Latest Results on the Standard Model Higgs Searches at the LHC

Koji Nakamura On behalf of CMS and ATLAS collaboration
Independence day in U.S.

• Examples of NEWS PAPERS

Physicists Find “Elusive Particle” Seen as Key to Universe.
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Examples of NEWS PAPERS

Physicists Find “Elusive Particle” Seen as Key to Universe.

Independence day in U.S.

of a New Boson
Seminar at July 4th

In summary

We have observed a new boson with a mass of \(125.3 \pm 0.6\) GeV at \(4.9\) \(\sigma\) significance!

Global Effort \(\Rightarrow\) Global Success

Results today only possible due to extraordinary performance of accelerators – experiments – Grid computing

Observation of a new particle consistent with a Higgs Boson (but which one...?)

Historic Milestone but only the beginning

Global Implications for the future

- How does it observed?
- What should we do next?
LHC experiments

- 7TeV collisions are Started in March 2010.
- Extremely successful operation for these 2.3 years.
- Upgraded CM energy to 8TeV in 2012.
• Thanks to very smooth operation of LHC, **4.8-5.1 fb^{-1}** of 7TeV and **5.3-5.8 fb^{-1}** of 8TeV data are available to use for the physics analysis.

• Thanks to 8TeV collisions, the same sensitivity can be achieved by 80% of integrated luminosity data (**25% gain**).
Understanding data

• We had many experience in these two years to understand both detector and Physics backgrounds.
  – Although need better understanding of the tail of SM processes to observe “New particle”.

• What we had to understand in addition to the 2010 and 2011 data was Pileup events!

Peak value of instantaneous luminosity

<table>
<thead>
<tr>
<th>Year</th>
<th>Peak Luminosity [10^{33} cm^{-2} s^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
</tr>
</tbody>
</table>

Number of interaction per crossing

- ATLAS Online Luminosity

July 13th, 2011

IPMU seminar
Pileup effect and removals

- Each object reconstruction was affected by pileup jets.
- Track in jets can be used to suppress the effect since tracking can point the vertex.
- Defined Jet Vertex Fraction (JVF)
  \[ \text{JVF} = \frac{\sum_{PV} p_T^{track}}{\sum_{ALL} p_T^{track}} \]
- Jet: identify the jets by requiring JVF > 0.75 (0.5) in 2011 (2012) data.
- MET: JVF fractions are multiplied to the Jets before summing up the transverse energy.
  - Huge improvement of MET resolution.
- Lepton isolation: Npv correction have to be applied.
- Tau: track impact parameter ($Z_0$) are tightened to avoid pileup tracks.
Higgs production and decay @ LHC

Gluon Fusion (ggF)
Vector Boson Fusion
W/Z Associated
(tt/bb Associated)

All of bb, WW, ττ, γγ, ZZ can be observed!!
## Analysis Channels

### CMS

<table>
<thead>
<tr>
<th>H decay</th>
<th>H prod</th>
<th>Exclusive final states</th>
<th>Analyses</th>
<th>No. of channels</th>
<th>$m_H$ range (GeV)</th>
<th>$m_H$ resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma \gamma$</td>
<td>untagged</td>
<td>$\gamma \gamma$ (4 diphoton classes)</td>
<td>VBF-tag</td>
<td>4</td>
<td>110-150</td>
<td>1.2%</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>VH-tag</td>
<td>$b\bar{b}$ (with 2 b-jets)</td>
<td>(low or high $p_T^b$ for 8 TeV)</td>
<td>1 or 2</td>
<td>110-150</td>
<td>1.2%</td>
</tr>
<tr>
<td></td>
<td>VH-tag</td>
<td>$b\bar{b}$ (with 2 b-jets)</td>
<td>(low or high $p_T^b$)</td>
<td>10</td>
<td>110-135</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>VH-tag</td>
<td>$b\bar{b}$ (with 2 b-jets)</td>
<td>(with 2 or $\geq 3$ b-tagged jets)</td>
<td>9</td>
<td>110-140</td>
<td>5%</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+ \tau^-$</td>
<td>0/1-jets</td>
<td>$(\tau^+\tau^-)$ (with 0 or 1 jets)</td>
<td>VBF-tag</td>
<td>16</td>
<td>110-145</td>
<td>20%</td>
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<tr>
<td></td>
<td>0/1-jets</td>
<td>$(\tau^+\tau^-)$ (with 0 or 1 jets)</td>
<td>WH-tag</td>
<td>4</td>
<td>110-145</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>0/1-jets</td>
<td>$(\tau^+\tau^-)$ (with 0 or 1 jets)</td>
<td>2H-tag</td>
<td>8</td>
<td>110-160</td>
<td>5%</td>
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<tr>
<td>WW $\rightarrow l_1l_2q_1q_2$</td>
<td>untagged</td>
<td>WW $\rightarrow l_1l_2q_1q_2$ (DF or SF dileptons)</td>
<td>VBF-tag</td>
<td>3</td>
<td>110-140</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>0/1-jets</td>
<td>WW $\rightarrow l_1l_2q_1q_2$ (DF or SF dileptons)</td>
<td>WH-tag</td>
<td>4</td>
<td>110-600</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>0/1-jets</td>
<td>WW $\rightarrow l_1l_2q_1q_2$ (DF or SF dileptons)</td>
<td>2H-tag</td>
<td>1</td>
<td>110-200</td>
<td>4.9</td>
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<td>ZZ $\rightarrow 4\ell$</td>
<td>inclusive</td>
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<td>VBF-tag</td>
<td>4</td>
<td>110-600</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>inclusive</td>
<td>ZZ $\rightarrow 4\ell$ (with 0, 2 b-tags)</td>
<td>VBF-tag</td>
<td>8</td>
<td>110-600</td>
<td>10-15%</td>
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<td>ZZ $\rightarrow 2\ell_12\ell_2$</td>
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<td>ZZ $\rightarrow 2\ell_12\ell_2$ (with 0, 2 b-tags)</td>
<td>VBF-tag</td>
<td>6</td>
<td>130-164</td>
<td>3%</td>
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<td>ZZ $\rightarrow 2\ell_12\ell_2$ (with 0, 2 b-tags)</td>
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<td>6</td>
<td>200-600</td>
<td>7%</td>
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<td>ZZ $\rightarrow 2\ell_12\ell_2$</td>
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<td>ZZ $\rightarrow 2\ell_12\ell_2$ (with 0, 2 b-tags)</td>
<td>VBF-tag</td>
<td>2</td>
<td>200-600</td>
<td>7%</td>
</tr>
</tbody>
</table>

### ATLAS

<table>
<thead>
<tr>
<th>Higgs Decay</th>
<th>Subsequent Decay</th>
<th>Sub-Channels</th>
<th>$m_H$ Range [GeV]</th>
<th>$\int L , dt$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$\ell\ell\ell\ell$</td>
<td>$\ell\ell\ell\ell$</td>
<td>110-150</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>$\ell\ell\ell\ell$</td>
<td>$\ell\ell\ell\ell$</td>
<td>110-600</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>$\ell\ell\ell\ell$</td>
<td>$\ell\ell\ell\ell$</td>
<td>200-280-600</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\ell\ell\ell\ell$</td>
<td>$\ell\ell\ell\ell$</td>
<td>200-300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>$\tau^+\tau^-$</td>
<td>$\tau^+\tau^-$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\tau^+\tau^-$</td>
<td>$\tau^+\tau^-$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\tau^+\tau^-$</td>
<td>$\tau^+\tau^-$</td>
<td>300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$\ell\ell\ell\ell$</td>
<td>$\ell\ell\ell\ell$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\ell\ell\ell\ell$</td>
<td>$\ell\ell\ell\ell$</td>
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<td>$\ell\ell\ell\ell$</td>
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<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$\ell\ell\ell\ell$</td>
<td>$\ell\ell\ell\ell$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
</tbody>
</table>

### Additional Information

- **7 TeV**
- **8 TeV**
H → γγ
Event selection & categorization

- Select di-photon with MVA id. (except ATLAS 8TeV)
  - ATLAS : $p_T1 > 40\text{GeV}$, $p_T2 > 30\text{GeV}$
  - CMS : $p_T1 > m_{\gamma\gamma}/3$, $p_T2 > m_{\gamma\gamma}/4$

- Categorizers
  - Converted photon event or un-converted
  - Calorimeter transition region (ATLAS)
  - Higgs $p_T$ thrust variable (ATLAS)

- CMS used MVA selection
  - 4 category by MVA score.

- ATLAS have cut based 9 categories

- One (or two) more category “VBF” for experiments.

\[
\vec{t} = \vec{p}_T(\gamma_1) - \vec{p}_T(\gamma_2)
\]
Inclusive view

- These plots were not used for the any sensitivity calculations, but just illustrating purpose.
- CMS events are weighted by sensitivity. (1.67GeV/bin ??)
Results: Discovery significance

**ATLAS**

Expected significance $2.4\sigma$

Observed significance $4.5\sigma$ (global significance $3.6\sigma$)

**CMS**

Expected significance $2.6\sigma$

Observed significance $4.1\sigma$ (global significance $3.2\sigma$)
Signal cross section times branching ratio

**ATLAS**

**CMS**

Best fit Signal strength

1.9 ± 0.5

1.56 ± 0.43
H → ZZ
Event selection

- Select a pair of same-flavour opposite-charge di-leptons.
  - ATLAS: \( p_{T1,2,3,4} > 20,15,10,7(6) \) GeV for e(\(\mu\))
  - CMS: \( p_{T1,2,3,4} > 20,10,7(5),7(5) \) GeV for e(\(\mu\))

- At least one Z candidate have:
  - ATLAS: \( m_{\text{thr}} < m_{ll} < 120 \) \( m_{\text{thr}} = 17.5-50 \) (22.5 @125GeV)
  - CMS: \( 40 < m_{ll} < 120 \)
  - Isolations and \( dR(ll) \) cut(ATLAS) or \( m_{ll} \) for second Z \( m_{ll} > 4 \) GeV (CMS)

### Table

<table>
<thead>
<tr>
<th></th>
<th>ATLAS [120-130]</th>
<th>CMS [110-160]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ bkg.</td>
<td>(22.5±0.8)</td>
<td>15.5±1.0</td>
</tr>
<tr>
<td>Z+jets+top</td>
<td>(11.8±1.4)</td>
<td>4.4+2.2-1.7</td>
</tr>
<tr>
<td>Bkg total</td>
<td>5.1±0.8</td>
<td>19.9±2.4</td>
</tr>
<tr>
<td>mH 126GeV</td>
<td>5.3±0.8</td>
<td>8.3±1.2</td>
</tr>
</tbody>
</table>

() is the number for 0-160GeV

\( p_T \) of the 4 leptons

July 13th, 2011
Results: $m_{4l}$ distribution

ATLAS Preliminary

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

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

$\sqrt{s} = 8$ TeV: $\int L dt = 5.8$ fb$^{-1}$
CMS: Additional improvement by ME

- Decay kinematic fully described by 5 angles and 2 masses
  - discriminates spin 0 particle from background
  - analogous of $\Delta \phi$ in $H \rightarrow WW$ analysis
  - MELA: matrix element likelihood analysis

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

PRD81, 075022(2010)

Normalized plots showing SM H(125 GeV) and qqZZ.
Background

Signal @126GeV

Data points are the same for both plots.
Background

Data points are the same for both plots.

If data is only background, not much events are expected in this region.
Data points are the same for both plots. If data is only background, not much events are expected in this region.
Results: Discovery significance

Local $p_0$
ATLAS
3.4$\sigma$ at 125GeV, expected 2.6$\sigma$

Local $p_0$
CMS
3.2$\sigma$ at 125.5GeV, expected 3.8$\sigma$
$H \rightarrow WW$
Event selection & background estimation

- two leptons + Missing ET
- ggF : 0,1 jet, VBF : 2 jets

**W+jets**
Fake lepton background.
Prepare Loose lepton CR
And multiplied by Fake rate.

**WW**
Normalized by WW control region.

**Top**
Apply b-tagging to enhance ttbar background.

**Z+jets**
MET vs mll
Mainly for met correction.
Distributions in signal region

**ATLAS**

$\text{1s} = 7 \text{ TeV}, \int \text{L dt} = 4.7 \text{ fb}^{-1}$

$\text{H} \rightarrow \text{WW}^{(*)} \rightarrow \ell\ell\nu\nu + 0 \text{ jets}$

$\text{m}_T \text{[GeV]}$

$0\text{jet}$

$1\text{jet}$

**CMS**

$\text{CMS Preliminary} \quad \sqrt{s} = 8 \text{ TeV} \quad L = 5.10 \text{ fb}^{-1}$

$\Delta\phi_{1,1} \text{[°]}$

Events / 10 GeV

Events / 10.0°
Results: 95% CL upper limit

- Excluded wide range.
- No significant $>3\sigma$ excess.
- ATLAS will include 8TeV soon.
Observation of new particle (including $\tau\tau$ and $bb$)
Results: Discovery significance

ATLAS (expected=4.6σ)
Local $p_0 = 3.0 \times 10^{-7} \Rightarrow 5.0\sigma$ at 126.5GeV

CMS (expected=5.6σ)
Local $p_0 = 5.5 \times 10^{-7} \Rightarrow 4.9\sigma$ at ~125GeV
Large range and LEE?

Look Elsewhere Effect (global significance)
ATLAS
4.1σ (110-600GeV),
4.3σ (110-150GeV)
CMS
4.0σ (110-600GeV),
4.5σ (115-130GeV),
4.4σ (110-145GeV)

• Here is only one place we observed significant excess
• LEE is just a protection to avoid wrong discovery.
Signal strength as a function of $m_H$

Best Fit Signal Strength

**ATLAS Preliminary**

- $\sqrt{s} = 7$ TeV: $|Ldt| = 4.6-4.8$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV: $|Ldt| = 5.8-5.9$ fb$^{-1}$

- Best fit
- $-2 \ln \lambda(\mu) < 1$

**CMS Preliminary**

- $\sqrt{s} = 7$ TeV: $L = 5.1$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV: $L = 5.3$ fb$^{-1}$

- 68% CL band

**Best Fit Signal Strength**

- **ATLAS**: $1.2^{+0.3}_{-0.3}$ at 126.5 GeV
- **CMS**: $0.88^{+0.22}_{-0.22}$ at $\sim$125 GeV

July 13th, 2011
History of the observed significance

![Graph showing the history of the observed significance over time, with data points from EPS July 2011, CERN Seminar 12/2011, Spring 2012, and 4 July 2012.]
Possibility of second Higgs?

- If second higgs have the same cross section...

  - Excluded except very high mass (>500GeV) by 99% CL

July 13th, 2011
IPMU seminar
Possibility of second Higgs?

• If the cross section is lower than SM...

• Of course possible.
What should we do next?
What should we do next?

- Mass measurement → can be done by $\gamma\gamma/ZZ$
  - To prove the scale of breaking?
  - But 0.5GeV precision is really necessary?
- Spin measurement → spin 0 or 2? WW/ZZ?
  - Spin 0 is necessary, if this is Higgs.
- Coupling measurement
  - Almost sure the quark Yukawa does exist (by ggF discovery) and may be via top Yukawa coupling.
  - But how about Yb? $Yb \sim m_b/246\text{GeV}$?
  - $H \rightarrow \tau\tau$ must be only the channel which can indicate about lepton Yukawa coupling.
Mass measurement

Note: ATLAS did not mention this as “mass measurement”. But only the “consistency among channels”

CMS: mX = 125.3 ± 0.6 GeV
Spin of the observed particle

• It should be spin 0 or 2 by observation of $\gamma\gamma$ decay.
• But which?
  – We heavily rely on the spin=0 information in the analysis. $\rightarrow$ WW and ZZ

Truth level study
No acceptance cut applied

Need to perform quantitative study
Coupling I

- Gauge boson and fermion.

\[ \text{CMS all channel fit.} \]

- \( c_V = \) coupling to W and Z
- \( c_F = \) coupling to fermion
- \( \gamma \gamma \Rightarrow \) ratios from the SM Higgs

\[ R_{WW/ZZ} = \frac{G_w}{G_z} = 0.9^{+1.1}_{-0.6} \]

Measured by CMS.
Coupling II

- Fermion coupling!
- Need $\tau\tau$ and $bb$. 

![Diagram of fermion coupling and Higgs decays](image-url)
H → bb
Main background and estimation.

Top, W+jets, Z+jets bkg are normalized by control region and side band region.

Top

WH : 3jets instead of two.
ZH : Zmass veto + MissingEt.

W/Z+jets
replace/loosen the b-tagging cut.
Results: distributions (a part)

**ATLAS**

- $WH \rightarrow \ell vv b\bar{b}$
- $ZH \rightarrow \nu\bar{\nu} b\bar{b}$

**CMS**

- $WH \rightarrow \ell vv b\bar{b}$
- $ZH \rightarrow \ell^+ \ell^- b\bar{b}$

July 13th, 2011

IPMU seminar
Result: ATLAS 7TeV (5fb⁻¹)

- Set 95% CL upper limit on xsec.
  - Expected: 2.5-5 x SM
  - Observed: 4.6 xSM @ 125GeV
- 2012 analyses with improvements are now ongoing.

- Almost reached to the SM xsec at mH<115GeV
  - Expected limits are ~1.1xSM
- Observed (Expected) limits @125GeV are 2(1.6)xSM
Event Topology and channels

- Three Higgs production processes are considered in this analysis.
  - Separately analysis for three different $\tau\tau$ decay modes:
    - $\text{lep-lep} = l\ell 4\nu : (ee) + e\mu + \mu\mu$
    - $\text{lep-had} = l\tau_{\text{had}} 3\nu : e\tau_{\text{had}} + \mu\tau_{\text{had}}$
    - $\text{had-had} = \tau_{\text{had}} \tau_{\text{had}} 2\nu : (\tau_{\text{had}} \tau_{\text{had}})$
  - Combined all three channels to search for $H \rightarrow \tau \tau$ signature.
Event selection & background modeling

- Opposite sign tau decay products are required.
- High Missing ET and low MT cuts are added.

\(Z \rightarrow \tau\tau \) estimated by embedding -- used \(Z \rightarrow \mu\mu\) data and replace by full simulated \(\tau\)

\(Z \rightarrow ee/\mu\mu + \text{jets, Top} \) Estimated by MC with correction.

**QCD** – Estimated from Same Sign events (lephad) -- Template fit by loose selection (lep-lep,hadhad)
Result: Distributions (a part)

ATLAS

CMS

July 13th, 2011

IPMU seminar
Result: CMS 7TeV(4.9fb⁻¹)+8TeV(5.1fb⁻¹)

- Analysis improved. 2x improvement from 2011.
- Observed(Expected) limit is 1.06(1.3)xSM!

Observed limit: 2.8-12.1
Expected limit: 3.4-8.0
@ 100-150GeV Higgs mass
2012 analyses with improvements are now ongoing.
Observed limit: 2.8-12.1
Expected limit: 3.4-8.0
@ 100-150GeV Higgs mass
2012 analyses with improvements are now ongoing.

Improvement from 2011.
• Observed (Expected) limit is 1.06(1.3)xSM!
Result: CMS 7TeV(4.9fb$^{-1}$)+8TeV(5.1fb$^{-1}$)

- Is this happened even if SM Signal exist?
- Made limit plot by injecting SM signal
- Signal cross section best fit value:
  - ggF dominant category: consistent to SM prediction.
  - VBF category: downward fluctuation. In consistent to SM prediction.

![Graph showing CMS Preliminary results for H → ττ (0/1 jet), H → ττ (VBF tag), and H → ττ (VH tag) with m$_H$ = 125 GeV.]
Discussions about $\tau\tau$ and $bb$

- $\tau\tau$ and $bb$ decay modes are some of the most important channels to determine:
  - what we see is the Higgs!!
- ATLAS 2012 results will be published in September.
- Significant observation will be seen soon! (if exist)
- An anomaly(?) was observed by CMS VBF tautau channel.
  - Need to see the ATLAS results if we observed the same properties.
- First precision measurement coming soon!!

If your model would like to be tested could you let us know?
Coupling II

• Fermion coupling!
• Need $\tau \tau$ and $b\bar{b}$.

ATLAS Preliminary

-2ln$\lambda(\mu)<1$ Intervals

<table>
<thead>
<tr>
<th>Signal</th>
<th>$m_H = 119$ GeV</th>
<th>$m_H = 126.5$ GeV</th>
<th>$m_H = 130$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W, Z H \rightarrow b\bar{b}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau \tau$</td>
<td>$\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.8 - 4.7$ fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>$\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7$ fb$^{-1}$</td>
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<tr>
<td>$H \rightarrow WW$</td>
<td>$\sqrt{s} = 8$ TeV, $\mathcal{L} = 5.8$ fb$^{-1}$</td>
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<tr>
<td>$H \rightarrow ZZ$</td>
<td>$\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.8$ fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Combined | | | |
| $\mu = 0.5^{+0.2}_{-0.2}$ | | | |

2011 + 2012 Data

CMS Preliminary

-2ln$\lambda(\mu)<1$ Intervals

<table>
<thead>
<tr>
<th>Signal</th>
<th>$\sqrt{s} = 7$ TeV, $\mathcal{L} = 5.1$ fb$^{-1}$</th>
<th>$\sqrt{s} = 8$ TeV, $\mathcal{L} = 5.3$ fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$ (VH tag)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow bb$ (ttH tag)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow t\bar{t}$ (O/1 jet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau \tau$ (VH tag)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ (untagged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ (VBF tag)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW$ (O/1 jet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW$ (VBF tag)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Best fit $\sigma/\sigma_{SMH}$ | | |
| $\sigma/\sigma_{SMH} = 8$ | | |
Coupling II

- Fermion coupling!
- Need $\tau\tau$ and $bb$.

Will see how the couplings are converged.

$-2\ln\lambda(\mu) < 1$ Intervals

**ATLAS Preliminary**

$m_t = 119$ GeV

$m_t = 126.5$ GeV

$m_t = 130$ GeV

**CMS Preliminary**

$\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$

$\sqrt{s} = 8$ TeV, $L = 5.3$ fb$^{-1}$

$W, Z \rightarrow bb$

$\sqrt{s} = 7$ TeV, $L = 4.8 - 4.7$ fb$^{-1}$

$H \rightarrow \tau\tau$

$\sqrt{s} = 7$ TeV, $L = 4.7$ fb$^{-1}$

$H \rightarrow WW(1) \rightarrow $ $llll$

$\sqrt{s} = 7$ TeV, $L = 4.7$ fb$^{-1}$

$H \rightarrow \gamma\gamma$

$\sqrt{s} = 8$ TeV, $L = 5.9$ fb$^{-1}$

$H \rightarrow ZZ(1) \rightarrow$ IIII

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

Combined

$\sqrt{s} = 8$ TeV, $L = 5.8 - 5.9$ fb$^{-1}$

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

$\mu = -0.3^{+0.2}_{-0.0}$

$\mu = 1.2^{+0.3}_{-0.3}$

$\mu = 0.5^{+0.2}_{-0.2}$
Conclusion
Conclusion

![Graph showing diphoton sample data from ATLAS Preliminary.

- **Selected diphoton sample**
- **Data 2011 and 2012**
- **Sig + Bkg inclusive fit (m$_{jj} = 126.5$ GeV)**
- **4th order polynomial**

- **$\sqrt{s} = 7$ TeV, $\int Ldt = 4.8$ fb$^{-1}$**
- **$\sqrt{s} = 8$ TeV, $\int Ldt = 5.9$ fb$^{-1}$**

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Conclusion
Conclusion
Conclusion
Conclusion

Observation of a new boson at ~126GeV
Observation of a new boson at \(~126\text{GeV}\)

This is just the BEGINNING of Measuring properties And Prove New Physics!!
Back up
Generating MC events

- MC events of Minimum bias collisions are mixed to the each background and signal MC events.
- Pileup condition is certainly getting heavier as getting higher instantaneous luminosity.
- MC samples are generated for corresponding pileup conditions and re-weighting by data/MC so that the same pileup conditions are obtained in data and MC.

![Graph showing the average interactions per BX for different pileup conditions and the recorded luminosity for the 2011 pileup.]
Results: mass distribution ATLAS 7TeV

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Results: mass distribution ATLAS 8TeV
Results: mass distribution CMS 7TeV

![Graphs showing mass distribution for CMS 7TeV data with different categories: Untagged 0, Untagged 1, Untagged 2, Untagged 3, and Dijet tag.]
Results: mass distribution CMS 8TeV

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Weighted sensitivity

ATLAS Preliminary

Data 2011, $\sqrt{s} = 7$ TeV, $\int L dt = 4.8$ fb$^{-1}$

Data 2012, $\sqrt{s} = 8$ TeV, $\int L dt = 5.9$ fb$^{-1}$
Signal strength break down

- No single channel is deviated from SM expectation.
  - ■ is VBF dominant category.
  - □ is ggF dominant category.
4 lepton event yield

**event yields in 110-160 GeV**

<table>
<thead>
<tr>
<th>Channel</th>
<th>4e</th>
<th>4µ</th>
<th>2e2µ</th>
<th>4ℓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ background</td>
<td>2.7 ± 0.3</td>
<td>5.7 ± 0.6</td>
<td>7.2 ± 0.8</td>
<td>15.5 ± 1.0</td>
</tr>
<tr>
<td>Z+X</td>
<td>1.2^{+1.1}_{-0.8}</td>
<td>0.9^{+0.7}_{-0.6}</td>
<td>2.3^{+1.8}_{-1.4}</td>
<td>4.4^{+2.2}_{-1.7}</td>
</tr>
<tr>
<td>All backgrounds</td>
<td>3.9^{+1.1}_{-0.8}</td>
<td>6.6^{+0.9}_{-0.8}</td>
<td>9.5^{+2.0}_{-1.6}</td>
<td>19.9^{+2.4}_{-2.0}</td>
</tr>
<tr>
<td>$m_H = 120$ GeV</td>
<td>0.8 ± 0.2</td>
<td>1.6 ± 0.3</td>
<td>1.9 ± 0.5</td>
<td>4.4 ± 0.6</td>
</tr>
<tr>
<td>$m_H = 126$ GeV</td>
<td>1.5 ± 0.5</td>
<td>3.0 ± 0.6</td>
<td>3.8 ± 0.9</td>
<td>8.3 ± 1.2</td>
</tr>
<tr>
<td>$m_H = 130$ GeV</td>
<td>2.1 ± 0.7</td>
<td>4.1 ± 0.8</td>
<td>5.4 ± 1.3</td>
<td>11.6 ± 1.6</td>
</tr>
<tr>
<td>Observed</td>
<td>6</td>
<td>6</td>
<td>9</td>
<td>21</td>
</tr>
</tbody>
</table>

**for m_{4l} region with 125±5 GeV**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>2011</th>
<th>2012</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. Background</td>
<td>2.1±0.3</td>
<td>2.9±0.4</td>
<td>5.1±0.8</td>
</tr>
<tr>
<td>Exp. Signal</td>
<td>2.0±0.3</td>
<td>3.3±0.5</td>
<td>5.3±0.8</td>
</tr>
<tr>
<td>Observed</td>
<td>4</td>
<td>9</td>
<td>13</td>
</tr>
</tbody>
</table>
Mass resolution

- **ATLAS**
  - $4\mu : 1.8\text{GeV}$
  - $2e2\mu : 2.0\text{GeV}$
  - $4e : 2.5\text{GeV}$

- **CMS**
  - 1-2% (~1.3-2.6GeV@130GeV?)
One slide for $\text{ttH} \rightarrow \text{ttbb}$ (CMS)

- Direct $Y_t$ measurement.
- Huge $tt(+bb)$ and Combinatorial background.
- Need Multivariate analysis.
- Split events by
  - Lepton+jets or di-lepton
  - Lepton flavor
  - Number of $b$-tagging

$l+6\text{jet}(4\text{tag})$
Exclusion (CL$_s$ limit)

\[
q_\mu = -2 \ln \frac{\mathcal{L}(\text{obs} \mid \mu \cdot s + b, \hat{\theta}_\mu)}{\mathcal{L}(\text{obs} \mid \hat{\mu} \cdot s + b, \hat{\theta})}
\]

\[
\text{CL}_s = \frac{\text{P}(q_\mu \geq q_\mu^{\text{obs}} \mid \mu \cdot s + b)}{\text{P}(q_\mu \geq q_\mu^{\text{obs}} \mid b)} \leq \alpha.
\]

Excess ($p_0$)

\[
q_0 = -2 \ln \frac{\mathcal{L}(\text{obs} \mid b, \hat{\theta}_0)}{\mathcal{L}(\text{obs} \mid \hat{\mu} \cdot s + b, \hat{\theta})}
\]

\[
p_0 = \text{P}(q_0 \geq q_0^{\text{obs}} \mid b)
\]

\[
p_0 = \int_{z}^{+\infty} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2) \, dx
\]

\[
p_{\text{global}} = p_{\text{local}}^{\text{min}} + C \cdot e^{-Z_{\text{local}}^2/2}
\]

Extraction of signal parameters

\[
q(a) = -2 \ln \frac{\mathcal{L}(\text{obs} \mid s(a) + b, \hat{\theta}_a)}{\mathcal{L}(\text{obs} \mid s(\hat{a}) + b, \hat{\theta})}
\]

1D ... 1.0(3.8) for 68%(95%)
2D ... 2.3(6.0) for 68%(95%)
Discovery significance break down
Event selection & Analysis

- Three final states are considered.

  - **Boosted event**: Require High momentum vector boson (p$_T^V$) was used to enhance S/N ratio.
  - **ATLAS**: Cut based analysis. 4(3) p$_T^V$ bins for lvbb, llbb (vvbb)
    - mbb for the final discriminant.
  - **CMS**: Multivariate (BDT) analysis with 2 p$_T^V$ bins.
    - BDT score for the final discriminant.
Result: ATLAS 7TeV (5fb⁻¹)

- Used mass of the two b quark as a discriminant.
- Showed highest $p_T^\nu$ categories for each final state.
Result: ATLAS 7TeV(5fb⁻¹)

- No significant excess beyond background was observed.
- Set 95% CL upper limit on xsec:
  - Expected: 2.5-5 x SM
  - Observed: 4.6 xSM @ 125GeV
- Most sensitive channels are lvbb and vvbb
- 2012 analyses with improvements are now ongoing.
Result: CMS 7TeV(5fb$^{-1}$)+8TeV(5.1fb$^{-1}$)
Result: CMS 7TeV(5fb⁻¹)+8TeV(5.1fb⁻¹)

- Almost reached to the SM xsec at mH<115GeV
  - Expected limits are ≈1.1xSM
- **Observed(Expected) limits @125GeV are 2(1.6)xSM**
Mass reconstruction

Event by Event estimator of true di-τ mass likelihood. Full reconstruction of event kinematics.

**CMS**

- Exact Matrix Element used for $\tau \rightarrow l\nu\nu$
- Phase-Space is used for $\tau \rightarrow \pi$
- Mass peaks at true value
- Better separation between H and Z.

**ATLAS**

- Solve $\tau$, $E_T^{\text{miss}}$ in $\Delta\phi(\tau_{\text{vis}},\nu)$ parameter space using $\Delta\theta_{3D}(\tau_{\text{vis}},\nu)$ template from simulation as PDF.

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Result: ATLAS 7TeV (4.7 fb⁻¹)

- 1 jet category.
  - dominated by ggF process.
- Boost Higgs events are selected (hadhad)
  - Non negligible VBF contribution (1/3)
Result: ATLAS 7TeV(4.7fb$^{-1}$)

- VBF category
  - High $p_T$ forward jets with large $m_{jj}$ and $\Delta \eta_{jj}$.

\[ \int L \, dt = 4.7 \, fb^{-1} \]
\[ \sqrt{s} = 7 \, TeV \]
\[ ATLAS \]
Result: ATLAS 7TeV(4.7fb⁻¹)

Combination of three channels

**Observed limit:** 2.8-12.1

**Expected limit:** 3.4-8.0

@ 100-150GeV Higgs mass
Result: CMS 7TeV(4.9fb⁻¹)+8TeV(5.1fb⁻¹)

• **1jet category**

• Enhances ggF production.

• Splitted to High/Low pT events.

• High pt events have better mass resolution.
Result: CMS 7TeV(4.9fb$^{-1}$)+8TeV(5.1fb$^{-1}$)

- VBF category
  - High pt forward jets with large $m_{jj}$ and $\Delta\eta_{jj}$.
  - Highest sensitivity. ($m_{H}<130$GeV)

![Graphs showing CMS results for different VBF categories: $\mu\tau$ VBF, $e\tau$ VBF, $\mu\mu$ VBF, and $e\mu$ VBF.](image)
Result: CMS 7TeV(4.9fb⁻¹)+8TeV(5.1fb⁻¹)

- Analysis improved. 2x improvement from 2011.
- Observed(Expected) limit is 1.06(1.3)xSM!
Result: CMS 7TeV(4.9fb⁻¹)+8TeV(5.1fb⁻¹)

- Is this happened even if SM Signal exist?
- Made limit plot by injecting SM signal
- Signal cross section best fit value:
  - ggF dominant category: consistent to SM prediction.
  - VBF category: downward fluctuation. In consistent to SM prediction.

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Schedule for coming 10 years

- **Length of LS2:** minimum 12 months
- **2019 commissioning:** several months

**Timeline:**
- 2012: Chamonix
- 2013: LS1
- 2014: Linac 4 ready, PSB H-injection could be available
- 2015: LS2
- 2016: SPS e-cloud mitigation, 200 MHz power upgrade
- 2017: PSB-PS transfer 1.4 GeV → 2 GeV
- 2018: Injectors commissioned
- 2019: "Ultimate Physics"

**Physics @ 6.5/7 TeV**

**NB:** not yet fully approved