jet spectrum, but a slight excess in the back-to-back dijets is seen

- N.B.: important to understand whether effect is real: we assume SM production in the search and if the $p_T$ spectrum is harder, the results may be biased

![Graphs showing differential measurements](image-url)

$\int L dt = 20.3 \text{ fb}^{-1}$
CMS H(γγ) Results

- Main analysis: MVA; cross-check: cut-in-categories (CiC)
  - Significances:
    - MVA: 3.2σ (4.2σ expected)
    - CiC: 3.9σ (3.5σ expected)
  - Mass: 125.4 ± 0.8 GeV

<table>
<thead>
<tr>
<th>μ-values:</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVA analysis (at m_H=125 GeV)</td>
</tr>
<tr>
<td>7 TeV</td>
</tr>
<tr>
<td>1.69±0.65</td>
</tr>
<tr>
<td>2.27±0.80</td>
</tr>
</tbody>
</table>

μ-values:

\[
\mu_{\text{MVA}} = 3.2 \sigma \\
\mu_{\text{CiC}} = 3.9 \sigma
\]

Mass: 125.4 ± 0.8 GeV
Main analysis: MVA; cross-check: cut-in-categories (CiC)

- Significances:
  - MVA: 3.2σ (4.2σ expected)
  - CiC: 3.9σ (3.5σ expected)

- Mass: $125.4 \pm 0.8$ GeV

### Significances

<table>
<thead>
<tr>
<th>Energy</th>
<th>MVA</th>
<th>CiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>1.69+0.65−0.59</td>
<td>2.27+0.80−0.74</td>
</tr>
<tr>
<td>8 TeV</td>
<td>0.55+0.29−0.27</td>
<td>0.93+0.34−0.32</td>
</tr>
<tr>
<td>7 + 8 TeV</td>
<td>0.78+0.28−0.26</td>
<td>1.11+0.32−0.30</td>
</tr>
</tbody>
</table>

μ-values:
Angular/Width Analysis

- Use CiC/MVA $H(\gamma\gamma)$ analyses to:
  - Look for additional Higgs bosons (with SM-like couplings; in gg fusion only; and VBF only)
  - Look for nearly mass-degenerate additional Higgs bosons
  - Set a limit on the Higgs boson width
  - Study the Higgs boson spin-parity (see Fabio’s talk)

- $\Gamma_H < 6.9 \ (5.9 \text{ exp.})$ GeV - first direct limit on the width

$(\sigma \times \text{Br})_{\text{SM}} = 0.044 \text{ pb @ 8 TeV}$

$\Gamma_H < 6.9 \ (5.9 \text{ exp.})$ GeV - first direct limit on the width

CMS PAS HIG-13-016

$\Gamma_H < 6.9 \ (5.9 \text{ exp.})$ GeV - first direct limit on the width

CMS Preliminary

$\Gamma_H < 6.9 \ (5.9 \text{ exp.})$ GeV - first direct limit on the width

CMS Preliminary

$\Gamma_H < 6.9 \ (5.9 \text{ exp.})$ GeV - first direct limit on the width
- High-yield, low-resolution channel
  - Most discriminating variables: $M_{ll}$ and $M_T$ (dilepton transverse mass)
  - Search done in 0-, 1-, and 2-jet categories; in the ee, $e\mu$, and $\mu\mu$ channels

- ATLAS: fit to the $M_T$ distribution
- CMS: 2D analysis in $M_{ll}$ vs. $M_T$ for the $e\mu$ channel and cut-based analysis for the same-flavor channels (also as a cross-check in $e\mu$)
Significant excess is observed:

**ATLAS**

- \( m_H = 125.5 \text{ GeV} \)
- \( \sigma^{(\text{stat})} \)
- \( \sigma^{(\text{sys})} \)
- Total uncertainty \( \pm 1\sigma \) on \( \mu \)

<table>
<thead>
<tr>
<th>Process</th>
<th>( \mu ) (95% CL)</th>
<th>( \sigma^{(\text{sys})} )</th>
<th>( \sigma^{(\text{theo})} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow WW^{(*)} \rightarrow l\nu\nu )</td>
<td>0.99±0.31</td>
<td>±0.21</td>
<td>±0.12</td>
</tr>
<tr>
<td>0+1 jet</td>
<td>0.82±0.33</td>
<td>±0.22</td>
<td>±0.5</td>
</tr>
<tr>
<td>2 jet VBF</td>
<td>1.4±0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \sqrt{s} = 8 \text{ TeV} \) \( \int L dt = 20.7 \text{ fb}^{-1} \)

**ATLAS Preliminary**

- \( m_H = 125 \text{ GeV} \)
- signal significance: 3.8\( \sigma \) observed
- 3.8\( \sigma \) expected

**CMS**

- \( m_H = 125 \text{ GeV} \)
- signal significance: 4.0\( \sigma \) observed
- 5.1\( \sigma \) expected

**Observation**

- \( \mu = 0.76 \pm 0.21 \)

**ATLAS-CONF-2013-030**

**CMS PAS HIG-13-003**
**Significant excess is observed:**

**ATLAS**

- $m_H = 125.5$ GeV
- $\sigma_{\text{(stat)}}$
- $\sigma_{\text{(sys)}}$
- $\sigma_{\text{(theo)}}$
- Total uncertainty
- $\pm 1\sigma$ on $\mu$

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow WW^* \rightarrow l^+l^-\nu\bar{\nu}$</td>
<td>$0.99^{+0.31}_{-0.28}$</td>
<td>$0.12$</td>
</tr>
<tr>
<td>$0+1$ jet</td>
<td>$0.82^{+0.33}_{-0.32}$</td>
<td>$0.22$</td>
</tr>
<tr>
<td>$2+1$ jet VBF</td>
<td>$1.4^{+0.7}_{-0.6}$</td>
<td>$0.5$</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 7$ TeV, $\int L dt = 4.6-4.8$ fb$^{-1}$

$\sqrt{s} = 8$ TeV, $\int L dt = 20.7$ fb$^{-1}$

**Signal strength ($\mu$)**

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\int L dt$</th>
<th>$\sigma$ ($\pm 1\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$7$ TeV</td>
<td>$4.6-4.8$ fb$^{-1}$</td>
<td>$0.21$</td>
</tr>
<tr>
<td>$8$ TeV</td>
<td>$20.7$ fb$^{-1}$</td>
<td>$0.21$</td>
</tr>
</tbody>
</table>

**NEW!**

**ATLAS**

- Preliminary
- $H \rightarrow WW \rightarrow e^+e^-\nu\bar{\nu}$, SM width
- $\sqrt{s} = 8$ TeV, $\int L dt = 20.7$ fb$^{-1}$

**95% C.L. Limit on $\sigma \times \text{BR}$ [pb]**

$\sigma_{\text{th}} \times \text{BR}$

**CMS**

- Preliminary
- $H \rightarrow WW \rightarrow 4l$ jet VBF
- $\sqrt{s} = 7$ TeV, $L = 4.9$ fb$^{-1}$
- $H \rightarrow WW \rightarrow 2l2\nu$ /0/1-jet

**CMS PAS HIG-13-003**

- Observed signal significance:
  - 4.0$\sigma$ observed
  - 5.1$\sigma$ expected
- $m_H = 125$ GeV

**ATLAS-CONF-2013-067**

Search for high-mass Higgs
Adding VH(WW)

- A bit extra help from the VH(WW) in 3-lepton (ATLAS+CMS), 4-lepton (ATLAS), and lljj (CMS) final states
- ATLAS: combination with the H(WW) analysis:
  - $4.0\sigma$ ($3.8\sigma$ exp.) significance at $m_H = 125$ GeV

ATLAS-CONF-2013-075

ATLAS Preliminary VH→VWW→3 or 4 leptons

- Obs.
- Exp.
- $\pm 1\sigma$
- $\pm 2\sigma$

$\sqrt{s} = 7$ TeV; $Ldt = 4.7$ fb$^{-1}$
$\sqrt{s} = 8$ TeV; $Ldt = 20.7$ fb$^{-1}$

W(lν)H(WW) + Z(ll)H(WW)

CMS PAS HIG-13-009

V(jj)H(WW)

95% CL limit on $\sigma/\sigma_{SM}$

Higgs mass (GeV)

110 115 120 125 130 135 140

SM $\sigma/\sigma_{SM}$

95% CL limit on $\sigma/\sigma_{SM}$

observed

median expected

expected $= 1\sigma$

expected $= 2\sigma$

L = 19.5 fb$^{-1}$ ($\sqrt{s} = 8$ TeV)

L = 4.9 fb$^{-1}$ (7 TeV) + 19.5 fb$^{-1}$ (8 TeV)

W(lν)H(WW)

CMS PAS HIG-13-009

95% CL limit on $\sigma/\sigma_{SM}$

Higgs mass [GeV]

110 120 130 140 150 160 170 180 190 200

observed

median expected

expected $= 1\sigma$

expected $= 2\sigma$
Visible Higgs
Sensitivity is dominated by the VH(bb) channel

Evidence for VZ(bb) production consistent with $\sigma_{SM} = 4.4 \pm 0.3$ pb

Spin-parity is being investigated as well (see Fabio’s talk)

$\sim 3\sigma$ significance @ $m_H = 125$ GeV
Search done in 0-, 1-, and 2-lepton categories, further split in bins of $p_T(V)$:

- $\mu = 0.2^{+0.7}_{-0.6}$
- Limit: $\mu < 1.4$ (1.3 exp.) at $m_H = 125$ GeV

$\mu_{VH(bb)} = 0.2^{+0.7}_{-0.6}$

Limit: $\mu < 1.4$ (1.3 exp.) at $m_H = 125$ GeV
Combines the W(lv) (including \(\tau\)), Z(ee,\(\mu\mu,\nu\nu\)) channels; BDT is used in most

- \(M_{bb}\) resolution \(\sim 10\%\), after regression

- Observed a \(2.1\sigma\) excess (\(2.1\sigma\) expected)
  - Over \(7\sigma\) significance for the VZ(bb) signal

- Corresponding signal strength:
  - \(\mu = 1.00 \pm 0.49\) at \(M_H = 125\) GeV
CMS: VBF H(bb)

- Interesting channel, directly comparable with VH(bb)
- New analysis from CMS @ 8 TeV
- Based on an ANN, with input variables describing properties of the two b-jets in the event and two VBF tagged jets
  - See a clear Z(bb) peak after preselection
- Combination done with the VH(bb) results
CMS: VBF H(bb)

- Interesting channel, directly comparable with VH(bb)
- New analysis from CMS @ 8 TeV
- Based on an ANN, with input variables describing properties of the two b-jets in the event and two VBF tagged jets
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CMS Preliminary
\( \sqrt{s} = 8 \text{ TeV} \)
\( L = 19.0 \text{ fb}^{-1} \)
VBF \( H \rightarrow b\bar{b} \)

Higgs Mass (GeV)
CMS: VBF $H(bb)$

- Interesting channel, directly comparable with VH$(bb)$
- New analysis from CMS @ 8 TeV
- Based on an ANN, with input variables describing properties of the two b-jets in the event and two VBF tagged jets
  - See a clear $Z(bb)$ peak after preselection
- Combination done with the VH$(bb)$ results

![Graph](attachment:image.png)
H(ττ) in CMS

- Updated to full statistics; based on eμ, μμ, eτh, μτh, and τhτh channels
- Analysis is done separately in 0-, 1-, and 2-jet (VBF) categories
  - 0- and 1-jet categories are each split in two, depending on the pT of the τ-decay products
  - τhτh doesn’t use 0-jet category and the 1- and 2-jet categories are not split
- Also include VH(ττ) channels
- Optimized ττ mass reconstruction (SVFIT) with ~20% resolution
- Benefits significantly from particle-flow reconstruction

Embedding (replace μ with simulated τ in Z(μμ) sample); normalization from Z(μμ) (5% syst.)

Dominated by W+jets; shape from simulation; normalization from control regions (10-20% syst.)

QCD: from SS sample (10% syst.)
CMS: H(ττ) Results

- Observed 2.9σ (2.6σ exp.) for m_H = 125 GeV
- Combined with VH(bb), CMS sees an evidence for the Hff coupling to the 3rd-generation down-type fermions at 3.4σ (3.4σ exp.)
- First mass measurement in this channel:
  - m_H = 120^{+9}_{-7} GeV

CMS PAS HIG-13-004

| m_H [GeV] | CMS Preliminary, \(\sqrt{s}=7-8 \text{ TeV}, L=24.3 \text{ fb}^{-1}, H \to \tau \tau \)
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>0.00</td>
</tr>
<tr>
<td>120</td>
<td>1.00 ± 1σ expected</td>
</tr>
<tr>
<td>130</td>
<td>2.00 ± 2σ expected</td>
</tr>
<tr>
<td>140</td>
<td>3.00 ± 3σ expected</td>
</tr>
</tbody>
</table>

Observed 2.9σ (2.6σ exp.) for m_H = 125 GeV

Combined with VH(bb), CMS sees an evidence for the Hff coupling to the 3rd-generation down-type fermions at 3.4σ (3.4σ exp.)

First mass measurement in this channel:

- m_H = 120^{+9}_{-7} GeV

CMS PAS HIG-13-004
H(ττ) in ATLAS

- Analysis hasn’t been updated to full statistics yet
- Uses similar techniques as the CMS analysis
- \( \mu = 0.7 \pm 0.7; \) significance 1.1σ (1.7σ exp.)
H(Z\gamma) Results

- Similar branching fraction to H(\gamma\gamma), but an additional price to pay for the leptonic branching fraction of the Z
- Decay can be enhanced/suppressed independently of H(\gamma\gamma)
  - Sensitive to new physics via loops
- Not sensitive to the SM Higgs boson (yet), set the following limits:
  - ATLAS: \( \mu < 18.2 \) @ 95% CL (13.5 expected)
  - CMS: \( \mu < 10 \) @ 95% CL (10 expected)
Observing $H(\mu\mu)$ decay may be the only way to prove non-flavor-universal couplings of the Higgs boson

- N.B. Coupling to charm is very hard to probe
- Requires very large statistics for observation: a strong case for HL-LHC
- First search has been done already by ATLAS
  - Sets limit $\mu < 9.8$ (8.2 expected) @ 95% CL
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$$Br = 3.0^{+1.0}_{-0.9} \times 10^{-9}$$
ttH - the New Player

- Very challenging mode, requires tour-de-force analysis
- Important backgrounds from tt+X, typically poorly known theoretically and experimentally
- The only channel that offers direct probe of the Htt coupling at tree level
- Long history: from the first paper suggesting this as a promising channel at the Tevatron (2001), to “oscillations” on whether it is feasible at the LHC, to first successful analysis a decade later
  - First LHC search: CMS, JHEP 05 (2013) 145 (March 2013)
- Today, we are close to an answer to the feasibility question!
CMS Search in $ttH(bb+\tau\tau)$

- **New analysis; supersedes recent publication arXiv:1303.0763 based on 5+5 fb$^{-1}$**
  - Updated to the full 2012 statistics (7 TeV not reanalyzed) and added the $\tau\tau$ decay channel (8 TeV only)
  - $tt$ decays are reconstructed in the lepton+jets and dilepton channel; 2 or more b-tagged jets required for the $ttH(bb)$ search
  - $H(\tau\tau)$ decays are looked for in $\tau_1\tau_2$ channel, with $tt$ decaying in lepton+jets, with 1 or 2 b-tagged jets
  - Signal extraction via BDTs; separate BDTs for each jet and b-tagged jet multiplicity

**CMS PAS HIG-13-019**

![Slide](image-url)
ttH Results

✦ ttH(bb+ττ) results:
  ○ μ < 5.2 (4.1 exp.) @ 95% CL, m_H = 125 GeV
  ○ Also a recent result in ttH(γγ) channel
    ○ All-hadronic and semileptonic tt decays with loose selection and at least one b-tagged jet
    ○ Analysis of the diphoton mass spectrum similar to that in the H(γγ) analysis
    ○ μ < 5.4 (5.3 exp.) @ 95% CL, m_H = 125 GeV
CMS combined results:
- $\mu < 3.4$ (2.7 expected)
- Would improve even more when additional channels are added and combined with ATLAS (once the analysis is updated)
- Closing on the SM Higgs boson sensitivity!
  - Soon to become the 6th of the “big” channels and can be moved into “visible” category of my talk!

[Graph of ttH Combination]

- CMS PAS HIG-13-015
- CMS PAS HIG-13-019
- arXiv:1303.0763

Breaking news - brand new ATLAS ttH($\gamma\gamma$) 8 TeV result: $\mu < 5.3$ (6.4 exp.)
Invisible Higgs
Given the accuracy of present measurement of Higgs branching fractions, there is a lot of room for non-SM decays, e.g. decays into invisible particles.

Many theoretical models predict such decays, e.g.:
- Higgs coupled to light dark matter
- Hidden valley models
- Right-handed neutrino models

Search is done in associated production with the Z boson decaying leptonically.

- Discriminating variables: $M_{E_T}$ (ATLAS), $M_T$ (CMS)

**ATLAS** ($4.7 + 13.0 \text{ fb}^{-1}$):
- $\text{Br}(H \rightarrow \chi \chi) < 65\%$ (84\% exp.) @ 95\% CL, $m_H = 125 \text{ GeV}$

**CMS** ($5 + 20 \text{ fb}^{-1}$):
- $\text{Br}(H \rightarrow \chi \chi) < 75\%$ (91\% exp.) @ 95\% CL, $m_H = 125 \text{ GeV}$
Invincible Higgs
Many extensions of the SM predict more than one Higgs doublet

A classic realization of 2HDM (two-Higgs-doublet model) is SUSY, or its constrained version, MSSM

- Additional heavy CP-even neutral Higgs boson $H$, CP-odd neutral $A$, and $H^\pm$

Thus, it’s very important to continue searches for additional Higgs bosons at high and low masses, in both SM and exotic decay channels

This has been by now realized even by the journal editors!
Look for heavy CP-conserving Higgs boson $H(WW)$ decays

Consider separately VBF and gluon fusion production

Probe two type of 2HDM:
- Type I - all quarks couple only to one doublet
- Type II - all up-type right-handed quarks couple to one doublet, and down-type to the other

Ratio of VBF and gluon fusion production is modified

Important parameters: $\tan\beta$ - the ratio of two vevs, and $\cos\alpha$, which determines coupling of $H$ to fermions ($\sim \sin\alpha/\sin\beta$ in Type I or to up quarks in Type II)
MSSM Higgs Searches

- Most recent results on the H/A(ττ), including the new LHCb search exploiting τ’s in the forward region.
- Also, limits on charged Higgs from top decays in τν (ATLAS+CMS) and cs (ATLAS) channels and search for NMSSM h → a₀a₀ → 4μ (CMS, D0), 4γ (ATLAS) and a₁ → 2μ (ATLAS & CMS), as well as Y(1S,2S) → a₀γ → ττγ, μμγ (BaBar, Belle); and ggγ, and ssγ (BaBar).

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ATLAS Preliminary
MSSM combination
∫ Ldt = 4.7 - 4.8 fb⁻¹
L = 7 TeV
mₚmax, μ>0

- Observed CLs
- Expected CLs
- ± 1σ
- ± 2σ
- LEP

CMS Preliminary, √s = 7+8 TeV, L = 17 fb⁻¹
95% CL Excluded Regions

- Observed
- LEP

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LHCb Collaboration
arXiv:1304.2591
Additional Higgs Searches

- **γγ/WW channels** (shown earlier in the talk)
- **Invisible channel:**
  - Heavy Higgs decaying into ZZ(llνν) or ZZ(lljj)

**ATLAS-CONF-2013-011**

**CMS PAS HIG-13-014**

**CMS Preliminary 2012 5.3,19.6 fb⁻¹ ∫ = 7.8 TeV, s⁻¹**

**CMS PAS HIG-12-024**

**NEW!**

- Higgs boson mass [GeV] 200 400 600 800 1000
- 95% CL limit: \( \frac{\sigma_{ZH,SM}}{\sigma_{ZH}} \)
A combined high-mass ZZ search to full statistics

- Probes SM-like heavy Higgs up to ~900 GeV
- Also explore modified couplings and reduced (by $C'^2$) width of an additional Higgs boson

$C^2 + C'^2 = 1$
Higgs: Boosted Topology

- New search in the $W(l\nu)W(\text{"jet")}$ channel in a boosted regime
  - Sensitive to Higgs masses above ~600 GeV
- Also $t\bar{t}$ resonance searches can be reinterpreted as limits on a heavy Higgs boson

![Graph showing Higgs boson mass and limits](image)

**CMS PAS HIG-13-008**

![Graph showing Z' mass and limits](image)

**ATLAS Preliminary**

**CMS PAS B2G-12-006**

![Graph showing tt invariant mass and limits](image)
Higgs physics remains the apex of the LHC program

- Amazing progress since the discovery of a Higgs boson just a year ago:
  - Seen beyond any doubts in three bosonic channels
  - Looks more and more like the SM Higgs boson
  - No evidence for non-SM decays yet
  - No evidence for additional Higgs bosons at higher or lower mass so far
- Coupling to the top quarks has been established via gluon fusion production mechanism
- Couplings to the down-type third-generation fermions are established at >3 sigma level, thanks to the Tevatron and the LHC efforts
- The spin and the mass of a new state have been determined (see next talk)
- Many new directions of studies, with an exciting LHC program that will last some two decades
  - Cf. nearly 20 years of beautiful top physics since its discovery in 1995
- The goal is to shrink the error bars to dots on the “Regge plot” above and fill it in

**Slide**

**Conclusions**

**CMS PAS HIG-13-005**
Thank You!