Properties Measurement of $H \rightarrow ZZ^{*} \rightarrow 4\ell$ and $Z \rightarrow 4\ell$ with ATLAS

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LHC mini-Workshop
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Outline

- Discovery of the Higgs Boson
- Higgs Production and Decays at LHC
- Event Selection of \( H \rightarrow ZZ^* \rightarrow 4\ell \)
- Higgs Properties: mass, width, spin, parity, couplings
- Analysis of Single Resonance \( Z \rightarrow 4\ell \): cross section, BR
- Summary

References:

- PLB 726 pp.88-119, pp. 120-144 (2013)
Higgs boson is proposed to responsible for the electroweak symmetry breaking, particles acquire mass when interacting with the Higgs field.

- The Higgs boson was discovered by ATLAS and CMS at LHC in July, 2012.
- F. Englert and P. Higgs won the Nobel Prize in Physics in 2013.
CERN’s Large Hadron Collider (LHC)

LHC is the world’s largest collider (7-14 TeV)
ATLAS Collaboration (38 countries, 174 institutions, ~ 3000)
CMS Collaboration (41 counties, 179 institutions, ~3300)

隧道 (26.7 公里)
LHC: Proton-Proton Collisions

Proton-Proton Collisions

- 2835 bunch/beam
- Protons/bunch: $10^{11}$
- Beam energy: 7 TeV ($7 \times 10^{12}$ eV)
- Luminosity: $10^{34}$ cm$^{-2}$ s$^{-1}$
- Crossing rate: 40 MHz
- Collisions: $10^7 - 10^9$ Hz

Major challenge:
Higgs $\rightarrow$ ZZ* $\rightarrow$ 4l 产生几率为10万亿分之一

Selection of 1 in $10,000,000,000,000$
The ATLAS Detector: Huge Camera

取数：4千万次/秒

46 x 25 x 25 米, 7000 吨
~3000 研究人员
Different particles have different signatures in detectors

- **Muon Spectrometer**: muon identification and momentum measurement
- **Hadronic calorimeter**: Measurement of jets and missing energy
- **Electromagnetic calo**: $e/\gamma$ identification and energy measurement
- **Tracking system**: Charged particle momentum, vertexing
ATLAS Data Samples

- **7 TeV data samples (2011)**
  - 4.5 fb\(^{-1}\) for physics analysis
  - Peak luminosity \(3.6 \times 10^{33}\text{ cm}^{-2}\text{s}^{-1}\)

- **8 TeV data samples (2012)**
  - 20.3 fb\(^{-1}\) for physics analysis
  - Peak luminosity \(7.7 \times 10^{33}\text{ cm}^{-2}\text{s}^{-1}\)

- **Data-taking efficiency:** \(~95.5\%\)

- **Significant pileup events**
Major Challenge (Large Pileup)

- Large pileup events result in big challenge to the detector, reconstruction and particle identification (eg. e, γ, τ, b)!
Boosted Decision Trees (BDT)

Boosted decision trees as an alternative to artificial neural networks for particle identification

Byron P. Roe, Hai-Jun Yang, Ji Zhu, Yong Liu, Ion Stancu, Gordon McGregor

Abstract

The efficacy of particle identification in high energy physics is improved by using artificial neural networks. The boosted decision tree (BDT) algorithm is a powerful tool for this purpose.

Total citations Cited by 231

1. Introduction

The artificial neural network has been widely used in high energy physics, especially in the ANN to the LSND experiment [2]. It is a crucial experiment which will imply new physics beyond the standard model.
Gluon-gluon fusion $gg \rightarrow H$ and vector-boson fusion $qq \rightarrow qqH$ are dominant

@125 GeV: $\sigma_{ggH} = 19.5$ pb, $\sigma_{VBF} = 1.6$ pb, $\sigma_{WH} = 0.70$ pb, $\sigma_{ZH} = 0.39$ pb, $\sigma_{tH} = 0.13$ pb
Higgs Boson Decay

Higgs decay branching ratio at $m_H=125$ GeV

- $bb$: 57.7% (huge QCD background)
- $WW$: 21.5% (easy identification in di-lepton mode, complex background)
- $\tau\tau$: 6.3% (complex final states with $\tau$ leptonic and/or hadronic decays)
- $ZZ^*$: 2.6% (“gold-plated”, clean signature of 4-lepton, high S/B, excellent mass peak)
- $\gamma\gamma$: 0.23% (excellent mass resolution, high sensitivity)

Higgs to $ZZ^* \to 4l$ production rate: 1 out of $10^{13}$ collision events
H → ZZ* → 4ℓ Overview

- Extremely clean – “Gold-plated” channel
  - Fully reconstructed final states
  - Good mass resolution (~ 1.6-2.4 GeV)
  - High S/B ratio (~ 1-2)
  - Low decay branching fraction

- Currently statistically limited
  - 4.5 fb⁻¹ @ 7 TeV + 20.3 fb⁻¹ @ 8 TeV
  - Expect 68 SM H → ZZ* → 4ℓ (e,μ) events

- Properties measurement
  - Higgs mass, width, spin, parity, couplings.
  - Critical to determine whether it is fully compatible with the SM Higgs boson
H→ZZ*→4l Event Selection

- Trigger match with single and/or di-lepton trigger
- Four sub-channels: 4e, 2e2μ, 2μ2e, 4μ

<table>
<thead>
<tr>
<th>Event Pre-selection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrons</strong></td>
</tr>
<tr>
<td>“MultiLepton” quality GSF electrons with $E_T &gt; 7$ GeV and $</td>
</tr>
<tr>
<td><strong>Muons</strong></td>
</tr>
<tr>
<td>combined or segment-tagged muons with $p_T &gt; 6$ GeV and $</td>
</tr>
<tr>
<td>Maximum one calor-tagged or standalone muon</td>
</tr>
<tr>
<td>calor-tagged muons with $p_T &gt; 15$ GeV and $</td>
</tr>
<tr>
<td>standalone muons with $p_T &gt; 6$ GeV, $2.5 &lt;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kinematic Selection</strong></td>
</tr>
<tr>
<td>Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements:</td>
</tr>
<tr>
<td>$p_T$ thresholds for three leading leptons in the quadruplet 20, 15 and 10 GeV</td>
</tr>
<tr>
<td>Leading di-lepton mass requirement $50$ GeV &lt; $m_{12}$ &lt; $106$ GeV</td>
</tr>
<tr>
<td>Sub-leading di-lepton mass requirement $m_{\text{threshold}} &lt; m_{34} &lt; 115$ GeV</td>
</tr>
<tr>
<td>Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} &lt; 5$ GeV $\Delta R(\ell,\ell') &gt; 0.10,(0.20)$ for all same (different) flavour leptons in the quadruplet.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton track isolation ($\Delta R = 0.20$): $\Sigma p_T / p_T &lt; 0.15$</td>
</tr>
<tr>
<td>Electron calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T / E_T &lt; 0.20$</td>
</tr>
<tr>
<td>Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T / E_T &lt; 0.30$</td>
</tr>
<tr>
<td>Stand-Alone muons calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T / E_T &lt; 0.15$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impact Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apply impact parameter significance cut to all leptons of the quadruplet.</td>
</tr>
<tr>
<td>For electrons: $d_0 / \sigma_{d_0} &lt; 6.5$</td>
</tr>
<tr>
<td>For muons: $d_0 / \sigma_{d_0} &lt; 3.5$</td>
</tr>
</tbody>
</table>
Main background is $ZZ(*)$ production
- MC simulation, scaled to theoretical cross section

Reducible backgrounds:
- $Z\bar{b}b$, $Z+$light jets, $t\bar{t}$
- Estimated using data-driven methods
  - Define background-enriched/signal-depleted control regions
  - Extrapolate to signal region using transfer factors

Estimates agree well with data in control region where isolation and $d_0$ requirements are removed for subleading pair
Selected Higgs Candidates

TABLE III. The number of events expected and observed for a $m_H = 125$ GeV hypothesis for the four-lepton final states. The second column shows the number of expected signal events for the full mass range. The other columns show the number of expected signal events, the number of $ZZ^*$ and reducible background events, and the signal-to-background ratio ($s/b$), together with the numbers of observed events, in a window of $120 < m_{4l} < 130$ GeV for 4.5 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 20.3 fb$^{-1}$ at $\sqrt{s} = 8$ TeV as well as for the combined sample.

<table>
<thead>
<tr>
<th>Final state</th>
<th>Signal Full mass range</th>
<th>Signal</th>
<th>$ZZ^*$</th>
<th>$Z + \text{jets, } t\bar{t}$</th>
<th>$s/b$</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4\mu$</td>
<td>$1.00 \pm 0.10$</td>
<td>$0.91 \pm 0.09$</td>
<td>$0.46 \pm 0.02$</td>
<td>$0.10 \pm 0.04$</td>
<td>1.7</td>
<td>$1.47 \pm 0.10$</td>
<td>2</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$0.66 \pm 0.06$</td>
<td>$0.58 \pm 0.06$</td>
<td>$0.32 \pm 0.02$</td>
<td>$0.09 \pm 0.03$</td>
<td>1.5</td>
<td>$0.99 \pm 0.07$</td>
<td>2</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>$0.50 \pm 0.05$</td>
<td>$0.44 \pm 0.04$</td>
<td>$0.21 \pm 0.01$</td>
<td>$0.36 \pm 0.08$</td>
<td>0.8</td>
<td>$1.01 \pm 0.09$</td>
<td>1</td>
</tr>
<tr>
<td>$4e$</td>
<td>$0.46 \pm 0.05$</td>
<td>$0.39 \pm 0.04$</td>
<td>$0.19 \pm 0.01$</td>
<td>$0.40 \pm 0.09$</td>
<td>0.7</td>
<td>$0.98 \pm 0.10$</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>$2.62 \pm 0.26$</td>
<td>$2.32 \pm 0.23$</td>
<td>$1.17 \pm 0.06$</td>
<td>$0.96 \pm 0.18$</td>
<td>1.1</td>
<td>$4.45 \pm 0.30$</td>
<td>6</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4\mu$</td>
<td>$5.80 \pm 0.57$</td>
<td>$5.28 \pm 0.52$</td>
<td>$2.36 \pm 0.12$</td>
<td>$0.69 \pm 0.13$</td>
<td>1.7</td>
<td>$8.33 \pm 0.6$</td>
<td>12</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$3.92 \pm 0.39$</td>
<td>$3.45 \pm 0.34$</td>
<td>$1.67 \pm 0.08$</td>
<td>$0.60 \pm 0.10$</td>
<td>1.5</td>
<td>$5.72 \pm 0.37$</td>
<td>7</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>$3.06 \pm 0.31$</td>
<td>$2.71 \pm 0.28$</td>
<td>$1.17 \pm 0.07$</td>
<td>$0.36 \pm 0.08$</td>
<td>1.8</td>
<td>$4.23 \pm 0.30$</td>
<td>5</td>
</tr>
<tr>
<td>$4e$</td>
<td>$2.79 \pm 0.29$</td>
<td>$2.38 \pm 0.25$</td>
<td>$1.03 \pm 0.07$</td>
<td>$0.35 \pm 0.07$</td>
<td>1.7</td>
<td>$3.77 \pm 0.27$</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>$15.6 \pm 1.6$</td>
<td>$13.8 \pm 1.4$</td>
<td>$6.24 \pm 0.34$</td>
<td>$2.00 \pm 0.28$</td>
<td>1.7</td>
<td>$22.1 \pm 1.5$</td>
<td>31</td>
</tr>
<tr>
<td>$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4\mu$</td>
<td>$6.80 \pm 0.67$</td>
<td>$6.20 \pm 0.61$</td>
<td>$2.82 \pm 0.14$</td>
<td>$0.79 \pm 0.13$</td>
<td>1.7</td>
<td>$9.81 \pm 0.64$</td>
<td>14</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$4.58 \pm 0.45$</td>
<td>$4.04 \pm 0.40$</td>
<td>$1.99 \pm 0.10$</td>
<td>$0.69 \pm 0.11$</td>
<td>1.5</td>
<td>$6.72 \pm 0.42$</td>
<td>9</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>$3.56 \pm 0.36$</td>
<td>$3.15 \pm 0.32$</td>
<td>$1.38 \pm 0.08$</td>
<td>$0.72 \pm 0.12$</td>
<td>1.5</td>
<td>$5.24 \pm 0.35$</td>
<td>6</td>
</tr>
<tr>
<td>$4e$</td>
<td>$3.25 \pm 0.34$</td>
<td>$2.77 \pm 0.29$</td>
<td>$1.22 \pm 0.08$</td>
<td>$0.76 \pm 0.11$</td>
<td>1.4</td>
<td>$4.75 \pm 0.32$</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>$18.2 \pm 1.8$</td>
<td>$16.2 \pm 1.6$</td>
<td>$7.41 \pm 0.40$</td>
<td>$2.95 \pm 0.33$</td>
<td>1.6</td>
<td>$26.5 \pm 1.7$</td>
<td>37</td>
</tr>
</tbody>
</table>
Candidates of 4-lepton

- $\text{BR}(H \rightarrow ZZ^*) = 2.63\%$, $\text{BR}(ZZ^* \rightarrow 4l) = 0.45\%$
- About 68 $H \rightarrow ZZ^* \rightarrow 4l$ events produced
- Observed 37 candidates with 16 $Higgs \rightarrow ZZ^* \rightarrow 4l$ signal
ATLAS $H \rightarrow ZZ^* \rightarrow 4\mu$ Candidate

- $M_{4\mu} = 125.1$ GeV, $M_{12} = 86.3$ GeV, $M_{34} = 31.6$ GeV
Higgs $\rightarrow ZZ^* \rightarrow 4l$ Candidates Evolution
Candidates of 4-lepton

- Left: $\text{BDT}_{\text{ZZ}}$ output with requirement of $120 < m_{4l} < 130$ GeV
- Right: $m_{4l}$ output with requirement of $\text{BDT}_{\text{ZZ}} > 0$
Higgs Mass Measurement

- Two dimensional (2D) fit to $m_{4l}$ and BDT$_{ZZ^*}$ based on profile likelihood method to obtain Higgs mass.
Higgs Mass Measurements

\[
\Lambda(\Delta m_H) = \frac{L(\Delta m_H, \hat{\mu}_{\gamma\gamma}(\Delta m_H), \hat{\mu}_{4\ell}(\Delta m_H), \hat{m}_H(\Delta m_H), \hat{\theta}(\Delta m_H))}{L(\Delta m_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{m}_H, \hat{\theta})}
\]

\[
\Delta m_H = 1.47 \pm 0.67\text{(stat)} \pm 0.28\text{(syst)} \text{ GeV}
\]

\[
= 1.47 \pm 0.72 \text{ GeV}
\]

**Fitted Higgs mass**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass measurement [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$125.98 \pm 0.42\text{(stat)} \pm 0.28\text{(syst)} = 125.98 \pm 0.50$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>$124.51 \pm 0.52\text{(stat)} \pm 0.06\text{(syst)} = 124.51 \pm 0.52$</td>
</tr>
<tr>
<td>Combined</td>
<td>$125.36 \pm 0.37\text{(stat)} \pm 0.18\text{(syst)} = 125.36 \pm 0.41$</td>
</tr>
</tbody>
</table>

*It is compatible with $\Delta M_H = 0$ at the level of 4.8%, 2.0$\sigma$*
Measurements of Higgs Signal Strength

- Signal strength: $\mu = 1.3 \pm 0.2$ (ATLAS)
- $\mu = 0.8 \pm 0.14$ (CMS)

CMS-HIG-13-005

ATLAS Prelim.
$m_H = 125.5$ GeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mu$</th>
<th>$\sigma$(stat.)</th>
<th>$\sigma$(sys inc.)</th>
<th>$\sigma$(theory)</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$1.57 \pm 0.33$</td>
<td>$0.23$</td>
<td>$0.22$</td>
<td></td>
<td>$\pm 1\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$1.44 \pm 0.40$</td>
<td>$0.21$</td>
<td>$0.21$</td>
<td></td>
<td>$\pm 1\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow ll\nu\nu$</td>
<td>$1.00 \pm 0.23$</td>
<td>$0.21$</td>
<td>$0.19$</td>
<td></td>
<td>$\pm 1\sigma$</td>
</tr>
<tr>
<td>Combined $H\rightarrow\gamma\gamma, ZZ^<em>, WW^</em>$</td>
<td>$1.35 \pm 0.21$</td>
<td>$0.21$</td>
<td>$0.16$</td>
<td></td>
<td>$\pm 1\sigma$</td>
</tr>
<tr>
<td>$W, Z \rightarrow b\bar{b}$</td>
<td>$0.2 \pm 0.7$</td>
<td>$0.3$</td>
<td>$0.3$</td>
<td></td>
<td>$\pm 0.4$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ (8 TeV data only)</td>
<td>$1.4 \pm 0.5$</td>
<td>$0.3$</td>
<td>$0.4$</td>
<td></td>
<td>$\pm 0.3$</td>
</tr>
<tr>
<td>Combined $H\rightarrow b\bar{b}, \tau\tau$</td>
<td>$1.09 \pm 0.36$</td>
<td>$0.24$</td>
<td>$0.27$</td>
<td></td>
<td>$\pm 0.32$</td>
</tr>
</tbody>
</table>

CMS Preliminary
$m_H = 125.7$ GeV

$\sqrt{s} = 7$ TeV, $L \leq 5.1$ fb$^{-1}$  $\sqrt{s} = 8$ TeV, $L \leq 19.6$ fb$^{-1}$

$\sigma_{SM} = \times Br(S\times Br( ))$
**Significance of H$\rightarrow$ZZ$^*$→4l**

- Higgs mass $m_H = 124.51$ and $125.36$ GeV,
  - Expected significances are $5.8\sigma$ and $6.2\sigma$,
  - Observed significances are $8.2\sigma$ and $8.1\sigma$. 

![Graph showing significance versus Higgs mass](image)
Direct Measurement of Higgs Width

- Using per-event-error method, direct limit on the total width of the Higgs boson $\Gamma_H < 2.6$ GeV @ 95% C.L.
Indirect Measurement of Higgs Width

- High-mass off-peak region of the $H \rightarrow ZZ \rightarrow 4l$ channel above the $2M_V$ threshold have sensitivity to Higgs production through off-shell and background interference effects.  

(Ref: ATL-COM-PHYS-2014-1403)

The combination of both on-shell and off-shell measurements of signal strength achieve a significantly higher sensitivity to the total width $\Gamma_H$. 
The expected 95% C.L. upper limits on $\mu_{\text{off-shell}}$. 

<table>
<thead>
<tr>
<th>Without systematics</th>
<th>With systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME</td>
<td>1.00 (8.85)</td>
</tr>
<tr>
<td>BDT</td>
<td>1.00 (8.52)</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 8 \text{ TeV}$; $L_{\text{int}} = 20.3 \text{ fb}^{-1}$

-2$\Delta \ln \Lambda$

**ATLAS** Internal

$H \rightarrow ZZ \rightarrow 4\ell$

- Events normalised to unit area / 0.2

- ME discriminant

- BDTG_KD discriminant
The expected 95% C.L. upper limits on $\mu_{\text{off-shell}}$, is 10.1 and the observed limit is 5.
H → ZZ* → 4l : Spin and Parity

- In $X \rightarrow ZZ^{(*)} \rightarrow 4\ell$ decays, $m_{Z_1}$, $m_{Z_2}$ and the production and decay angles are sensitive to the spin-parity of $X$
  $\{m_{4\ell}, m_{Z_1}, m_{Z_2}, \cos \theta_1, \cos \theta_2, \phi, \cos \theta^*, \phi_1\}$

- Construct a discriminant between different hypotheses using two different multivariate techniques:
  - BDT (machine learning)
  - $J^P$-MELA (use theoretical differential decay rates to construct a matrix element based likelihood ratio)

- Use events in range $115 < m_{4\ell} < 130$ GeV

- Test SM $0^+$ hypothesis against alternative hypotheses $0^-, 1^+, 1^-, 2^+_m$
H → ZZ* → 4l : Spin and Parity

**BDT analysis variables:**

- $m_{Z1}$, $m_{Z2}$ from Higgs → ZZ* → 4l
- + production and decay angles

**Exclusion (1-CL$_S$):**

- Observed $0^-$ exclusion 97.8%
- Observed $1^+$ exclusion 99.8%
- Observed $2^+_m$ exclusion 83.2%
Probing Higgs Production (VBF)

- Event characteristics allow measurement of signal strength from different production modes

**Vector Boson Fusion (VBF)**

\[ \sigma / \sigma_{\text{Total}} \]

\[ 7\% \]

- \( \geq 2 \) jets with \( p_T > 25 \) (30) GeV and \( |\eta| < 2.5 \) (2.5 < |\eta| < 4.5)
- \( \Delta \eta_{WW} > 3; M_{WW} > 350 \) GeV
- 8 observed candidates

**Associated Production (VH)**

\[ \tilde{q} \rightarrow \text{W}, Z \rightarrow \text{W}, Z, H^0 \]

\[ 5\% \]

- Additional lepton with \( p_T > 8 \) GeV
- 1 observed candidate

**Gluon Gluon Fusion (ggF)**

\[ 87\% \]

**tt Fusion (ttH)**

\[ 0.5\% \]

Consistent with expected background

One VBF candidate with \( m_{4\ell} = 123.5 \) GeV

In 120-130 GeV:
- Expected \( N_{\text{signal}} = 0.71 \pm 0.10 \)
- Expected \( N_{\text{VBF}} \sim 0.4 \)
- Expected \( S/B \sim 5 \)
Probing Higgs Production (VBF)

- BDT_{VBF} based on 5 variables:
  - $M_{jj}$, $\eta_{jj}$, $\eta_{leading\ jet}$
  - $p_T$ of leading and subleading jets

![Graph and chart illustrating the BDT output for VBF enriched category.]
The compatibility of VBF production with the SM expectation is 30%.

\[
\frac{\mu_{VBF+VH}}{\mu_{ggF+b\bar{b}H+t\bar{t}H}} = 0.2^{+1.2}_{-0.5}
\]

\[
\mu_{ggF+b\bar{b}H+t\bar{t}H} \times \frac{B}{B_{SM}} = 1.66^{+0.45}_{-0.41} \text{ (stat)}^{+0.25}_{-0.15} \text{ (syst)}
\]

\[
\mu_{VBF+VH} \times \frac{B}{B_{SM}} = 0.26^{+1.60}_{-0.91} \text{ (stat)}^{+0.36}_{-0.23} \text{ (syst)}
\]
Fermion and Vector Couplings

- The likelihood scan as a function of the ratio of fermion to vector-boson coupling scale factors, \( \lambda_{FV} = \frac{\kappa_F}{\kappa_V} \)

- The value of \( \lambda_{FV} = 0 \) is disfavored at the 4\( \sigma \) level.
Coupling scale factors
2-parameter benchmark model:

\[ \kappa_V = \kappa_W = \kappa_Z \]
\[ \kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g \]

(Gluon coupling are related to top, b, and their interference in tree level loop diagrams)

Assume no BSM contributions to loops: \( gg \rightarrow H \) and no BSM decays (no invisible decays)

\[ \kappa_V = 1.15 \pm 0.08 \]
\[ \kappa_F = 0.99^{+0.17}_{-0.15} \]

\( \Rightarrow \kappa_F = 0 \) is excluded (>5\( \sigma \))
Analysis of Single Resonance $Z \to 4\ell$

- The $Z \to 4\ell$ production was first observed at the LHC by ATLAS and CMS along with the Higgs boson discovery in $4\ell$ decay channel.
- Cross section measurement of the $Z \to 4\ell$ production provides:
  - A SM test for a rare decay process, meas. of $\sigma(4\ell)$ and $\text{BR}(Z \to 4\ell)$
  - A complementary test of the detector response for $H \to 4\ell$ detection

Production of single resonance $Z \rightarrow 4l$

- Four lepton 4$\ell$ final states: 4e, 4m and 2e2m
- **Resonant 4$\ell$ production** via an s-channel $Z \rightarrow t^+t^-$ include an additional $t^+t^-$ from internal conversion of $Z^*/\gamma^*$
  - $> 96\%$ 4$\ell$ event rate from s-channel at Z resonance ($80 < m_{4\ell} < 100$ GeV, $m_{2\ell}>5$ GeV)
- **Non-resonant 4$\ell$ production**
  - via t-channel: $qq \rightarrow Z^*/\gamma^* +Z^*/\gamma^* \rightarrow 4\ell$ including the Z production with ISR internal conversion ($< 4\%$ 4$\ell$ event rate at the Z resonance)
  - via $gg \rightarrow ZZ \rightarrow 4\ell$ ($\sim 0.1\%$ 4$\ell$ event rate at the Z resonance)
Cuts Optimization

**ATLAS Higgs → ZZ* → 4l selection:**
- $p_T_{\text{min}} > 7 \ (6) \text{ GeV}$ for $e \ (\mu)$
- $m_{12} > 50 \ \text{GeV}; \ m_{34} > 12 \ \text{GeV}$
- Select 37 $Z \rightarrow 4l$ events in $Z$ mass window

- The $Z \rightarrow 4l$ process is dominant by low mass $m_{34}$ and low $p_T$ leptons (the $p_T$-ordered 4$^{th}$ leptons)
- Need to detect low $p_T$ leptons

Loosen some Higgs cuts:
- $e: \ p_T > 20, 15, 10, 7 \ \text{GeV}$
- $\mu: \ p_T > 20, 15, 8, 4 \ \text{GeV}$
- $m_{12} > 20 \ \text{GeV}, \ m_{34} > 5 \ \text{GeV}$

Increase statistics by a factor of 5
# ATLAS: Selected Z→4l Events

<table>
<thead>
<tr>
<th>√s (TeV)</th>
<th>Channel</th>
<th>Data</th>
<th>Total expected</th>
<th>MC signal (Z/ZZ → 4ℓ)</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>eeee</td>
<td>1</td>
<td>1.8 ± 0.3</td>
<td>1.7 ± 0.3</td>
<td>0.12 ± 0.04</td>
</tr>
<tr>
<td>7</td>
<td>eeμμ</td>
<td>7</td>
<td>8.0 ± 0.4</td>
<td>7.7 ± 0.4</td>
<td>0.18 ± 0.09</td>
</tr>
<tr>
<td>7</td>
<td>μμee</td>
<td>5</td>
<td>3.3 ± 0.3</td>
<td>3.2 ± 0.3</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td>7</td>
<td>μμμμ</td>
<td>8</td>
<td>11.3 ± 0.5</td>
<td>11.2 ± 0.3</td>
<td>0.09 ± 0.04</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td>21</td>
<td>24.4 ± 1.2</td>
<td>23.8 ± 1.2</td>
<td>0.47 ± 0.11</td>
</tr>
<tr>
<td>8</td>
<td>eeee</td>
<td>16</td>
<td>14.4 ± 1.2</td>
<td>14.3 ± 1.2</td>
<td>0.16 ± 0.03</td>
</tr>
<tr>
<td>8</td>
<td>eeμμ</td>
<td>48</td>
<td>43.2 ± 2.3</td>
<td>42.9 ± 2.2</td>
<td>0.36 ± 0.05</td>
</tr>
<tr>
<td>8</td>
<td>μμee</td>
<td>16</td>
<td>19.3 ± 1.2</td>
<td>19.1 ± 1.2</td>
<td>0.21 ± 0.04</td>
</tr>
<tr>
<td>8</td>
<td>μμμμ</td>
<td>71</td>
<td>68.8 ± 3.0</td>
<td>68.4 ± 2.9</td>
<td>0.41 ± 0.05</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td>151</td>
<td>145.7 ± 7.7</td>
<td>145 ± 7</td>
<td>1.14 ± 0.13</td>
</tr>
</tbody>
</table>

\[\text{Events / 2.5 GeV}\]
\[\text{Events / 3 GeV}\]
Acceptance $A_{4l}$ and Correction Factor $C_{4l}$

- **Definition of Fiducial Volume**

$$
\begin{align*}
    p_T^{\ell_1} &> 20 \text{ GeV}; \\
p_T^{\ell_2} &> 15 \text{ GeV}; \\
p_T^{\ell_3} &> 10 \text{ GeV (if electron), } > 8 \text{ GeV (if muon)}; \\
p_T^{\ell_4} &> 7 \text{ GeV (if electron), } > 4 \text{ GeV (if muon)}; \\
|\eta^\mu| &< 2.7 \text{ for all muons; } |\eta^e| < 2.5 \text{ for all electrons}; \\
\Delta R(\ell, \ell') &> 0.1 \text{ for all same flavor pairings and } > 0.2 \text{ for different flavor pairings}; \\
M_{\ell^+\ell^-} &> 20 \text{ GeV for at least one SFOS lepton pair}; \\
M_{\ell^+\ell^-} &> 5 \text{ GeV for all SFOS lepton pair}; \\
80 &< M_{4\ell} < 100 \text{ GeV}.
\end{align*}
$$

$$
A_{4l} = \frac{\text{Number of 4l events selected in the fiducial volume}}{\text{Number of 4l events in the phase space}}
$$

$$
C_{4l} = \frac{\text{Number of 4l events passing full event selection}}{\text{Number of 4l events selected in the fiducial volume}}
$$
### ATLAS: Fiducial Cross Sections

The fiducial cross section for $Z \rightarrow 4\ell$ is given by

$$\sigma_{\text{fiducial}}^{Z \rightarrow 4\ell} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L}C_{Z \rightarrow 4\ell}}$$

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>Final state</th>
<th>$C_{4\ell}$</th>
<th>Measured $\sigma^{\text{Fid}}$ fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$e e e e$</td>
<td>21.5%</td>
<td>$0.910^{+1.39}_{-0.72}$ (stat) ± $0.14$ (syst) ± $0.02$ (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$\mu \mu \mu \mu$</td>
<td>59.2%</td>
<td>$2.970^{+1.18}_{-0.94}$ (stat) ± $0.07$ (syst) ± $0.05$ (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$e e \mu \mu$</td>
<td>49.0%</td>
<td>$3.091^{+1.35}_{-1.05}$ (stat) ± $0.16$ (syst) ± $0.05$ (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$\mu \mu e e$</td>
<td>36.3%</td>
<td>$3.015^{+1.57}_{-1.17}$ (stat) ± $0.30$ (syst) ± $0.06$ (lumi) fb</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$e e e e$</td>
<td>36.06%</td>
<td>$2.16^{+0.59}_{-0.50}$ (stat) ± $0.16$ (syst) ± $0.06$ (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$\mu \mu \mu \mu$</td>
<td>71.13%</td>
<td>$4.89^{+0.66}_{-0.56}$ (stat) ± $0.13$ (syst) ± $0.14$ (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$e e \mu \mu$</td>
<td>55.54%</td>
<td>$4.23^{+0.65}_{-0.59}$ (stat) ± $0.15$ (syst) ± $0.12$ (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$\mu \mu e e$</td>
<td>46.24%</td>
<td>$1.68^{+0.46}_{-0.39}$ (stat) ± $0.07$ (syst) ± $0.04$ (lumi) fb</td>
</tr>
</tbody>
</table>
### ATLAS: Phase-space xsections

**ATLAS measurement in final phase space $80 < m_{4\ell} < 100$ GeV and $m_{\ell^+\ell^-} > 5$ GeV**

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>4\ell\ state</th>
<th>$N^{obs}_{4\ell}$</th>
<th>$N^{exp}_{4\ell}$</th>
<th>$N^{bkg}_{4\ell}$</th>
<th>$C_{4\ell}$</th>
<th>$\sigma^{fid}_{Z \rightarrow 4\ell}$ [fb]</th>
<th>$A_{4\ell}$</th>
<th>$\sigma_{Z \rightarrow 4\ell}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$ee + ee$</td>
<td>1</td>
<td>1.8 ± 0.3</td>
<td>0.12 ± 0.04</td>
<td>21.5%</td>
<td>$0.9^{+1.4}_{-0.7} \pm 0.14 \pm 0.02$</td>
<td>7.5%</td>
<td>32 ± 11 ± 1.0 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu + \mu\mu$</td>
<td>8</td>
<td>11.3 ± 0.5</td>
<td>0.08 ± 0.04</td>
<td>59.2%</td>
<td>$3.0^{+1.2}_{-0.9} \pm 0.07 \pm 0.05$</td>
<td>18.3%</td>
<td>44 ± 14 ± 3.3 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>$ee + \mu\mu$</td>
<td>7</td>
<td>7.9 ± 0.4</td>
<td>0.18 ± 0.09</td>
<td>49.0%</td>
<td>$3.1^{+1.4}_{-1.1} \pm 0.16 \pm 0.05$</td>
<td>15.8%</td>
<td>76 ± 18 ± 4 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu + ee$</td>
<td>5</td>
<td>3.3 ± 0.3</td>
<td>0.07 ± 0.04</td>
<td>36.3%</td>
<td>$3.0^{+1.6}_{-1.2} \pm 0.30 \pm 0.06$</td>
<td>8.8%</td>
<td>32 ± 11 ± 1.0 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>combined</td>
<td>21</td>
<td>24.2 ± 1.2</td>
<td>0.44 ± 0.14</td>
<td></td>
<td></td>
<td></td>
<td>76 ± 18 ± 4 ± 1.4</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$ee + ee$</td>
<td>16</td>
<td>14.4 ± 1.4</td>
<td>0.14 ± 0.03</td>
<td>36.1%</td>
<td>$2.2^{+0.6}_{-0.5} \pm 0.20 \pm 0.06$</td>
<td>7.3%</td>
<td>56 ± 6 ± 1.8 ± 1.6</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu + \mu\mu$</td>
<td>71</td>
<td>68.8 ± 2.7</td>
<td>0.34 ± 0.05</td>
<td>71.1%</td>
<td>$4.9^{+0.7}_{-0.6} \pm 0.13 \pm 0.14$</td>
<td>17.8%</td>
<td>52 ± 7 ± 2.4 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>$ee + \mu\mu$</td>
<td>48</td>
<td>43.2 ± 2.1</td>
<td>0.32 ± 0.05</td>
<td>55.5%</td>
<td>$4.2^{+0.7}_{-0.6} \pm 0.16 \pm 0.12$</td>
<td>14.8%</td>
<td>76 ± 18 ± 4 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu + ee$</td>
<td>16</td>
<td>19.3 ± 1.3</td>
<td>0.18 ± 0.04</td>
<td>46.2%</td>
<td>$1.7^{+0.5}_{-0.4} \pm 0.10 \pm 0.04$</td>
<td>7.9%</td>
<td>107 ± 9 ± 4 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>combined</td>
<td>151</td>
<td>146 ± 7</td>
<td>1.0 ± 0.11</td>
<td></td>
<td></td>
<td></td>
<td>107 ± 9 ± 4 ± 3.0</td>
</tr>
</tbody>
</table>

### ATLAS

<table>
<thead>
<tr>
<th>Phase-space Cross Section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM NLO Prediction (7 TeV)</td>
</tr>
<tr>
<td>Measured (7 TeV)</td>
</tr>
<tr>
<td>SM NLO Prediction (8 TeV)</td>
</tr>
<tr>
<td>Measured (8 TeV)</td>
</tr>
</tbody>
</table>
ATLAS: BR of $Z \rightarrow 4\ell$

- Measure the $Z \rightarrow 2\mu$ cross section and take the known $\text{Br}(Z \rightarrow 2\mu)$ to get inclusive cross section of $Z$ from pp collisions
- Cancels luminosity uncertainty and theoretical uncertainty of $\sigma(pp \rightarrow Z)$
- Derive the BR ($Z \rightarrow 4\ell$) as below

$$\text{BR}(Z \rightarrow 4\ell) = \text{BR}(Z \rightarrow 2\mu)(1 - f_t) \frac{(N_{\text{obs.}} - N_{\text{bkg.}})^{4\ell}}{(N_{\text{obs.}} - N_{\text{bkg.}})^{2\mu}} \frac{(C \times A)^{2\mu}}{(C \times A)^{4\ell}}$$

Uncertainty on $\text{BR}(Z \rightarrow 2\mu)$ is small. $f_t = \text{fraction of } t\text{-channel in phase-space}$.

- Cancel luminosity uncertainty: 2.8% (8 TeV)
- Cancel NLO $\sigma(Z)$ calculation uncertainties (Scales, PDF, NNLO correction): 4%
Branching Ratio of $Z \rightarrow 4l$

Branching fraction result uses an error weighted combination of the 7 and 8 TeV results. For $(m_{2l} > 5 \text{ GeV}, 80 < m_{4l} < 100 \text{ GeV})$

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$\sqrt{s}$</th>
<th>Value</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>7 TeV</td>
<td>$(2.67 \pm 0.62 \text{ (stat)} \pm 0.14 \text{ (syst)}) \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 TeV</td>
<td>$(3.33 \pm 0.27 \text{ (stat)} \pm 0.11 \text{ (syst)}) \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>$(3.20 \pm 0.25 \text{ (stat)} \pm 0.13 \text{ (syst)}) \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Expected</td>
<td></td>
<td>$(3.33 \pm 0.01) \times 10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>

For $M_{ll} > 4 \text{ GeV}$

- We observe $(4.31 \pm 0.34 \text{ (stat)} \pm 0.16 \text{ (syst)}) \times 10^{-6}$ and expect $(4.50 \pm 0.01) \times 10^{-6}$, (ATLAS combining 7 & 8 TeV measurements)
- CMS observes $(4.2^{+0.9}_{-0.8} \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-6}$ and expects $4.45 \times 10^{-6}$. 
ATLAS: 4-lepton Mass Scale

- 4-lepton mass fitted with the convolution of a Breit-Wigner and a Gaussian distributions for 4 channels
- Fitted results show good consistence with MC predictions
- Example of $4\mu$ mass fit for data and MC
Summary

- With 2011 (4.5 fb\(^{-1}\) @ 7TeV) and 2012 (20.3 fb\(^{-1}\) @ 8 TeV) datasets, the Higgs boson is observed in the \(H \rightarrow ZZ^* \rightarrow 4\ell\) channel with local significance of 8.1\(\sigma\).

- The best fit mass of the Higgs boson from \(H \rightarrow ZZ^* \rightarrow 4\ell\) is 124.51 ± 0.52(stat) ± 0.06(syst) = 124.51 ± 0.52 GeV.

- The ratio of signal strength for bosonic (VBF+VH) and fermionic (ggF+ttH) production modes are measured, the compatibility of VBF production with SM expectation is 30%.

- The SM Higgs boson with \(J^{P} = 0^{+}\) hypothesis is favored.

- The Higgs mass width \(\Gamma_{H} < 2.6\) GeV / 42 MeV @ 95% C.L. for direct / indirect measurements.

- BR of \(Z \rightarrow 4\ell\) is \(4.3 \times 10^{-6}\) which agree with SM prediction.
CMS: Z\rightarrow 4l Analysis

Phase space cuts

80 < M_{4l} < 100 \text{ GeV}; \ M_{2l} > 4 \text{ GeV}

SM prediction (FEWZ @ NNLO):

\sigma(pp \rightarrow Z \rightarrow 4l) = 120 \pm 5 \text{ fb}

BR(Z \rightarrow 4l) = 4.45 \times 10^{-6} \text{ (LO CalcHEP)}

\sigma(pp \rightarrow Z) B(Z \rightarrow 4l) = 112^{+23}_{-20} \text{ (stat.)}^{+7}_{-5} \text{ (syst.)}^{+3}_{-2} \text{ (lum.) fb,}

B(Z \rightarrow 4l) = (4.2^{+0.9}_{-0.8} \text{ (stat.)} \pm 0.2 \text{ (syst.)}) \times 10^{-6}
## Categories of $H \Rightarrow ZZ^* \Rightarrow 4l$ Events

Table 12: Expected and observed yields in the $VBF$ enriched, $VH$-hadronic enriched, $VH$-leptonic enriched and $ggF$ enriched categories. The yields are given for the different production modes and the $ZZ^*$ and reducible background for 4.6 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 20.3 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. The estimates are given for both the $m_{4\ell}$ mass range 120–130 GeV and the mass range above 110 GeV.

<table>
<thead>
<tr>
<th>Enriched category</th>
<th>$ggF + bbH + t\bar{t}H$</th>
<th>Signal</th>
<th>VH-hadronic</th>
<th>VH-leptonic</th>
<th>Background</th>
<th>Total expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>VBF</td>
<td></td>
<td></td>
<td>$ZZ^*$</td>
<td>$Z + \text{jets, } t\bar{t}$</td>
<td></td>
</tr>
<tr>
<td>$m_{4\ell} &gt; 110$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$VBF$</td>
<td>1.4 ± 0.4</td>
<td>0.82 ± 0.05</td>
<td>0.092 ± 0.007</td>
<td>0.022 ± 0.002</td>
<td>20 ± 4</td>
<td>1.6 ± 0.9</td>
<td>24. ± 4.</td>
</tr>
<tr>
<td>(BDT$_{VBF} &gt; 0$)</td>
<td>0.54 ± 0.17</td>
<td>0.68 ± 0.04</td>
<td>0.025 ± 0.002</td>
<td>0.007 ± 0.001</td>
<td>8.2 ± 1.6</td>
<td>0.6 ± 0.3</td>
<td>10.0 ± 1.6</td>
</tr>
<tr>
<td>$VH$-hadronic</td>
<td>0.46 ± 0.14</td>
<td>0.038 ± 0.004</td>
<td>0.23 ± 0.01</td>
<td>0.015 ± 0.001</td>
<td>9.0 ± 1.2</td>
<td>0.6 ± 0.2</td>
<td>10.3 ± 1.2</td>
</tr>
<tr>
<td>$VH$-leptonic</td>
<td>0.026 ± 0.004</td>
<td>&lt; 0.002</td>
<td>&lt; 0.002</td>
<td>0.15 ± 0.01</td>
<td>0.63 ± 0.04</td>
<td>0.11 ± 0.14</td>
<td>0.92 ± 0.16</td>
</tr>
<tr>
<td>$ggF$</td>
<td>14.1 ± 1.5</td>
<td>0.63 ± 0.02</td>
<td>0.27 ± 0.01</td>
<td>0.17 ± 0.01</td>
<td>351. ± 20</td>
<td>16.6 ± 2.2</td>
<td>383. ± 20</td>
</tr>
</tbody>
</table>
CMS: $H \rightarrow ZZ^* \rightarrow 4l$

- The observed and expected Higgs significance is $6.8\sigma$ and $6.7\sigma$, respectively.
- $m_{4l} = 125.6$ GeV

$$\mu = 0.93^{+0.26}_{-0.23} \text{ (stat.)} +^{0.13}_{-0.09} \text{ (syst.)}$$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measured mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4e</td>
<td>$126.2^{+1.5}_{-1.8}$</td>
</tr>
<tr>
<td>2e2μ</td>
<td>$126.3^{+0.9}_{-0.7}$</td>
</tr>
<tr>
<td>4μ</td>
<td>$125.1^{+0.6}_{-0.9}$</td>
</tr>
<tr>
<td>4ℓ</td>
<td>$125.6 \pm 0.4 \text{ (stat.)} \pm 0.2 \text{ (syst.)}$</td>
</tr>
</tbody>
</table>
The expected upper limit of Higgs mass width is 2.8 GeV and the observed upper limit is 3.4 GeV, at a 95% CL.
The production cross section as a function of $m_{ZZ}$ can be written as:

$$
\frac{d\sigma_{gg\to H\to ZZ}}{dm_{ZZ}^2} \propto g_{ggH}^2 g_{HZZ}^2 \frac{F(m_{ZZ})}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}.
$$

(1)

where $g_{ggH}$ ($g_{HZZ}$) is the coupling constant of the Higgs boson to gluons (to $Z$ bosons), and $F(m_{ZZ})$ is a function which depends on the (virtual) Higgs and $Z$ boson production and decay dynamics. In the resonant and off-shell regions, the integrated cross sections are

$$
\sigma_{\text{on-peak}}^{gg\to H\to ZZ} \propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}, \quad \sigma_{\text{off-peak}}^{gg\to H\to ZZ} \propto g_{ggH}^2 g_{HZZ}^2.
$$

(2)

<table>
<thead>
<tr>
<th></th>
<th>4$\ell$</th>
<th>2$\ell2\nu$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected 95% CL limit, $r$</td>
<td>11.5</td>
<td>10.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Observed 95% CL limit, $r$</td>
<td>6.6</td>
<td>6.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Observed 95% CL limit, $\Gamma_H$ (MeV)</td>
<td>27.4</td>
<td>26.6</td>
<td>17.4</td>
</tr>
<tr>
<td>Observed best fit, $r$</td>
<td>0.5 $^{+2.3}_{-0.5}$</td>
<td>0.2 $^{+2.2}_{-0.2}$</td>
<td>0.3 $^{+1.5}_{-0.3}$</td>
</tr>
<tr>
<td>Observed best fit, $\Gamma_H$ (MeV)</td>
<td>2.0 $^{+9.6}_{-2.0}$</td>
<td>0.8 $^{+9.1}_{-0.8}$</td>
<td>1.4 $^{+6.1}_{-1.4}$</td>
</tr>
</tbody>
</table>
Higgs Width (CMS)


\[ \Gamma_H < 33 \text{ MeV (42 MeV) at 95\% C.L.} \]
New heavy particles may contribute to loops

- Introduce effective $\kappa_g$, $\kappa_\gamma$ to allow heavy BSM particles contribute to the loops
- Tree-level couplings: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau$ etc set to 1
  - Absorb all difference into loop couplings
  - Indirectly fixed normalization of Higgs width

ATLAS Preliminary

$m_H = 125.5$ GeV

Couplings tested for anomalies w.r.t. fermion and boson, W/Z & vertex loop contributions at ±10%-15% precision

3D Compatibility with SM: 18%
The data disfavor the hypotheses JP with a CLs value in the range of 0.001% - 10%.
### Higgs Detection Significance

<table>
<thead>
<tr>
<th>data set</th>
<th>observed</th>
<th>expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\min p_0$</td>
<td>significance $\left[ \sigma \right]$</td>
</tr>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td>$2.5 \times 10^{-3}$</td>
<td>2.8</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td>$8.8 \times 10^{-10}$</td>
<td>6.0</td>
</tr>
<tr>
<td>combined</td>
<td>$2.7 \times 10^{-11}$</td>
<td>6.6</td>
</tr>
</tbody>
</table>

- **Signal significance**: $6.6 \sigma$ (Measured)  
- **Expected**: $4.4 \sigma$ (Expected)  
- **> 5\sigma** discovery in $H \rightarrow ZZ^* \rightarrow 4\ell$ channel
Higgs Production: ggF vs. VBF

**ATLAS Prelim.**

$m_H = 125.5$ GeV

**Higgs Production Channels:**

- **$H \to \gamma\gamma$**
  - $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.2^{+0.8}_{-0.6}$

- **$H \to ZZ^* \to 4l$**
  - $\mu_{VBF+VH}/\mu_{ggF+ttH} = 0.6^{+2.4}_{-0.9}$

- **$H \to WW^* \to lvlv$**
  - $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.8^{+1.9}_{-1.0}$

- **$H \to \tau\tau$**
  - $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.7^{+∞}_{-1.2}$

- **Combined**
  - $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.4^{+0.7}_{-0.5}$

Compatibility with $\mu_{VBF} = 0 \Rightarrow 4.1\sigma$

- Standard Model
- Best fit
- 68% CL
- 95% CL

- $\sqrt{s} = 7$ TeV $\int L dt = 4.6 - 4.8$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$

- $m_H = 125.5$ GeV
For $J^P = 2^+_m$ model:
- Graviton-like tensor with minimal couplings to SM particles
- Production via $gg$ or $qq$

Scan fraction of $qq$ production between 0 and 100%

Sensitivity is stable as a function of $q\bar{q}$ fraction

Observed exclusion ($0^+$ vs $2^+_m$) at 83.2 CL for 100% $ggF$ produced state
Search for High Mass $H \rightarrow ZZ, WW$

Extend the Higgs search to high mass assume SM-like width, and decay to $WW/ZZ$

$WW^* \rightarrow l\nu l\nu$

$ZZ^* \rightarrow 4l$

95% C.L. exclusion of a SM-like heavy Higgs up to $\sim 650$ GeV
Constraints on BSM Loops

New particles may contribute to loops

- Introduce effective $\kappa_g$, $\kappa_\gamma$ to allow heavy BSM particles contribute to the loops
- Tree-level couplings: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_t$ set to 1
  - Absorb all difference into loop couplings
  - Indirectly fixed normalization of Higgs width

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - \text{BR}_{i,u})} \Gamma_{H}^{\text{SM}}$$

$$\kappa_g = 1.00^{+0.23}_{-0.16}$$
$$\kappa_\gamma = 1.17^{+0.16}_{-0.13}$$
$$\text{BR}_{i,u} = -0.16^{+0.29}_{-0.30}$$
Table 9: Summary of the triggers that are used during the 2012 data taking for the three analysis channels. When multiple chains are indicated, it is intended that the OR among them is requested.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Single-lepton</th>
<th>Di-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>4e</td>
<td>e24vhi_medium1, e60_medium1</td>
<td>2e12Tvh_loose1, 2e12Tvh_loose1_L2StarB(only data)</td>
</tr>
<tr>
<td>4μ</td>
<td>mu24i_tight, mu36_tight</td>
<td>2mu13, mu18_mu8_EFFS</td>
</tr>
<tr>
<td>2e2μ</td>
<td>4μ OR 4e OR e12Tvh_medium1_mu8 OR e24vhi_loose1_mu8</td>
<td></td>
</tr>
</tbody>
</table>

Table 10: Summary of the triggers that are used during the 2011 data taking. In each data taking period, the OR of single and di-lepton triggers is used to select each signature.

### Single-lepton triggers

<table>
<thead>
<tr>
<th>Period</th>
<th>B-I</th>
<th>J</th>
<th>K</th>
<th>L-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>4μ</td>
<td>EF_mu18_MG</td>
<td>EF_mu18_MG_medium</td>
<td>EF_mu18_MG_medium</td>
<td>EF_mu18_MG_medium</td>
</tr>
<tr>
<td>4e</td>
<td>EF_e20_medium</td>
<td>EF_e20_medium</td>
<td>EF_e22_medium</td>
<td>EF_e22vh_medium1</td>
</tr>
<tr>
<td>2e2μ</td>
<td></td>
<td></td>
<td>4μ OR 4e</td>
<td></td>
</tr>
</tbody>
</table>

### Di-lepton triggers

<table>
<thead>
<tr>
<th>Period</th>
<th>B-I</th>
<th>J</th>
<th>K</th>
<th>L-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>4μ</td>
<td>EF_2mu10_loose</td>
<td>EF_2mu10_loose</td>
<td>EF_2mu10_loose</td>
<td>EF_2mu10_loose</td>
</tr>
<tr>
<td>4e</td>
<td>EF_2e12_medium</td>
<td>EF_2e12_medium</td>
<td>EF_2e12T_medium</td>
<td>EF_2e12Tvh_medium</td>
</tr>
<tr>
<td>2e2μ</td>
<td></td>
<td>4μ OR 4e OR EF_c10_medium_mu6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2: Higgs boson production cross sections for gluon fusion, vector-boson fusion and associated production with a $W$ or $Z$ boson in $pp$ collisions at $\sqrt{s}$ of 7 TeV and 8 TeV [11]. The quoted uncertainties correspond to the total theoretical systematic uncertainties with linear sum of QCD scale and PDF+$\alpha_s$ uncertainties. The production cross section for the associated production with a $W$ or $Z$ boson is negligibly small for $m_H > 300$ GeV. The decay branching ratio for $H \rightarrow 4\ell$, with $\ell = e$ or $\mu$, is reported in the last column [11].

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\sigma (gg \rightarrow H)$ [pb]</th>
<th>$\sigma (qq' \rightarrow Hqq')$ [pb]</th>
<th>$\sigma (q\bar{q} \rightarrow WH)$ [pb]</th>
<th>$\sigma (q\bar{q} \rightarrow ZH)$ [pb]</th>
<th>BR $\left(H \rightarrow ZZ^{(*)} \rightarrow 4\ell\right)$ $[10^{-3}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>123</td>
<td>$15.8^{+2.3}_{-2.4}$</td>
<td>$1.25 \pm 0.03$</td>
<td>$0.60^{+0.02}_{-0.03}$</td>
<td>$0.33 \pm 0.02$</td>
<td>0.103</td>
</tr>
<tr>
<td>125</td>
<td>$15.3 \pm 2.3$</td>
<td>$1.22 \pm 0.03$</td>
<td>$0.57 \pm 0.02$</td>
<td>$0.32 \pm 0.02$</td>
<td>0.125</td>
</tr>
<tr>
<td>127</td>
<td>$14.9 \pm 2.2$</td>
<td>$1.20 \pm 0.03$</td>
<td>$0.54 \pm 0.02$</td>
<td>$0.30 \pm 0.02$</td>
<td>0.148</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>123</td>
<td>$20.2 \pm 3.0$</td>
<td>$1.61 \pm 0.05$</td>
<td>$0.73 \pm 0.03$</td>
<td>$0.42 \pm 0.02$</td>
<td>0.103</td>
</tr>
<tr>
<td>125</td>
<td>$19.5 \pm 2.9$</td>
<td>$1.58^{+0.04}_{-0.05}$</td>
<td>$0.70 \pm 0.03$</td>
<td>$0.39 \pm 0.02$</td>
<td>0.125</td>
</tr>
<tr>
<td>127</td>
<td>$18.9 \pm 2.8$</td>
<td>$1.55 \pm 0.05$</td>
<td>$0.66^{+0.02}_{-0.03}$</td>
<td>$0.37 \pm 0.02$</td>
<td>0.148</td>
</tr>
</tbody>
</table>
Is it the SM Higgs Boson?

- Higgs production \( (m_H = 125 \text{ GeV}) \)
  - \( 88\% \)
  - \( 7\% \)
  - \( 4.5\% \)
  - \( 0.5\% \)

- Higgs decays

- Couplings (new force!)
  \[ g_F \text{ (Yukawa coupling)} = \sqrt{2} \times \frac{m_F}{\nu} \]
  \[ g_V \text{ (Gauge coupling)} = \frac{2m_V^2}{\nu} \]
  (\( \nu \) is the vacuum expectation value)

- Spin and Parity
# Coupling Measurements

**Coupling strengths** $\kappa_i$ & ratio: $\kappa_F = g_F / g_{F,SM}$, $\kappa_V = g_V / g_{V,SM}$, $\lambda_{ij} = \kappa_i / \kappa_j$

<table>
<thead>
<tr>
<th>Model</th>
<th>Probed couplings</th>
<th>Parameters of interest</th>
<th>Functional assumptions</th>
<th>Example: $gg \rightarrow H \rightarrow \gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Couplings to fermions and bosons</td>
<td>$\kappa_V, \kappa_F$</td>
<td>$\sqrt{\cdot} \sqrt{\cdot} \sqrt{\cdot} \sqrt{\cdot} \sqrt{\cdot}$</td>
<td>$\kappa_F^2 \cdot \kappa_Y^2 (\kappa_F, \kappa_V) / \kappa_H^2 (\kappa_F, \kappa_V)$</td>
</tr>
<tr>
<td>2</td>
<td>$\lambda_{FV}, \kappa_{VV}$</td>
<td>$\sqrt{\cdot} \sqrt{\cdot} \sqrt{\cdot} \sqrt{\cdot} -$</td>
<td>$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_Y^2 (\lambda_{FV}, \kappa_{VV}, \lambda_{FV}, 1)$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Custodial symmetry</td>
<td>$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$</td>
<td>$- \sqrt{\cdot} \sqrt{\cdot} -$</td>
<td>$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_Y^2 (\lambda_{FZ}, \lambda_{WZ}, \lambda_{FZ}, \lambda_{WZ})$</td>
</tr>
<tr>
<td>4</td>
<td>$\lambda_{WZ}, \lambda_{FZ}, \lambda_{YZ}, \kappa_{ZZ}$</td>
<td>$- = 1 = 1$</td>
<td>$- -$</td>
<td>$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{YZ}^2$</td>
</tr>
<tr>
<td>5</td>
<td>Vertex loops</td>
<td>$\kappa_g, \kappa_\gamma$</td>
<td>$- - - \sqrt{\cdot}$</td>
<td>$\kappa_g^2 \cdot \kappa_\gamma^2 / \kappa_H^2 (\kappa_g, \kappa_\gamma)$</td>
</tr>
</tbody>
</table>

**Example $H \rightarrow \gamma\gamma$**

$$(\sigma \cdot BR) (gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

$\kappa_g, \kappa_\gamma$: loop coupling scale factors

$\kappa_H$ is the total Higgs width scale factor

$$\kappa_\gamma^2 = |1.28 \kappa_W - 0.28 \kappa_t + ...|^2$$
Spin Analysis with $H \rightarrow \gamma \gamma$

Polar angle $\theta^*$ of the photon decay in Collines-Soper frame, along with $m_{\gamma \gamma}$

$Z_{CS}$ bisects angle between the momenta of colliding hadrons

$$\cos \theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma_1} / m_{\gamma_1} \right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma \gamma}^2}$$

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

- Data
- $J^P = 0^+$ Expected
- $J^P = 0^+$ Data
- Bkg. syst. uncertainty

$H \rightarrow \gamma \gamma$

- Data
- $J^P = 2^+$ Expected
- $J^P = 2^+$ Data
- Bkg. syst. uncertainty

(f_{qq} = 0%)
Spin Analysis With $H \rightarrow WW^*$

Exclusion $(1 - CL_s)$:

- Observed $2^+$ (qq=100%) exclusion 99.96%
- Observed $2^+$ (qq = 0%) exclusion 95.2%
MVA Discriminant: Higgs Spin and CP