Properties of the New Boson

F. Cerutti – LBNL

On behalf of ATLAS, CMS, CDF and D0 Collaborations
Outline

Thanks to Greg for nice experimental overview on Higgs results which are input to properties determination

• Introduction

• Properties:
  – Mass measurements
  – Spin-Parity determination
  – Couplings from signal strengths \( \mu = \frac{\sigma \times \text{BR}}{\sigma \times \text{BR}_{\text{SM}}} \)
  – Differential cross-sections in \( \gamma \gamma \) final state

• Conclusions
Bibliography used in this talk

• **ATLAS:**
  
  http://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
  – Phys. Lett. B 716 (Discovery)
  – ATLAS-CONF 2013-040 (Spin)
  – ATLAS-CONF 2013-029 (γγ)
  – ATLAS-CONF 2013-031 (WW*)
  – ATLAS-CONF 2013-013 (ZZ*)
  – ATLAS-CONF-2013-079 (VH→bb)
  – ATLAS-CONF-2013-072 (H→γγ diff. σ)
  – ATLAS-PHYS-PUB 2012-001/002 (HL-LHC)

• **CMS:**
  
  http://cms.web.cern.ch/org/cms-papers-and-results
  – Phys. Lett. B 716 (Discovery)
  – CSM-PAS-HIG-13-016 (Properties γγ)
  – CMS-PAS-HIG-13-018 (ZH→Z-invisible)
  – CMS-PAS-HIG-13-005 (Couplings)
  – CMS-PAS-HIG-13-012 (H→bb)
  – CMS-PAS-HIG-13-001 (γγ)
  – CMS-PAS-HIG-13-002 (ZZ*, Spin)
  – CMS-PAS-HIG-13-003 (WW*)
  – CMS-PAS-HIG-13-004 (ττ)
  – CMS-NOTE-2012-006 (HL-LHC)

• **CDF + D0:**
  
  http://tevnphwg.fnal.gov/
  – D0 note 6387-CONF (Spin 2+ studies)

• **LHC-XS Higgs wg:**
  
  http://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
  – arXiv:1307.1347 (Yellow Report 3: σ, BR and coupling and spin/CP-fit models)

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**material form excellent parallel session talks !**
Introduction

• 1 year ago ATLAS and CMS Collaborations announced the discovery of a NEW neutral Boson supported by D0 and CDF results

• Since then the ATLAS, CMS, CDF and D0 Collaborations focused on two questions:
  – Is this new boson responsible for the EW symmetry breaking - BEH mechanism - providing masses to Fermions and Bosons: “the SM Higgs boson” ?
  – Can we find signs of Physics Beyond the SM (BSM) studying its properties ?

• Addressed experimentally by properties measurement in next slides ...
Measured from $\gamma \gamma$ and $ZZ^*(4\ell)$ mass spectra: needed to predict $\sigma \times BR$

ATLAS: $M_H = 125.5 \pm 0.2_{\text{stat}} \pm 0.6_{\text{sys}}$ GeV

CMS: $M_H = 125.7 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$ GeV

*Independent of signal strengths: used by ATLAS and CMS coupling/spin analyses

From $\gamma \gamma$: $\Gamma_H < 6.9$ GeV at 95% CL (direct)
Spin-Parity Determination:

*Experimental approach:*

- Use observables that are sensitive to Spin and Parity of the *New Boson* independent of the *coupling strengths*.

- Several alternative specific models: $0^-, 1^+, 1^-, 2^+$ tested against the *SM Higgs $0^+$ hypothesis*.

- On-shell $X(J=1) \rightarrow \gamma\gamma$ by Landau-Yang theorem.
Spin-Parity Determination

Analyzed channels:

- $H \to \gamma\gamma$ decay angle $\cos(\theta^*)$ in Collins-Sopper frame sensitive to $J$

- $H \to WW^* \to \ell\nu\ell\nu$ Several variables sensitive to $J^P$
  - $\Delta\phi_{\ell\ell}$, $M_{\ell\ell}$, ..
  - Combined with Boosted-Decision-Tree (BDT)

- $H \to ZZ^* \to 4\ell$: Full final state reconstruction sensitive to $J^P$
  - 2 masses ($M_{Z1}, M_{Z2}$) and 5 angles
  - Combined with BDT or Matrix-Element-based discriminant $D_{JP}$
Test of $0^+ \text{ vs } 0^-$

**ZZ* → 4ℓ channel used by CMS and ATLAS:**

Test Statistic: 

\[ q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\mu}_0^+, \hat{\theta}_0^+)}{\mathcal{L}(J^P_{\text{alt}}, \hat{\mu}_0, \hat{\theta}_0)} \]

**ATLAS:**

- $0^-$ Excluded @ 97.8% CL (exp. 99.6%)

**CMS:**

- $0^-$ Excluded @ 99.8% CL (exp. 99.5%)

Compatible with SM $0^+$
Beyond 2 hypotheses Test: $0^+ \text{ vs } 0^-$

CMS investigated sensitivity to different CP Amplitudes in $ZZ^*$ channel

$$A = v^{-1} \epsilon_2^v \epsilon_1^\mu \left( a_1 g_{\mu\nu} m_H^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right) = A_1 + A_2 + A_3$$

- SM Higgs at LO corresponds to $a_1=1$ and $a_2=a_3=0$
- $A_3=\text{CP odd Amplitude}$
- Fit for $f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)$: check the presence of a $0^-$ component (assuming $a_2=0$) - impact of interference very small on used observables

- CMS: $f_{a3} = 0.00 \pm 0.23 - 0.00$

$f_{a3} < 0.56$ at 95% CL (exp. 0.76)
Test of $0^+ \text{ vs } 2^+$

Graviton inspired model with minimal couplings to SM particles
It can be produced via $gg$ or $qq$ annihilation:
\[ f_{qq} = \text{faction of } qq/gg \text{ produced signals} \]
(In minimal model $2^+_m$ at LO in QCD expected $f_{qq}=4\%$)

ATLAS: Combined: $\gamma\gamma + ZZ^* \rightarrow 4\ell + WW^* \rightarrow \nu\ell\nu\ell$
- $2^+$ (100% $qq$) Excluded at $>99.9\%$ CL (exp. $>99.9\%$)
- $2^+$ (100% $gg$) Excluded at $>99.9\%$ CL (exp. 99.9\%)

CMS: Combined $ZZ^* \rightarrow 4\ell + WW^* \rightarrow \nu\ell\nu\ell$
- $2^+$ (100% $gg$) Excluded at $99.4\%$ CL (exp. 98.8\%)

Both experiments: Compatible with SM $0^+$

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### ATLAS and CMS: “bosonic” decay modes

- Strongly favor \( J^P = 0^+ \) SM quantum numbers

### All alternative \( J^P \) models tested:

- Excluded @ >95% CL
D0: Test of $0^+$ vs $2^+$

Graviton-inspired model with minimal couplings to SM

- $X=2^+ \sim \beta^5$ threshold behavior ($0^+ \sim \beta$) for $VX \rightarrow Vbb$ production: Sensitive observable *Mass (Transverse)* of the $VX$ system

assuming $\mu=1.23$ (as measured in the Data for the SM Higgs search) - Combining $\ell\ell bb$, $\ell\nu bb$ and $\nu\nu bb$

- $2^+$ Excluded at $99.9\%$ CL – $3.1\sigma$ ($\mu = 1$ exp. $99.9\%$)

Compatible with SM $0^+$

*Studies for $0^-$ hypothesis in the pipeline ...
NEW Boson Couplings

Crucial TEST of SM BEH mechanism → $g_F \alpha m_F$ and $g_{w,z,h} \alpha M^2_{w,z,h}$

- SM couplings tested introducing coupling scale factors $\kappa \rightarrow g_i = g_i^{SM} \times \kappa_i$
  - SM Tree-Level Amplitudes:
    - $\Gamma_{ff} \propto (\kappa_f \times m_f \nu)^2 \propto \kappa_f^2 \times \Gamma_{ff}^{SM}$ ($\nu = 246$ GeV from $G_F$)
    - $\Gamma_{WW} \propto (\kappa_W \times M_W^2 \nu)^2 \propto \kappa_W^2 \times \Gamma_{WW}^{SM}$
    - $\Gamma_{ZZ} \propto (\kappa_Z \times M_Z^2 \nu)^2 \propto \kappa_Z^2 \times \Gamma_{ZZ}^{SM}$
  - SM Loop-level: best place to look for physics Beyond the Standard Mode
    - $\Gamma_{\gamma\gamma} \propto |1.28 \kappa_W - 0.28 \kappa_t|^2 \times \Gamma_{\gamma\gamma}^{SM} \rightarrow Wt$ interference
    - $\Gamma_{gg, \gamma Z, ...}$

- Theory errors for SM Higgs boson:
  - $\sigma_H \sim (11-5\%)$ larger in $ggH$ and $ttH$ - $BR_H \sim (3-6\%)$

*Mass dependency small: $Max \sim 4\%/0.5$ GeV for $\Gamma_{ZZ}$

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The Couplings Test

- Follow recommendations from LHC Higgs xs-wg: arXiv1307.1347 (YR3) **assuming**:
  - 1 resonance + **Zero-Width Approx.** + SM Lagrangian Tensor Structure \( (J^P=0^+) \)
  
  \[
  \sigma \times BR(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}
  \]

- **Approach suitable to test SM predictions** exploiting correlations between production \( (gg, VBF, VH, ttH) \) and decay modes with current precision

- e.g., measured yield \( ZH \rightarrow Zbb \) parameterized as:

  \[
  \mu(ZH \rightarrow Zbb) = \frac{[\sigma_{ZH} \times BR(H \rightarrow bb)]}{[\sigma_{ZH} \times BR(H \rightarrow bb)]_{SM}} = \left( \kappa_Z^2 \times \kappa_b^2 \right) / \kappa_H^2
  \]

  **SM Higgs boson** \( \rightarrow \) All \( \mu \) and \( \kappa \) compatible with \( 1 \)

- **Loop scaling factors** \( \kappa_\gamma, \kappa_g \) can be:
  - Expressed as a function of SM couplings scale factors: \( \kappa_\gamma(\kappa_W, \kappa_t) \)
  - Treated as free parameter to test BSM contributions

- \( \Gamma_H \) need assumptions: ratios, relationships \( \kappa_H = \kappa_H(\kappa_b, \kappa_W, ...) \), ...
The signal Strength $\mu$

- **Combined** $\mu \rightarrow$ Best accuracy but no strong physics motivation:
  - **ATLAS** ($\gamma\gamma$, $WW^*$ and $ZZ^*$) \[ \mu = (1.33 \pm 0.20) \quad (1.23\pm0.18 \text{ including } bb \text{ and } \tau\tau) \]
  - **CMS** ($\gamma\gamma$, $\tau\tau$, $bb$, $WW^*$ and $ZZ^*$) \[ \mu = (0.80 \pm 0.14) \]
  - **TEVATRON** ($bb$, $\gamma\gamma$, $\tau\tau$, $WW^*$) \[ \mu = (1.44 \pm 0.60) \]

**Compatible with SM Higgs boson expectation:** Accuracy $\sim 15\%$
Evidence for V-mediated Production

Disentangle production modes: V-mediated vs F-mediated

Fit to $\mu_{\text{VBF+VH}}/\mu_{\text{gg+ttH}}$ in different channels (BR’s cancels out):

- CMS: Evidence for V-boson mediated production \(3.2\sigma\)
- ATLAS: Evidence for VBF production (VH “profiled”) \(3.3\sigma\)

V-mediated production compatible with SM prediction
Test of Vector vs Fermion sectors $\kappa_V - \kappa_F$

- **Assumptions:**
  - All Fermion couplings scale as $\kappa_F (= \kappa_t = \kappa_b = \kappa_{\tau} = \ldots)$
  - All Vector Boson couplings scale as $\kappa_V (= \kappa_W = \kappa_Z)$
  - No BSM contributions to $\Gamma_H \to \kappa_V^2 H(\kappa_F \kappa_V) \sim 0.7 \kappa_F^2 + 0.3 \kappa_V^2$ and $\kappa_g(\kappa_F \kappa_V) \kappa_\gamma(\kappa_F \kappa_V)$

- All experiments compatible with SM predictions: accuracy $\sim 10$-$20%$
  - **ATLAS:** $\kappa_v [1.05, 1.22]$ at 68% CL - $\kappa_F [0.76, 1.18]$ at 68% CL
  - **CMS:** $\kappa_v [0.74, 1.06]$ at 95% CL - $\kappa_F [0.61, 1.33]$ at 95% CL
- $\kappa_F = 0$ Excluded at $>5\sigma$ (mainly indirect via $gg$ loop)
Test of loop induced couplings: $\kappa_g$ vs $\kappa_\gamma$

- **Assumptions:**
  - Tree-level Coupling to SM particles as in SM: $\kappa_b = \kappa_W = \kappa_Z = \kappa_\tau = \kappa_t \ldots = 1$
  - No BSM contributions to $\Gamma_H \rightarrow \kappa_H \sim 0.9 \pm 0.1$ $\kappa_g$

- Both experiments: **compatible with SM predictions** - Accuracy $\sim 10\text{-}15\%$
  - ATLAS: $\kappa_g = (1.04 \pm 0.14)$ at 68% CL - $\kappa_\gamma = (1.20 \pm 0.15)$ at 68% CL
  - CMS: $\kappa_g = [0.63, 1.05]$ at 95% CL - $\kappa_\gamma = [0.59, 1.30]$ at 95% CL
Constraints on $\text{BR}_{\text{BSM}}$

- Greg has shown direct search for: $ZH \rightarrow ll$-Invisible
  - ATLAS: $\text{BR}_{\text{inv}} < 0.60$ @ 95% CL (0.84 exp.)
  - CMS: $\text{BR}_{\text{inv}} < 0.75$ @ 95% CL (0.91 exp.)

- We can parameterize: $\Gamma_H = \Gamma_{\text{SM}} + \Gamma_{\text{BSM}}$
  \[ \text{BR}_{\text{BSM}} = \frac{\Gamma_{\text{BSM}}}{\Gamma_H} \]

- This quantity is sensitive also to other undetectable decay modes: $H \rightarrow$ light hadrons

- ATLAS:
  - Assumptions three-level couplings: $\kappa_b = \kappa_W \ldots = 1$
  - 3 Fitted Par.: $\kappa_{\gamma} \kappa_g + \text{BR}_{\text{BSM}}$
  - $\text{BR}_{\text{BSM}} < 0.60$ @ 95% CL (0.67 exp.)

- CMS:
  - Assumption: $\kappa_V \leq 1$ (motivated by EWSB)
  - 7 Fitted Par.: $\kappa_V \kappa_b \kappa_\tau \kappa_t \kappa_{\gamma} \kappa_g + \text{BR}_{\text{BSM}}$
  - $\text{BR}_{\text{BSM}} < 0.64$ @ 95% CL (0.66 exp.)
• Different *Sectors* of the New Boson Couplings tested: $P_{SM} > 12\%$

**All compatible with SM Higgs expectations**

**Couplings Overview**

![Graph showing couplings overview](image)

CMS Preliminary

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

ATLAS

$m_H = 125.5$ GeV

$\sqrt{s} = 7$ TeV $fLdt = 4.6-4.8$ fb$^{-1}$
$\sqrt{s} = 8$ TeV $fLdt = 20.7$ fb$^{-1}$

Combined $H \rightarrow \gamma\gamma$, ZZ*, WW*

Total uncertainty

$\pm 1\sigma$  
$\pm 2\sigma$

Parameter value

$P_{SM} = 12\%$

$P_{SM} = 20\%$

$P_{SM} = 14\%$

$P_{SM} = 12\%$

$P_{SM} = 14\%$
**Differential Cross sections in $\gamma\gamma$ final state**

- ATLAS: fiducial differential cross-sections
  - $d\sigma/dP_T^{\gamma\gamma}$, $d|y^{\gamma\gamma}|$, $d|\cos(\theta^*)|$, $dN_{\text{jets}}$, $d\phi_{JJ}$, ...
  - Unfolded to particle level
  - Sensitive to: PDF, QCD, production mechanism, spin, Lagrangian tensor structure, ...

### Probabilities of $\chi^2$ compatibility tests for Data vs Predictions for different observables

| $N_{\text{jets}}$ | $p_T^{\gamma\gamma}$ | $|y^{\gamma\gamma}|$ | $|\cos(\theta^*)|$ | $p_T^{j_1}$ | $\Delta\phi_{jj}$ | $p_T^{\gamma\gamma jj}$ |
|------------------|---------------------|----------------|----------------|-----------|-----------|----------------|
| POWHEG           | 0.54                | 0.55            | 0.38           | 0.69      | 0.79      | 0.42          | 0.50          |
| MINLO            | 0.44                | –               | –              | 0.67      | 0.73      | 0.45          | 0.49          |
| HRES 1.0         | –                   | 0.39            | 0.44           | –         | –         | –             | –             |

- **Data in agreement with tested predictions (Powheg, MINLO, Hres1.0) within current experimental accuracy**

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Conclusions

• 1 year after the discovery properties of the New boson measured with increasing precision thanks to outstanding LHC performance and improved analysis from CDF and D0:
  – Mass measured at the 3 per mill level
  – Evidence for scalar nature $0^+$ (though CP mixing not excluded)
  – Evidence for couplings to Fermions: $direct > 3\sigma$ and $indirect > 5\sigma$
  – Evidence for V-mediated and VBF production
  – Coupling Tests compatible with SM predictions
  – No sign (yet ?) for BSM contributions: invisible decays, $\Gamma_{BSM}$, loop couplings ..

All measured properties compatible with the SM Higgs boson

• Coming soon: final RUN1 publications from CMS and ATLAS
• In 2015 LHC will increase $E_{CM}$ ($\sigma_H \sim 2.6$) and Luminosity ($10^{34}$cm$^{-2}$s$^{-1}$)
  – Increase sensitivity to challenge the SM predictions:

This is just the beginning of a rich and exciting “Higgs physics program” !
Thanks to Parallel Sessions Speakers!

- Material from the excellent talks in parallel session:

Mass Measurements

From $\gamma\gamma$ and $ZZ^*(4\ell)$ mass spectra

**ATLAS**: $M_H = 124.3 \pm 0.6^\text{stat} \pm 0.4^\text{sys}$ GeV

**CMS**: $M_H = 125.8 \pm 0.5^\text{stat} \pm 0.2^\text{sys}$ GeV

**ATLAS**: $M_H = 126.8 \pm 0.2^\text{stat} \pm 0.7^\text{sys}$ GeV

**CMS**: $M_H = 125.4 \pm 0.5^\text{stat} \pm 0.6^\text{sys}$ GeV

**ATLAS**: $M_H = 125.5 \pm 0.2^\text{stat} \pm 0.6^\text{sys}$ GeV

**CMS**: $M_H = 125.7 \pm 0.3^\text{stat} \pm 0.3^\text{sys}$ GeV
Mass Measurement: ATLAS

ATLAS tension between $\gamma\gamma$ and $ZZ^*(4\ell)$ mass measurements

- Dedicated Likelihood with different mass parameterization:
  - $M_H$ and $\Delta M_H$

  $$\Delta M_H = 2.3 \pm 0.7_{\text{stat}} \pm 0.6_{\text{sys}} \text{ GeV} = 2.3 \pm 0.9_{\text{tot}} \quad (M_H \text{ “profiled”})$$

- Probability to observe such a large (or larger) difference if $\Delta M_H = 0$
  - evaluated at $1.5\%$ ($2.4\sigma$)

- If main systematics on Electromagnetic-Energy Scale shifted by $1\sigma$
  - probability increases to $8\%$

- Updates final $\gamma\gamma$ and $ZZ^*(4\ell)$ publications this fall:
  - better EES calibration (material description, ..), improved $ZZ^*$ mass analysis (MVA techniques, event by event errors, ..)
Spin-Parity determination

- Used as test statistics the likelihood ratio $q$:

\[
L(J^P, \mu, \theta) = \prod_{j} \prod_{i} \left[ \frac{N_{chann} \cdot N_{bins}}{P(N_{i,j} \mid \mu_j \cdot S_{i,j}^{(J^P)}(\theta) + B_{i,j}(\theta)) \times \mathcal{A}_j(\theta)} \right]
\]

\[
q = \log \frac{L(J^P = 0^+, \hat{\mu}_{0^+}, \hat{\theta}_{0^+})}{L(J^P_{alt}, \hat{\mu}_{J^P_{alt}}, \hat{\theta}_{J^P_{alt}})}
\]

- Signal strengths $\mu_{J^P}$ treated as independent Nuisance-Parameter for each channel and each spin hypothesis

- Probability distributions for different $J^P$ hypothesis derived via pseudo-experiments

- When deriving exclusions use $CL_s$:

\[
CL_s(J^P_{alt}) = \frac{p_0(J^P_{alt})}{1 - p_0(0^+)}
\]
Test of $0^+ \text{ vs } 1^+ / 1^-$

**ATLAS:** combined $WW^* \rightarrow \nu\ell\nu\ell + ZZ^* \rightarrow 4\ell$

- $1^+$ Excluded at 99.97% CL (exp. 99.95%)
- $1^-$ Excluded at 99.7% CL (exp. 99.4%)

**CMS:** $ZZ^* \rightarrow 4\ell$

- $1^+$ Excluded at $>99.9\%$ CL (exp. 99.7\%)
- $1^-$ Excluded at $>99.9\%$ CL (exp. 99.5\%)

Compatible with SM Higgs $0^+$
Test of $0^+ \, \text{vs} \, 2^+_m f_{qq}$ scan

Graviton inspired with minimal couplings to SM particles

Tensor can be produced via $gg$ or $qq$ annihilation

**ATLAS: $\gamma\gamma + WW^* + ZZ^*$**

- $2^+_m (100\% \, qq)$ Excluded at $>99.99\% \, \text{CL}$ (exp. $>99.99\%$)
- $2^+_m (100\% \, gg)$ Excluded at $99.98\% \, \text{CL}$ (exp. 99.94\%)

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### Channels/Categories used in the coupling tests

**CMS - CSM-PAS-HIG-13-005**

<table>
<thead>
<tr>
<th>H decay</th>
<th>Prod. tag</th>
<th>Exclusive final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau\tau$</td>
<td>$\tau\tau$ (4 diphoton classes)</td>
<td>$\tau\tau + (\ell\ell)$ (two dijet classes for 8 TeV)</td>
</tr>
<tr>
<td>ZZ → $4\ell$</td>
<td>$N_{\ell\ell} &lt; 2$ \hspace{1cm} $N_{\ell\ell} \geq 2$</td>
<td>$4e, 4\mu, 2e\mu$</td>
</tr>
<tr>
<td>WW → $\ell\nu\ell\nu$</td>
<td>VBF-tag \hspace{1cm} VH-tag</td>
<td>$3\ell\nu$ (same-sign SF and otherwise)</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Higgs Boson Decay</th>
<th>Subsequent Decay</th>
<th>Sub-Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to ZZ^{(*)}$</td>
<td>4$\ell$ \hspace{1cm} 4$\ell$</td>
<td>10 categories</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>– \hspace{1cm} [(\ell\ell\Delta T) &amp; (\ell\ell\rightarrow\gamma\gamma)]</td>
<td>2 $\gamma$ categories</td>
</tr>
<tr>
<td>$H \to WW^{(*)}$</td>
<td>$\ell\nu\ell\nu$ \hspace{1cm} $ee\mu\mu(+\ell\ell\rightarrow\gamma\gamma)$</td>
<td>14 categories</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH → $\ell\nu\ell\nu$ 2-jet channels</td>
<td>4×(5 b-tag categories)</td>
</tr>
<tr>
<td>WH → $\ell\nu\ell\nu$ 3-jet channels</td>
<td>3×(2 b-tag categories)</td>
</tr>
<tr>
<td>ZH → $\nu\nu\ell\nu$</td>
<td>$H \rightarrow \nu\nu$</td>
</tr>
<tr>
<td>ZH → $\ell\ell\rightarrow\nu\nu$ 2-jet channels</td>
<td>2×(4 b-tag categories)</td>
</tr>
<tr>
<td>ZH → $\ell\ell\rightarrow\nu\nu$ 3-jet channels</td>
<td>2×(4 b-tag categories)</td>
</tr>
<tr>
<td>WH + ZH → $\nu\nu\ell\nu$ 2-jet categories</td>
<td>2×(2 b-tag categories)</td>
</tr>
<tr>
<td>tH → $W^+W^-\rightarrow b\bar{b}$</td>
<td>4 jets, 5 jets, 6 jets, 7 b-jets, 8 b-jets</td>
</tr>
</tbody>
</table>


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<tr>
<td>ZH → $\nu\nu\ell\nu$</td>
<td>$H \rightarrow \nu\nu$</td>
</tr>
<tr>
<td>ZH → $\ell\ell\rightarrow\nu\nu$ 2-jet channels</td>
<td>2×(4 b-tag categories)</td>
</tr>
<tr>
<td>H → $W^+W^-$</td>
<td>2×(0 jet), 1×(≥ 2 jets) + 1×(low-m_{ll})</td>
</tr>
<tr>
<td>H → $W^+W^-$</td>
<td>$H \rightarrow \nu\nu$</td>
</tr>
<tr>
<td>WH → $W^+W^-$ (same-sign leptons) + (tri-leptons)</td>
<td>$H \rightarrow W^+W^-$</td>
</tr>
<tr>
<td>WH → $W^+W^-$ (tri-leptons with 1 $\tau$)</td>
<td>$H \rightarrow W^+W^-$</td>
</tr>
<tr>
<td>ZH → $ZW^+W^-$ (tri-leptons with 1 $\tau$)</td>
<td>$H \rightarrow W^+W^-$</td>
</tr>
<tr>
<td>H → $H^+H^-$</td>
<td>1×(0 jet) + 1×(≥ 2 jets) + 2×(all jets)</td>
</tr>
<tr>
<td>H → $ZZ$ (four leptons)</td>
<td>$H \rightarrow ZZ$</td>
</tr>
</tbody>
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Production/Decay with *Signal* above $2\sigma$

- **Measure:** Yields $\rightarrow$ Production $\times$ Decay
  - Production modes: $gg$, VBF, $W/ZH$, $ttH$
  - Decay Channels: $\gamma\gamma$, $WW^*$, $ZZ^*$, $bb$, $\tau\tau$, $\mu\mu$, $Z\gamma$

  **Observations Above $2\sigma$:**

- **ATLAS:**
  - Production Modes: gluon-gluon($>5\sigma$), VBF($>3\sigma$), VH
  - Decay Channels: $WW^*(3.8\sigma)$, $ZZ^*(>5\sigma)$, $\gamma\gamma(>5\sigma)$

- **CMS:**
  - Production Modes: gluon-gluon($>5\sigma$), VH, VBF, ($V+VBF)H(>3\sigma)$
  - Decay Channels: $WW^*(4\sigma)$, $ZZ^*(>5\sigma)$, $\gamma\gamma(>3\sigma)$, $\tau\tau$, $bb$, combined $\tau\tau+bb(>3\sigma)$

- **D0+CDF:**
  - Production Modes: VH($>3\sigma$)
  - Decay Channels: $bb(>3\sigma)$
Evidence for Direct Couplings to Fermions

- **TEVATRON**: CDF+D0 Combined VH→bb
  - 2.1σ excess
  - σ(VH)×BR(H→bb) = (0.19 ± 0.09) pb - SM for M_H=125 GeV → (0.12 ± 0.01) pb

- **CMS** (for M_H=125 GeV):
  - (VBF+V)H → bb combination 2.1σ excess
  - H→ττ 2.85σ excess
  - Combined H→(ττ + bb) 3.4σ excess

- **ATLAS** (for M_H=125 GeV):
  - H→ττ μ= (0.7 ± 0.7) (compatible with SM, with or without Higgs boson)
  - VH→bb μ= (0.2 ± 0.7) (compatible with SM, with or without Higgs boson)
The Couplings fit

- Loop contributions can:
  - Expressed as a function of SM couplings
  - Treated as free parameter (test possible BSM contributions)

- Total width $\Gamma_H$ two kind of assumptions
  - Only SM particles contribute to $\Gamma_H(\Gamma_i)$
  - Measure ratio of couplings $\lambda$

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{SM}} = \left\{ \frac{\kappa_g^2}{\kappa_g^2} \right\}$$

$$\frac{\sigma_{VBF}}{\sigma_{SM}} = \kappa_{VBF}^2 \left( \kappa_W, \kappa_Z, m_H \right)$$

$$\frac{\sigma_{WH}}{\sigma_{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{ttH}}{\sigma_{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW(*)}}{\Gamma_{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ(*)}}{\Gamma_{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{bb}}{\Gamma_{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^+\tau^-}}{\Gamma_{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{SM}} = \left\{ \kappa_{\gamma}^2 \left( \kappa_b, \kappa_t, \kappa_t, \kappa_W, m_H \right) \right\}$$

$\kappa_{\gamma}^2 = (1.6 \kappa_W^2 + 0.07 \kappa_t^2 - 0.67 \kappa_W \kappa_t)$
Inputs to the Fit

- Input to coupling fit: event yields per category $k$ (list of channels/category used in backup)
  - $N^k = n_{signal}^k + n_{background}^k$
- Signal scaling factors per Production $i$ and Decay $f$

$$n_{signal}^k = \left( \sum_i \mu_i \sigma_{i,SM} \times A_i^k \times \varepsilon_{if}^k \right) \times \mu_f \times B_{f,SM} \times L^k$$

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LHC Coupling Fit: statistical approach

- Use profile likelihood ratio: 
  \[ q(a) = -2 \ln \frac{\mathcal{L}(\text{obs} | s(a) + b, \hat{a})}{\mathcal{L}(\text{obs} | s(\hat{a}) + b, \hat{\theta})} \]

- \( \alpha \) Parameter(s) of Interest: Signal Strength, Coupl. scale factor, Mass, ...

- \( \theta \) Nuisance parameter(s): Systematics, ...

- CL intervals: Asymptotic approximation:
  - 1D: 68% \( q(\alpha) = 1 \) - 95% \( q(\alpha) = 3.84 \)
  - 2D: 68% \( q(\alpha_i, \alpha_j) = 2.3 \) - 95% \( q(\alpha_i, \alpha_j) = 6 \)
  - Cross checked with “pseudo-experiments”

\[ q_\mu = -2 \Delta \ln \mathcal{L} = -2 \ln \frac{\mathcal{L}(\text{data} | \mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data} | \hat{\mu}, \hat{\theta})} \]
Evidence for different Production modes

Model independent fit to $\mu_{\text{VBF}+\text{VH}}/\mu_{\text{gg}+\text{ttH}}$ in different channels (BR’s cancels out):

- **ATLAS**: Evidence for VBF production $3.1\sigma$
- **CMS**: Evidence for $V$-boson mediated production

### ATLAS

<table>
<thead>
<tr>
<th>$m_h = 125.5$ GeV</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\mu_{\text{VBF}+\text{VH}}/\mu_{\text{gg}+\text{ttH}} = 1.1^{+0.9}_{-0.5}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$\mu_{\text{VBF}+\text{VH}}/\mu_{\text{gg}+\text{ttH}} = 0.6^{+2.4}_{-0.9}$</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow lv\nu$</td>
<td>$\mu_{\text{VBF}+\text{VH}}/\mu_{\text{gg}+\text{ttH}} = 2.0^{+2.2}_{-1.0}$</td>
</tr>
<tr>
<td>Combined $H \rightarrow \gamma\gamma, ZZ^<em>, WW^</em>$</td>
<td>$\mu_{\text{VBF}+\text{VH}}/\mu_{\text{gg}+\text{ttH}} = 1.4^{+0.7}_{-0.5}$</td>
</tr>
</tbody>
</table>

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

$\Delta \ln L$ vs. $\mu_{\text{VBF}+\text{VH}}/\mu_{\text{gg}+\text{ttH}}$ for different processes:

- **Black**: Combined
- **Purple**: $H \rightarrow \tau\tau$
- **Blue**: $H \rightarrow WW$
- **Red**: $H \rightarrow ZZ$
- **Green**: $H \rightarrow \gamma\gamma$

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

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

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Test of W/Z coupling: $\lambda_{W/Z}$

- Ratio is independent of assumptions on $\Gamma_H$
- Tested under different assumptions
  - More model independent: using only “untagged” $WW^*$ and $ZZ^*$ channels
    - CMS: $\lambda_{W/Z} [0.60, 1.40]$ at 95% CL
    - ATLAS: $\lambda_{W/Z} = (0.81 \pm 0.16)$ at 68% CL
  - Assuming SM content in $\gamma\gamma$ loop and using VBF+VH production
    - ATLAS: $\lambda_{W/Z} [0.61, 1.04]$ at 68% CL
    - CMS: $\lambda_{W/Z} [0.62, 1.19]$ at 95% CL

Compatible with SM prediction:

Accuracy $\sim 20\%$
6 parameters fits: $K_V K_b K_\tau K_g K_\gamma K_t$

- 6 Parameters Fit: $K_V K_b K_\tau K_g K_\gamma K_t \rightarrow$ Assumptions $\Gamma_{BSM} = 0$, $\kappa_W = \kappa_Z = \kappa_V$

Compatible with SM: Accuracy 20-100%
Higgs boson production at LHC

- Main production mode: $ggH$
- Access to top (direct and Loop), $W$ and $Z$ couplings via production cross section
Higgs boson production at LHC

8 TeV

<table>
<thead>
<tr>
<th>$M_H$(125 GeV)</th>
<th>$\sigma$(fb)</th>
<th>$\delta$(th)$_{TOT}$</th>
<th>$\delta$(th)$_{QCD-Scale}$</th>
<th>$\delta$(th)$_{PDF+\alpha_s}$</th>
<th>$\delta\sigma/\delta M(.5$GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH</td>
<td>19.5 x $10^3$</td>
<td>11%</td>
<td>8%</td>
<td>7%</td>
<td>0.8%</td>
</tr>
<tr>
<td>VBF</td>
<td>1.58 x $10^3$</td>
<td>3%</td>
<td>0.2%</td>
<td>3%</td>
<td>0.4%</td>
</tr>
<tr>
<td>WH</td>
<td>697</td>
<td>4%</td>
<td>0.5%</td>
<td>4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>ZH</td>
<td>394</td>
<td>5%</td>
<td>1.5%</td>
<td>4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>130</td>
<td>11%</td>
<td>7%</td>
<td>8%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

- Cross-sections are **LARGE**: LHC is the first Higgs Factory $\rightarrow$ Produced $H \sim 600k/Exp$.
- **Theory systematics** more relevant for $ggH$ and $t\bar{t}H$ - Mass dependency very weak
Higgs boson decay at LHC

- Experimentally accessible:
  - $b\bar{b}$, $\tau\tau$, $WW^*$, $ZZ^*$, $\gamma\gamma$, $Z\gamma$, $\mu\mu$
- $\Gamma_H(125) \sim 4$ MeV NO direct measure at LHC

<table>
<thead>
<tr>
<th>Process</th>
<th>Branching ratio</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to b\bar{b}$</td>
<td>$5.77 \times 10^{-1}$</td>
<td>$+3.2%$ $-3.3%$</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>$6.32 \times 10^{-2}$</td>
<td>$+5.7%$ $-5.7%$</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>$2.20 \times 10^{-4}$</td>
<td>$+6.0%$ $-5.9%$</td>
</tr>
<tr>
<td>$H \to cc$</td>
<td>$2.91 \times 10^{-2}$</td>
<td>$+12.2%$ $-12.2%$</td>
</tr>
<tr>
<td>$H \to gg$</td>
<td>$8.57 \times 10^{-2}$</td>
<td>$+10.2%$ $-10.0%$</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$2.28 \times 10^{-3}$</td>
<td>$+5.0%$ $-4.9%$</td>
</tr>
<tr>
<td>$H \to Z\gamma$</td>
<td>$1.54 \times 10^{-3}$</td>
<td>$+9.0%$ $-8.8%$</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>$2.15 \times 10^{-1}$</td>
<td>$+4.3%$ $-4.2%$</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>$2.64 \times 10^{-2}$</td>
<td>$+4.3%$ $-4.2%$</td>
</tr>
</tbody>
</table>

$\Gamma_H [\text{GeV}]$ | $4.07 \times 10^{-3}$ | $+4.0\%$ $-3.9\%$

Mass dependency:
- $\delta BR(b\bar{b}) / 0.5 \text{ GeV} \rightarrow 1\%$
- $\delta BR(WW^*) / 0.5 \text{ GeV} \rightarrow 4\%$
- $\delta BR(ZZ^*) / 0.5 \text{ GeV} \rightarrow 4\%$
The Couplings roadmap

Test Higgs boson couplings depending on available L:

- Total signal yield $\mu$: tested at 20% ($\kappa$ tested at 10%)
- Couplings to Fermions and Vector Bosons 20-30%
- Loop couplings tested at 40%
- *Custodial symmetry W/Z Couplings* tested at 30%
- Test Down vs Up fermion couplings
- Test Lepton vs Quark fermion couplings
- Top Yukawa direct measurement $ttH$: $\kappa_t$
- Test second generation fermion couplings: $\kappa_{\mu}$
- Higgs self-couplings couplings $HHH$: $\kappa_H$

*results in backup slides*
High Luminosity LHC: The timeline

- **2009**: LHC startup, $\sqrt{s} = 900$ GeV
- **2010-2011**: $\sqrt{s} \approx 8$ TeV, $L = 6 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, bunch spacing 50 ns
- **2012-2013**: Go to design energy, nominal luminosity (Phase-0)
- **2014-2015**: $\sqrt{s} = 13-14$ TeV, $L \approx 1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
- **2016-2017**: Injector and LHC Phase-I upgrade to full design luminosity
- **2018-2019**: $\sqrt{s} = 14$ TeV, $L \approx 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
- **2020-2021**: HL-LHC Phase-II upgrade, IR, crab cavities
- **2022-2023**: $\sqrt{s} = 14$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, luminosity levelling
- **2030?**

- **Done**: ~20-25 fb$^{-1}$
- **Approved**: ~75-100 fb$^{-1}$
- **300 fb$^{-1}$ at 14 TeV**
- **HL-LHC: 3000 fb$^{-1}$ at 14 TeV**
High Luminosity LHC: the detectors upgrades

• Both detectors are planning **important upgrades** to stand the harsher running conditions at HL-LHC: pile-up, rates, radiation damage
  – Pile-up ~ 4-5 times more pile-up then today

• Plan: keep detector performance for **main physics objects** at the same level as we have today
  – Improved trigger system
  – New tracking systems
  – Improved forward detectors
  – ....

• **CRUCIAL** to profit of L increase
Signal $\sigma$ and Yields: HL/HE

<table>
<thead>
<tr>
<th>Process</th>
<th>$3000 \text{ fb}^{-1} 14 \text{ TeV}$</th>
<th>$300 \text{ fb}^{-1} 33 \text{ TeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggH \rightarrow \gamma\gamma$</td>
<td>350k</td>
<td>123k</td>
</tr>
<tr>
<td>$ggH \rightarrow 4\ell$</td>
<td>19k</td>
<td>6.7k</td>
</tr>
<tr>
<td>$ttH \rightarrow \gamma\gamma$</td>
<td>42k</td>
<td>30k</td>
</tr>
<tr>
<td>$ttH \rightarrow 4\ell/\mu\mu$</td>
<td>0.2k/0.4k</td>
<td>0.16k/0.3k</td>
</tr>
<tr>
<td>$ggH \rightarrow HH \rightarrow bb\gamma\gamma$</td>
<td>270</td>
<td>160</td>
</tr>
</tbody>
</table>

LHC upgrades give access to rare decays
Better signal Yields at HL-LHC
BUT Pile-up and S/B better at HE-LHC
CMS: Couplings f at HL-LHC

**Higgs Projections: 300(0) fb⁻¹**

**Goal: ultimate precision of ~5% or better**

**CMS Projection**

**Assumption** NO invisible/undetectable contribution to $\Gamma_H$:
- Scenario 1: system./Theory err. unchanged w.r.t. current analysis (also unchanged)
- Scenario 2: systematics scaled by $1/\sqrt{L}$, theory errors scaled by $\frac{1}{2}$

- $\gamma\gamma$ loop at 2-5% level
- down-type fermion couplings at 2-10% level
- direct top coupling at 7-10% level
- gg loop at 3-5% level
**ATLAS: Coupling Ratios at HL-LHC**

**ATLAS Preliminary (Simulation)**

- **Fit to coupling ratios:**
  - No assumption BSM contributions to $\Gamma_H$
  - Some theory systematics cancels in the ratios

- **Loop-induced Couplings $\gamma\gamma$ and $gg$ treated as independent parameter**
  - $\kappa_{\gamma}/\kappa_Z$ tested at 2%
  - $gg$ loop (BSM) $\kappa_t/\kappa_g$ at 7-12%
  - 2$^{nd}$ generation ferm. $\kappa_\mu/\kappa_Z$ at 8%

$\sqrt{s} = 14$ TeV: $\int Ldt = 300$ fb$^{-1}$; $\int Ldt = 3000$ fb$^{-1}$

$\int Ldt = 300$ fb$^{-1}$ extrapolated from 7+8 TeV

- $\Gamma_Z/\Gamma_g$
- $\Gamma_t/\Gamma_g$
- $\Gamma_t/\Gamma_\mu$
- $\Gamma_\mu/\Gamma_Z$
- $\Gamma_t/\Gamma_Z$
- $\Gamma_W/\Gamma_Z$
- $\Gamma_\gamma/\Gamma_Z$
- $\Gamma_g\cdot\Gamma_Z/\Gamma_H$

$\Delta(\Gamma_X/\Gamma_\gamma) \approx 2 \frac{\Delta(\kappa_X/\kappa_\gamma)}{\kappa_X/\kappa_\gamma}$

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**HL-LHC outlook**

LHC 300 fb\(^{-1}\) at 14 TeV:
- Mass: <100 MeV (statistical)
- Coupling \(\kappa\) rel. precision*
  - \(Z, W, b, \tau\) 10-15%
  - \(t, \mu\) 3-2 \(\sigma\) observation
  - \(\gamma\gamma\) and \(gg\) 5-11%

HL-LHC 3000 fb\(^{-1}\) at 14 TeV:
- Mass: << 50 MeV (statistical)
- Couplings \(\kappa\) rel. precision*
  - \(Z, W, b, \tau, t, \mu\) 2-10%
  - \(\gamma\gamma\) and \(gg\) 2-5%

*Assuming sizeable (1/2) reduction of theory errors
- “QCD scale” go to Higher order QCD computation?
- \(gg\) “PDF” from LHC data?

**Mass Measurement:**
Several exp./theory challenges to reach 50 MeV (e/\(\gamma/\mu\) calibration E-scale, Interference, FSR, ..)