Experimental Status of the Scalar Sector

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European Physical Society
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• Introduction

• 125 GeV Higgs Properties
  • Mass
  • Spin/CP
  • Width and lifetime
  • Differential cross sections
  • Higgs couplings

• Beyond the SM
  • High mass searches
  • Implications of BSM Higgs physics from couplings
  • Exotic decays

• Conclusions and Outlook
First Run 1 Higgs results with full dataset were first presented in March of 2013.

In the last two years, detectors were re-calibrated, reconstruction and analysis techniques were improved, and the data were re-analyzed.

The final Run 1 results are in general significantly better than those presented in early 2013.


Final results on Higgs spin CP and couplings from ATLAS recently submitted: arxiv:507.04548, arxiv:1506.05669
A comprehensive program to test the SM Higgs hypothesis:

- Precision mass measurements
- Measurement of couplings
  - Main production modes: \(ggH, WH, ZH, VBF, ttH\)
  - Main decay modes:
    - \(\gamma\gamma, WW, ZZ, tt, bb\)
- Rare Decay modes:
  - \(\mu\mu, Z\gamma, J/\psi \gamma\)
- Rare production modes:
  - \(tH, hh, bbH\)
- Spin and CP-mixing properties
- Width
  - Direct, off-shell couplings, interference, lifetime
- Fiducial and differential measurements
The SM does not predict the Higgs boson mass: we need to measure it. Given a mass, we can make predictions* for the production cross section and decay rates.

Higgs mass measurements (GeV):

**ATLAS:** $125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)}$

**CMS:** $125.02 \pm 0.27 \text{ (stat)} \pm 0.15 \text{ (syst)}$

**LHC combination:** $125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)}$

*Precision measurement: <0.2%*

*a lot of progress by theory community, LHCXSWG. Improvements continue…*
Impact of Higgs Mass Measurement on Electroweak Fits

Higgs Production at the LHC

SM Production Modes
(M_H = 125 GeV)

<table>
<thead>
<tr>
<th>process</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>19 pb</td>
<td>44 pb</td>
</tr>
<tr>
<td>VBF</td>
<td>1.6 pb</td>
<td>3.7 pb</td>
</tr>
<tr>
<td>VH</td>
<td>1.1 pb</td>
<td>2.2 pb</td>
</tr>
<tr>
<td>ttH</td>
<td>0.13 pb</td>
<td>0.51 pb</td>
</tr>
<tr>
<td>tH</td>
<td>~20 fb</td>
<td>~90 fb</td>
</tr>
</tbody>
</table>

ggF: gluon-gluon fusion
VBF: vector-boson fusion
VH: associated production
ttH: associated production
tH: Associated production
At $m_H = 125$ GeV, many decay channels can be studied.

### SM Decay Modes

<table>
<thead>
<tr>
<th>Process</th>
<th>Br</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb$</td>
<td>0.58</td>
</tr>
<tr>
<td>$WW$</td>
<td>0.22</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>0.06</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.027</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.0023</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>0.0016</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>0.0002</td>
</tr>
</tbody>
</table>
### Main Production and Decays

Analyses performed by either ATLAS or CMS targeting specific production and decay modes

<table>
<thead>
<tr>
<th></th>
<th>WW</th>
<th>ZZ</th>
<th>γγ</th>
<th>bb</th>
<th>ττ</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>VBF</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>WH</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>ZH</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>ttH</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
5σ Observation in all Decays to Bosons

**ATLAS**

\[H \rightarrow ZZ^* \rightarrow 4l\] \(\ell = 7\) TeV, \(L = 4.5\) fb\(^{-1}\); \(\ell = 8\) TeV, \(L = 19.7\) fb\(^{-1}\)

\[\mu = 124.5\text{ GeV} \pm 1.66\]

**CMS**

\[H \rightarrow \gamma\gamma\]

\(\ell = 7\) TeV, \(L = 4.5\) fb\(^{-1}\); \(\ell = 8\) TeV, \(L = 19.7\) fb\(^{-1}\)

\(\mu = 124.79 \pm 0.34\text{ GeV}\)

**ATLAS**

\[s = 8\text{ TeV}, 20.3\text{ fb}\(^{-1}\)

(a) \(n_l \leq 1, \ell\mu + ee/\mu\mu\)

- Obs \pm stat
- Bkg \pm syst

**Background-subtracted**

- Obs - Bkg
- Bkg \pm syst

**Higgs**

**WW**

**ZZ**

**Misid**

**VV**

**Top**

**DY**

**CMS**

\[4.9\text{ fb}\(^{-1}\) (7 TeV) + 19.4\text{ fb}\(^{-1}\) (8 TeV)

- data - backgrounds
- \(H \rightarrow WW\)
- \(\ell\mu 0/1\)-jet

\(m_H = 125\text{ GeV}\)
Significance obs. (exp.)

**CMS:**
• 3.2 (3.7) $\sigma$

**ATLAS:**
• 4.5 (3.4) $\sigma$
**NEW!** arXiv:1506.01010

**Significance obs. (exp.)**

**CMS(VH+VBF*+ttH):**
- 2.6 (2.7) $\sigma$

**Tevatron(VH)**
- 2.2 (1.4) $\sigma$

**ATLAS(VH+ttH):**
- 1.8 (2.8) $\sigma$

**my estimate from:** Phys. Rev. D 88, 052014 (2013)
Test Yukawa coupling of the top quark (large! \( \sim 1.0 \) in the SM)

Production cross section is small (<1% of ggH) but spectacular final state

Very large top background…

**Combination of signal strengths:**

**CMS:** \( \mu = 2.8 +/- 1.0 \)

**ATLAS:** \( \mu = 1.8 +/- 0.8 \)
Test Yukawa coupling of the top quark (~1.0 in the SM)

Production cross section is small (<1% of ggH) but spectacular final state

Very large top background…

Combination of signal strengths:

**CMS:** $\mu = 2.8 \pm 1.0$

**ATLAS:** $\mu = 1.8 \pm 0.8$
Searches for rare decays performed in various channels

Observation of these decays in Run 1 would signal BSM physics

Non-universal coupling of Higgs to leptons:

- $\mu\mu$ signal would be 280 times larger than SM if $\mu$ coupling was equal to that of $\tau$

<table>
<thead>
<tr>
<th>Process</th>
<th>limit (times SM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu$ (ATLAS)</td>
<td>7.0</td>
</tr>
<tr>
<td>$\mu\mu$ (CMS)</td>
<td>7.4</td>
</tr>
<tr>
<td>$Z\gamma$ (ATLAS)</td>
<td>11</td>
</tr>
<tr>
<td>$Z\gamma$ (CMS)</td>
<td>9</td>
</tr>
<tr>
<td>$\gamma\gamma^*$ (CMS)</td>
<td>7.7</td>
</tr>
<tr>
<td>$J/\psi\gamma$ (ATLAS)</td>
<td>540</td>
</tr>
<tr>
<td>$J/\psi\gamma$ (CMS)</td>
<td>540</td>
</tr>
<tr>
<td>$ee$ (CMS)</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>
Tests of spin/CP properties performed in ZZ, γγ, WW channels

ZZ: full kinematic information available for spin/CP determination
Test alternative fixed spin and parity hypotheses relative to the SM $0^+$ hypothesis

Results favour the spin $0^+$ hypothesis

Alternatives: 0-, 1-, 1+, various spin 2 models are typically excluded at $>99.9\%$ CL

Large anomalous couplings are excluded. Next step: look for presence of smaller contributions

\[ \tilde{q} = \log \frac{\mathcal{L}(J^P_{\text{SM}}, \hat{\mu}_{J^P_{\text{SM}}}, \hat{\theta}_{J^P_{\text{SM}}})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\mu}_{J^P_{\text{alt}}}, \hat{\theta}_{J^P_{\text{alt}}})} \]

Also Tevatron results:
PRL 114, 151802 (2015)
Probe potential CP-mixing and tensor structure of Higgs interactions

- Amplitude describing interaction between a spin 0 and two spin 1 particles:

\[
A(HVV) \sim \left[ a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{* (1)} f^{* (2), \mu\nu} + a_3^{VV} f_{\mu\nu}^{* (1)} \tilde{f}^{* (2), \mu\nu}
\]

- **SM**
- **BSM CP-even**
- **BSM CP-odd**

ATLAS: different formulation (see backup), but results can be compared

No significant contributions from BSM terms are observed (yet...)
SM Higgs theory predictions for kinematics: combination of $\gamma\gamma$ and ZZ

- $p_T(H)$
- $N_{\text{jets}}$
- $|y(H)|$
- $p_T(j_1)$
- Study tensor structure and strength of Higgs interactions in the context of an Effective Field Theory framework
- Use Strongly Interacting Light Higgs (SILH) formulation:

\[ \mathcal{L} = \bar{c}_y O_y + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} \\
+ \bar{c}_y \bar{O}_y + \bar{c}_g \bar{O}_g + \bar{c}_{HW} \bar{O}_{HW} + \bar{c}_{HB} \bar{O}_{HB} \]

Statistical combination of 5 \( \gamma \gamma \) input variables:
Higgs width measurements at LHC:

- **Direct** (limit at 95% CL obs. (exp.))
  - CMS ($\gamma\gamma$ +ZZ): 1.7 (2.3) GeV
  - ATLAS:
    - ZZ: 2.6 (6.2) GeV
    - $\gamma\gamma$: 5.0 (6.2) GeV
- **Via off-shell couplings:**
  - Direct measurement of Off Shell couplings (independent of width)
    - Measure width assuming SM running (or measure running assuming width)
  - Assuming* $\mu_{\text{OffShell}} = \mu_{\text{OnShell}}$
    - CMS: 22 (33) MeV (95%CL)
    - ATLAS: 23 (33) MeV (95%CL)
  - Interference in $\gamma\gamma$ (signal – continuum)
    - Expected mass shift ~50 MeV (ATL-PHYS-PUB-2013-014)
    - No assumptions but small effect
  - Lifetime (*Next slide*)

\*ATL-PHYS-PUB-2013-014
Enhancement of off-shell production possible through anomalous HVV couplings:

$$A(HVV) \propto \left[ a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{v1} + q_{v2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda_1}} \frac{(q_{v1}^2 + q_{v2}^2)}{(\Lambda_1)^2} \right] m_V^2 e_{v1}^* e_{v2}^* + a_2 f^{*1}_{\mu \nu} f_{(2),\mu \nu} + a_3 f^{*1}_{\mu \nu} f_{(2),\mu \nu}.$$ 

Width derived with/without profiling of cross section fraction:

$$f_{\Lambda Q} = \frac{m_H^4 / \Lambda_Q^4}{|a_1|^2 + m_H^4 / \Lambda_Q^4}$$
We measure event yields $n_{evt}$ and we need to extract signal yields $n_s$

Estimate and subtract backgrounds

$$n_s = n_{evt} - n_{bkg}$$

Production mode categories $c$ are contaminated by other signal processes

Global fit to all categories can take into account all contributions and correlations

We extract the signal strength $\mu$ : ratio of the observed yield to the SM prediction

$$n_{s,c,i} = \sum_p \left[ \mu^p \mu_{BR}^i \right] \times \left( \sigma^p \times Br^i \right)_{SM} \times A_{p,c,i} \times \epsilon_{p,c,i} \times Lumi$$

$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$
Obtain production signal strengths assuming SM ratios for branching ratios

**ATLAS**

- 68% CL: $\sqrt{s} = 7 \text{ TeV}, 4.5 - 4.7 \text{ fb}^{-1}$
- 95% CL: $\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

$$\mu_{ggF} = 1.23^{+0.23}_{-0.20}$$
$$\mu_{VBF} = 1.23 \pm 0.32$$
$$\mu_{VH} = 0.80 \pm 0.36$$
$$\mu_{t\bar{t}H} = 1.81 \pm 0.80$$

$m_H = 125.36 \text{ GeV}$

**CMS**

- 68% CL
- 95% CL

$$\mu_{ggH} = 0.85^{+0.19}_{-0.16}$$
$$\mu_{VBF} = 1.16^{+0.37}_{-0.34}$$
$$\mu_{VH} = 0.92^{+0.36}_{-0.36}$$
$$\mu_{t\bar{t}H} = 2.90^{+1.03}_{-0.94}$$

$19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})$
**Signal Strength for Decay Modes**

**ATLAS**

\[ m_H = 125.36 \text{ GeV} \]

<table>
<thead>
<tr>
<th>Decay</th>
<th>( \sigma(\text{stat.}) )</th>
<th>( \sigma(\text{sys inc.}) )</th>
<th>( \sigma(\text{theory}) )</th>
<th>Total uncertainty</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \gamma\gamma )</td>
<td>( 0.23 )</td>
<td>( 0.31 )</td>
<td>( 0.30 )</td>
<td>( \pm 1\sigma )</td>
<td>( 1.17 \pm 0.28 )</td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* )</td>
<td>( 0.35 )</td>
<td>( 0.30 )</td>
<td>( 0.32 )</td>
<td>( \pm 1\sigma )</td>
<td>( 1.46 \pm 0.40 )</td>
</tr>
<tr>
<td>( H \rightarrow WW^* )</td>
<td>( 0.16 )</td>
<td>( 0.17 )</td>
<td>( 0.17 )</td>
<td>( \pm 1\sigma )</td>
<td>( 1.18 \pm 0.24 )</td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>( 0.20 )</td>
<td>( 0.22 )</td>
<td>( 0.22 )</td>
<td>( \pm 1\sigma )</td>
<td>( 1.44 \pm 0.42 )</td>
</tr>
<tr>
<td>( H \rightarrow bb )</td>
<td>( 0.21 )</td>
<td>( 0.24 )</td>
<td>( 0.23 )</td>
<td>( \pm 1\sigma )</td>
<td>( 0.63 \pm 0.39 )</td>
</tr>
<tr>
<td>( H \rightarrow \mu\mu )</td>
<td>( 0.36 )</td>
<td>( 0.5 )</td>
<td>( 0.5 )</td>
<td>( \pm 1\sigma )</td>
<td>( -0.7 \pm 3.7 )</td>
</tr>
<tr>
<td>( H \rightarrow Z\gamma )</td>
<td>( 4.0 )</td>
<td>( 4.2 )</td>
<td>( 4.2 )</td>
<td>( \pm 1\sigma )</td>
<td>( 2.7 \pm 4.6 )</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>( 0.10 )</td>
<td>( 0.10 )</td>
<td>( 0.09 )</td>
<td>( \pm 1\sigma )</td>
<td>( 1.18 \pm 0.15 )</td>
</tr>
</tbody>
</table>

\( \mu = 1.00 \pm 0.14 \)

<table>
<thead>
<tr>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tagged</td>
</tr>
</tbody>
</table>

**CMS**

\[ m_H = 125 \text{ GeV} \]

\[ p_{SM} = 0.96 \]

<table>
<thead>
<tr>
<th>Decay</th>
<th>Best fit</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \gamma\gamma )</td>
<td>1.00 \pm 0.24</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow ZZ )</td>
<td>1.00 \pm 0.29</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow WW )</td>
<td>0.83 \pm 0.21</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>0.91 \pm 0.28</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow bb )</td>
<td>0.84 \pm 0.44</td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS:** individual \( \mu \) values from combination of channels

**CMS:** individual \( \mu \) values from tagged analyses
• $y_b : b$ yukawa

• $y_b : = \kappa_b \ y_b^{SM}$

• “$\kappa$ framework”: interpret signal strength parameters ($\mu_p, \mu_{BR}^i$) in terms of modifiers to the SM couplings:

  • Decay: $\Gamma_i = \kappa_i^2 \ \Gamma_i^{SM}$
  • Production: $\sigma_i = \kappa_i^2 \ \sigma_i^{SM}$
  • Width: $\Gamma_H = \Sigma_i \kappa_i^2 \ \Gamma_i^{SM}$

Assumptions (see LHCXSWG YR3):
• Only one Higgs
• SM production and decay kinematics
  • Tensor structure is that of SM
• 0+ scalar
• Narrow resonance

assuming no BSM particles in the loops

$\kappa_g^2 \propto 1.06 \times \kappa_t^2 - 0.07 \times \kappa_t \kappa_b + 0.01 \times \kappa_b^2$

$\kappa_y^2 \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$
Test gauge vs Yukawa couplings

**Assumptions:**

- Common scaling factor for fermions and gauge bosons:
  - $\kappa_F$ and $\kappa_V$
- No BSM contributions to width
- No BSM contributions to loops

**Interference in $\gamma\gamma$, tH, gg-$\to$ZH can resolve relative sign between $\kappa_F$ and $\kappa_V$

**Results compatible with SM**
“Absolute couplings”. Assumptions:

• No contributions to width from BSM particles
• No contributions to loops from BSM particles
Check coupling ratios between up-type and down-type fermions (left) and quarks and leptons (right)

- motivated by e.g. two Higgs doublet scenarios
Test for "heavy" BSM physics (BSM particles $> m_H/2$) with possible contributions to ggH, Hγγ (and HZγ) loops

- Assume no contributions to width from BSM particles (discussed later)
- Assume SM couplings for known particles

\[
\frac{(\sigma \cdot BR) (gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}
\]
• No assumptions on particle content in loops
• No assumptions on BSM decay or Higgs width

• Drawback: can only fit ratios

$19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})$

**CMS**

$k_{gZ} = 0.98^{+0.14}_{-0.13}$

$\lambda_{WZ} = 0.87^{+0.15}_{-0.13}$

$\lambda_{Zg} = 1.39^{+0.38}_{-0.28}$

$\lambda_{bZ} = 0.59^{+0.22}_{-0.23}$

$\lambda_{Z\gamma} = 0.93^{+0.17}_{-0.14}$

$\lambda_{\tau Z} = 0.79^{+0.19}_{-0.17}$

$\lambda_{\gamma g} = 2.18^{+0.54}_{-0.46}$

**ATLAS**

$\sqrt{s} = 7 \text{ TeV}, 4.5 - 4.7 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

$k_{gZ} = 1.18 \pm 0.16$

$\lambda_{Zg} = 1.09^{+0.26}_{-0.22}$

$\lambda_{WZ} \in [-1.04, -0.81] \cup [0.80, 1.06]$ \n
$\lambda_{\gamma g} \in [-1.70, -1.07] \cup [1.03, 1.73]$ \n
$\lambda_{bZ} = 0.60 \pm 0.27$

$\lambda_{\tau Z} = 0.95^{+0.23}_{-0.19}$

$(95\% CL) \lambda_{\mu Z} < 2.3$

$\lambda_{\gamma Z} = 0.90 \pm 0.15$

$(95\% CL) \lambda_{(\gamma \gamma)Z} < 3.2$

$m_{\gamma} = 125.36 \text{ GeV}$
Does the Higgs sector extend beyond the single doublet of the SM?

Different strategies:

1. Search for another Higgs boson

2. Search for exotic decays of the 125 GeV Higgs

3. Use the 125 GeV Higgs as a tool to find new physics
   - Tag a Higgs in decay chains
   - Use SM Higgs measurements to constrain BSM scenarios (observed Higgs constrains BSM parameter space)
A non-exhaustive list... Many of the searches below were performed in Run 1

### BSM Higgs Searches

#### Neutral Heavy Higgs to Fermions
- $H/A \rightarrow (b)\pi\pi (LL,LH,HH)$
- $H/A \rightarrow (b)\mu\mu$
- $H/A \rightarrow (b)bb$
- $H/A \rightarrow tt$

#### Neutral Heavy Higgs to Bosons
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow ZZ \rightarrow ll\nu\nu$
- $H \rightarrow ZZ \rightarrow llqq$
- $H \rightarrow ZZ \rightarrow \nu\nuqq$
- $H \rightarrow WW \rightarrow ll\nu\nu$
- $H \rightarrow WW \rightarrow llqq$

#### Neutral Heavy Higgs to Bosons, including light Higgs
- $(H)h \rightarrow \gamma\gamma bb$
- $(H)h \rightarrow 4b$
- $(H)h \rightarrow bb\pi\pi$
- $(H)h \rightarrow VV\gamma\gamma \rightarrow 4j\gamma\gamma$
- $(H)h \rightarrow WW\gamma\gamma \rightarrow llqq\gamma\gamma$
- $A \rightarrow Zh \rightarrow ll\pi\pi (LL,LH,HH)$
- $A \rightarrow Zh \rightarrow (ll\nu\nu)bb$

#### Heavy and light Charged Higgs
- $H \rightarrow \tau\nu+jets$
- $H \rightarrow tb$ (resolved)
- $H \rightarrow tb$ s-chan (had, L+j)
- $H \rightarrow \tau\nu+leps(s)$
- $H \rightarrow \mu\nu$
- $H \rightarrow cs$
- $H \rightarrow cb$
- $AW$
- $H \rightarrow Wh (WH, WA)$
- $H \rightarrow W\gamma$
- $H \rightarrow tb$ (boosted)
- $H \rightarrow WZ \rightarrow tb$ ($l\nuqq$, $qlq\nu$)

#### Exotics decays with MET, Dark-sector Inspired
- mono $H (\rightarrow \gamma\nu+MET)$
- mono $H (\rightarrow bb+MET)$
- mono $H (\rightarrow 4l+MET)$
- $H \rightarrow \gamma\gamma$ dark
- $ZH \rightarrow (ll)INV$
- $VBF H \rightarrow INV$
- $VH \rightarrow (jj)INV$
- $ttH \rightarrow INV$ (various)
- ggF $H \rightarrow INV$ (monojet).

#### LFV / FCNC / rare decays
- $H \rightarrow \tau\mu, \tau e$
- $H \rightarrow e\mu$
- $H \rightarrow J/\psi\gamma, \gamma\gamma$
- $H \rightarrow ZJ/\psi, Z\gamma$
- $H \rightarrow \phi\gamma$
- $t \rightarrow cH$ (various)

#### Exotics decays with no MET, Dark-sector / NMSSM Inspired
- $H \rightarrow Z_{dark}Z_{dark} \rightarrow 4l$
- $h \rightarrow 2a \rightarrow \mu\mu\mu$
- $h \rightarrow Za \rightarrow ll\mu\mu$
- $a \rightarrow \mu\mu$
- $h \rightarrow 2a \rightarrow 4\gamma$ (multiphoton)
- $h \rightarrow 2a \rightarrow bb\mu\mu$
- $h \rightarrow 2a \rightarrow bb\pi\pi$
- $(bb)a \rightarrow (bb)\tau\tau \rightarrow (bb)\mu\mu$
- $h \rightarrow 2a \rightarrow 4\tau$
- $H \rightarrow aW$
Run 1 Executive Summary: No significant excess yet...
A non-exhaustive list… Many of the searches below were performed in Run 1

**Run 1 Executive Summary:**
No significant excess yet…

Highlight a few recent results
Search for a SM-like Higgs boson decaying to WW or ZZ final states:

- WW-$\rightarrow$\(l\nu l\nu\)
- WW-$\rightarrow$\(l\nu jj\)
- ZZ-$\rightarrow$\(llll\)
- ZZ-$\rightarrow$\(ll\tau\tau\)
- ZZ-$\rightarrow$\(ll\nu\nu\)
- ZZ-$\rightarrow$\(llqq\)

- Search for electroweak singlet

  - \(C'^2 + C^2 = 1\)
  - \(C\): SM coupling
  - \(B_{\text{new}}\): BR to non-SM
High mass searches in WW and ZZ final states

- WW→lνlν
- WW→lνjj
- ZZ→llll
- ZZ→llνν
- ZZ→llqq

- Limits given for narrow width signal

- No significant deviations observed
Search for pseudoscalar (A) boson decaying to $\tau$ leptons

- Sensitive in high $\tan(\beta)$ regime

Searches performed at high and low mass

Results interpreted in the context of SUSY scenarios. Limits given on $\sigma \times \text{BR}$. 

**ATLAS** $\sqrt{s}=8 \text{ TeV}, \int L \text{ dt}=19.5 - 20.3 \text{ fb}^{-1}$

MSSM $m_h^{\text{mod+}}$ scenario, $M_{\text{SUSY}} = 1 \text{ TeV}, h/\tilde{H}A \rightarrow \tau\tau$

**CMS** Preliminary, $h, H, A \rightarrow \tau\tau$, $19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 4.9 \text{ fb}^{-1} (7 \text{ TeV})$

$\text{CL}_{0}(\text{MSSM,SM})<0.05$:

- **$m_h^{\text{mod+}}$**
- MSSM $m_h^{\text{mod}}$ scenario
- $m_h^{\text{MSSM}} \neq 125\pm 3 \text{ GeV}$
If $M_{\text{SUSY}} > 1\text{TeV}$, low values of $\tan(\beta)$ can accommodate $m_H = 125\text{ GeV}$

Decays $A \rightarrow ZH$, $H \rightarrow hh$ can have sizable branching ratios if $m_A, m_H < 2m_{\text{top}}$

Look at $AZ \rightarrow (ee, \mu\mu, \tau\tau)$ final states

ATLAS results with $H \rightarrow bb$ and $\tau\tau$ and CMS with $bb$
Combination of two analyses (llττ, ττbb) performed in the context of two BSM scenarios:

• MSSM low tan(b) -> $M_{\text{SUSY}}$ consistent with $m_h=125$ GeV
• 2HDM (Type II). Assume $m_H=m_A=m_{H^+}$
Measurements of the discovered Higgs boson can constrain parameters in various BSM scenarios (asymmetry)

- Right: 2HDM (type I and II)
- Below: simplified SUSY model hMSSM
Invisible Decays: Direct Searches

SM BR to invisible: 0.1% ($ZZ\rightarrow4\nu$)

Weak vector boson fusion is the most sensitive production mode

\[ \overline{q} \rightarrow W/Z H \rightarrow \overline{q}' q'' \]

• Require $E_T^{miss}$ and VBF signature:
  • Large separation between jets in $\eta$
  • Large $m_{jj}$

• Main backgrounds:
  • $Z(\nu\nu)$+jets, $W(\nu\nu)$+jets

• Results (95% CL) on BR:
  • ATLAS: 28% (31% exp.)
  • CMS: 58% (40% exp.)

• ATLAS combination with $Z(\nu\nu)H$ and $V(jj)H$:
  $BR(\text{inv}) < 25\%$ (27\% exp.) at 95\% CL
Search for LFV violating Higgs decays to $\tau\mu$ in hadronic $\tau$ decays (CMS and ATLAS) and leptonic $\tau$ decays (CMS)

- Some excess is observed: to be followed-up in Run 2

**CMS**

| $\mu \tau_e$ | $0.87^{+0.66}_{-0.62}$ | $0.81^{+0.85}_{-0.78}$ | $0.05^{+1.58}_{-0.97}$ |
| $\mu \tau_h$ | $0.41^{+1.20}_{-1.22}$ | $0.21^{+1.03}_{-1.09}$ | $1.48^{+1.16}_{-0.93}$ |
| $\mu \tau$ | | | $0.84^{+0.39}_{-0.37}$ |

**ATLAS**

- Best fit BR: $0.77 \pm 0.62 \%$
- Limit: $1.85 \%$ @ 95% CL (1.24% Exp.)
Conclusions

• A lot of progress made since the discovery 3 years ago
  • The measurements of the production and decay properties of the Higgs boson are consistent with SM predictions
    • The SM $0^+$ hypothesis is preferred over all other tested spin/parity alternatives (almost all excluded at > 95% CL)
    • Coupling strengths consistent with SM
  • No evidence of BSM physics in the scalar sector (yet…)

• Realization of Run 1 Higgs physics program made possible thanks to outstanding performance of the LHC

• We have a very exciting and challenging Higgs physics program for Run II
Backup Slides
Search for the production of invisible particles in association with a Higgs boson in $H \rightarrow \gamma \gamma$ channel

- Require:
  - $p_T(\gamma \gamma) > 70$ GeV
  - $E_T(\text{Miss}) > 90$ GeV

- Main SM background:
  - $ZH \rightarrow \nu \nu \gamma \gamma$ (irreducible)
  - $WH \rightarrow l \nu \gamma \gamma$ (lost lepton)

- Results interpreted in context of suppression scale $\Lambda$ for given EFT operators.

Example:
In some SUSY scenarios, the gravitino is the Dark Matter candidate, with final states with ETMiss + photon(s)

Selections target ggH and ZH channels

- **Backgrounds ggH:**
  - $Z(\nu\nu)+\gamma$
  - Mono-e
  - Mono jet
  - G+jet

- **Backgrounds ZH:**
  - $Z\gamma$
  - $Z+$jets
  - $ZW, ZZ$
  - Non-resonant dilepton

See also: ATLAS-CONF-2015-001
**Status of Rare SM Decays: $\mu\mu$**

**$\mu^+\mu^-$ analysis:**
- 2 analysis channels (ggF and VBF)
- Analytic background model (similar to $\gamma\gamma$)

**Results at 95% CL:**
$$\sigma.\text{Br} < 7.0 \ (7.2)(\sigma.\text{Br})_{\text{SM}}$$

Universal couplings (same as $\tau$ lepton) would imply signal $\sim$280 times SM

---

**Results at 95% CL:**
$$\sigma.\text{Br} < 7.4 \ (6.5)(\sigma.\text{Br})_{\text{SM}}$$
**Status of Rare SM Decays: Zγ**

### Zγ analysis strategy
- Detector and p_T categories
- Analytic background model (similarly to γγ)

**Results at 95% CL:**
\[ \sigma \cdot Br < 9 \ (9)(\sigma \cdot Br)_{SM} \]

---

**ATLAS**

**Results, 95% CL:**
\[ \sigma \cdot Br < 11 \ (9)(\sigma \cdot Br)_{SM} \]
Probe potential CP-mixing and tensor structure of Higgs interactions

- Amplitude describing interaction between a spin 0 and two spin 1 particles:

\[ A(HVV) \sim \left[ a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \sigma_1^{*} \sigma_2^{*} + a_2^{VV} f_{\mu \nu}^{*(1)} f_{\mu \nu}^{*(2)} + a_3^{VV} f_{\mu \nu}^{*(1)} f_{\mu \nu}^{*(2)} \]

\[ f_{\Lambda_1} = \frac{\sigma_{\Lambda_1}/(\Lambda_1^4)}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \sigma_{\Lambda_1}/(\Lambda_1^4) + \ldots}, \quad \phi_{\Lambda_1} \]

\[ f_{a_2} = \frac{|a_2|^2 \sigma_2}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \sigma_{\Lambda_1}/(\Lambda_1^4) + \ldots}, \quad \phi_{a_2} = \arg \left( \frac{a_2}{a_1} \right) \]

\[ f_{a_3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \sigma_{\Lambda_1}/(\Lambda_1^4) + \ldots}, \quad \phi_{a_3} = \arg \left( \frac{a_3}{a_1} \right) \]

- \[ \sigma_i : x_5 \text{ for } a_i = 1 \]

- \[ \Lambda_1 = 1 \text{ TeV} \]

- Phys Rev D. 89.035007

- 9.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
Lagrangian describing interaction between a spin 0 and a pair of W or Z bosons (from JHEP 1311 (2013) 043):

\[
\mathcal{L}_0^V = \left\{ c_\alpha \kappa_{\text{SM}} \left[ \frac{1}{2} g_{\text{HZZZ}} Z_\mu Z^\mu + g_{\text{HWWW}} W^+ W^- \right] \right. \\
- \frac{1}{4} \Lambda \left[ c_\alpha \kappa_{\text{HZZZ}} Z_{\mu \nu} Z^{\mu \nu} + s_\alpha \kappa_{\text{AZZZ}} Z_{\mu \nu} \tilde{Z}^{\mu \nu} \right] \\
- \frac{1}{2} \Lambda \left[ c_\alpha \kappa_{\text{HWWW}} W^+ W^- W^{\mu \nu} + s_\alpha \kappa_{\text{AWWW}} W^{\mu \nu} \tilde{W}^{\mu \nu} \right] \right\} X_0.
\]

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>Model</th>
<th>Choice of tensor couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^+$</td>
<td>Standard Model Higgs boson</td>
<td>$\kappa_{\text{SM}}$ 1, $\kappa_{\text{HVV}}$ 0, $\kappa_{\text{AVV}}$ 0, $\alpha$ 0</td>
</tr>
<tr>
<td>0$^-$</td>
<td>BSM spin-0 CP-even</td>
<td>$\kappa_{\text{SM}}$ 0, $\kappa_{\text{HVV}}$ 1, $\kappa_{\text{AVV}}$ 0, $\alpha$ 0</td>
</tr>
<tr>
<td>0$^-$</td>
<td>BSM spin-0 CP-odd</td>
<td>$\kappa_{\text{SM}}$ 0, $\kappa_{\text{HVV}}$ 0, $\kappa_{\text{AVV}}$ 1, $\alpha = \pi/2$</td>
</tr>
</tbody>
</table>

CMS/ATLAS comparison (Michael Duehrssen)

No significant contributions from BSM terms are observed
Calculate production ratios for each final state:

- Branching ratios cancel:

\[
\frac{\mu_{VBF+VH}^i}{\mu_{ggF+ttH}^i} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}
\]

CMS Result: \(1.25^{+0.62}_{-0.44}\)

ATLAS Result: \(0.96^{+0.43}_{-0.31}\)

CMS VBF significance: \(3.7\sigma\) (3.3\(\sigma\) expected) (assuming SM BRs)

ATLAS VBF significance: \(4.3\sigma\) (3.8\(\sigma\) expected)
Allow for contributions from BSM particles with mass < $m_H/2$

- Relax assumption on the width
- Right plots: include direct limits

**ATLAS Preliminary**

$\sqrt{s} = 7$ TeV, 4.5 - 4.7 fb$^{-1}$  $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

- $68\%$ CL: 
- $95\%$ CL: 

$\kappa_y = 1.00 \pm 0.12$

$\kappa_g = 1.12^{+0.14}_{-0.11}$

(95%CL) $\kappa_{Zy} < 3.3$

(95%CL) $BR_{t,u} < 0.27$

$\frac{BR_{t}}{BR_{H}} = 1.03^{+0.13}_{-0.03}$

$m_H = 125.36$ GeV

**CMS**

$\kappa_t=1$, $\kappa_g=1$, $BR_{inv}$

- Observed
- Exp. for SM H
Ongoing studies of Higgs physics potential at high luminosity

$Y_i$ vs. $m_i$ (GeV)

$H \rightarrow \gamma \gamma$ (comb.)
$H \rightarrow ZZ$ (comb.)
$H \rightarrow WW$ (comb.)
$H \rightarrow Z\gamma$ (incl.)
$H \rightarrow b\bar{b}$ (comb.)
$H \rightarrow \tau\tau$ (VBF-like)
$H \rightarrow \mu\mu$ (comb.)

$\Delta \mu/\mu$

$\int L dt = 300\ fb^{-1}$
$\int L dt = 3000\ fb^{-1}$

Run 3 and Beyond