Run-I Higgs results and prospects for Run-II (HL-LHC)

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Rencontres de Moriond
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The Higgs sector today

• Higgs boson discovery already “old news”

• Main focus measuring Higgs boson properties:
  - (On/off-shell/invisible) couplings
  - Mass, Spin/CP state

• Or look for rare decays or coupling to exotic particles (discussed by Paolo Meridiani later today)

• Finalized most of Run-I Higgs analyses!
  - Reduced experimental/theory systematic uncertainties
  - Increased sensitivity, especially to sub-leading production modes
  - Interpret possible deviations from SM within more general theory frameworks (e.g. Effective field theory)
What do we look for…

<table>
<thead>
<tr>
<th>Coupling analysis</th>
<th>Coupling analysis</th>
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<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
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<tr>
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<tr>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- mass measurement
- measurement of spin/CP
- off-shell coupling analysis
- search for invisible decays

Discussing by Stephanie Majewski in “top quark” session on Wednesday.
H to $\gamma\gamma$

- **Diphoton selection**
  - $t\bar{t}H$ leptonic
  - $t\bar{t}H$ hadronic
- **$VH$ dilepton** ($ZH \to t\bar{t}H$)
- **$VH$ one-lepton** ($WH \to t\bar{v}H$)
- **$VH E_T^{miss}$** ($ZH \to \nu\nu H; WH \to f\nu H$)
- **$VH$ hadronic** ($WH \to jjH; ZH \to jjH$)
- **VBF tight** ($qqV \to jjH$)
- **VBF loose** ($qqV \to jjH$)
- **Untagged** ($gg \to H$)

**ttH**

**VH**

**VBF**

**ggF**

**Theory uncertainties:**
- QCD scale (ggF: ±7%)
- PDF (ggF: ±7%)
- BR(H to $\gamma\gamma$) (±5%)
- Leading uncertainty despite NNLO+NNLL QCD computation

**Energy resolution:**
- Determined in Z to $ee + MC$ extrapolation

$\mu = 1.17 \pm 0.27$

<table>
<thead>
<tr>
<th>Uncertainty group</th>
<th>$\sigma_{\mu,y}^{\text{syst.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (yield)</td>
<td>0.09</td>
</tr>
<tr>
<td>Experimental (yield)</td>
<td>0.02</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.03</td>
</tr>
<tr>
<td>MC statistics</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Theory (migrations)</td>
<td>0.03</td>
</tr>
<tr>
<td>Experimental (migrations)</td>
<td>0.02</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.07</td>
</tr>
<tr>
<td>Mass scale</td>
<td>0.02</td>
</tr>
<tr>
<td>Background shape</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Schematic view of the event categorization is shown in Fig. 2. Events are assigned to this category if there is an extra lepton (candidate selected by the criteria described above is assigned to one of four categories (VBF enriched category is defined by events with two high-separated jets and the BDT discriminant is exploited in the fit. With respect to the 1D approach, there is an expected reduction of 6.0% for the muon momentum scale). The uncertainties on the lepton reconstruction and identification efficiencies are given in Table 9. Uncertainties on the theoretical predictions Higgs boson mass due to the uncertainties on the lepton reconstruction and identification efficiencies are 4.4% (8%). The uncertainties on the signal yield is presented in Table 10, expressed as the fractional uncertainties on the yields. The uncertainties on the theoretical predictions Higgs boson mass due to the uncertainties on the PDFs are 0.01, where half of this is expected to be from a true VBF signal, about 35% from ggF production and the remaining from backgrounds (violet histogram); the systematic uncertainty associated to the total background is 6.2%. A brief overview of the systematic uncertainties that a reach of 9.0% for the Higgs boson mass is presented in Table 9. The impact is presented for the individual final states and for the combined measurement.

### Systematic uncertainties in the inclusive signal strength measurement

The e + e−, W → lνH, Z → llH, W → jjH and Z → jjH signals are vetoed (red histogram). The background contribution is evaluated assuming the ATLAS combined mass measurement. The distribution for a simulated signal sample with mH = 125 GeV is shown in Fig. 13. The systematic uncertainty for both the signal and the background, and the observed number of events agrees well with the expectation as can be seen in Fig. 14.

### Coupling studies

The theory-related systematic uncertainty for both the signal and the background, and the observed number of events agrees well with the expectation as can be seen in Fig. 14.

### High mass two jets

- VBF enriched $P(m_{4\ell}, BDT_{VBF})$
- VH enriched $P(m_{4\ell})$
- ggF enriched $P(m_{4\ell}, O_{BDT_{Z\gamma*}}, m_H)$

- Theory uncertainty again dominant systematics
- Even higher for VBF (~20%), similar for VH (~10%)
- Jet energy scale systematics important for VBF and VH categories (~10%)
Mass measurement

Optimized categorization

<table>
<thead>
<tr>
<th>Category</th>
<th>$\sigma_{\text{eff}}$ [GeV]</th>
<th>$s/\sqrt{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>1.67</td>
<td>3.50</td>
</tr>
<tr>
<td>Unconv. central low $p_{T}$</td>
<td>1.35</td>
<td>1.88</td>
</tr>
<tr>
<td>Unconv. central high $p_{T}$</td>
<td>1.21</td>
<td>1.26</td>
</tr>
<tr>
<td>Unconv. rest low $p_{T}$</td>
<td>1.53</td>
<td>1.69</td>
</tr>
<tr>
<td>Unconv. rest high $p_{T}$</td>
<td>1.36</td>
<td>0.96</td>
</tr>
<tr>
<td>Unconv. transition</td>
<td>1.86</td>
<td>0.78</td>
</tr>
<tr>
<td>Conv. central low $p_{T}$</td>
<td>1.52</td>
<td>1.38</td>
</tr>
<tr>
<td>Conv. central high $p_{T}$</td>
<td>1.35</td>
<td>0.88</td>
</tr>
<tr>
<td>Conv. rest low $p_{T}$</td>
<td>1.88</td>
<td>1.56</td>
</tr>
<tr>
<td>Conv. rest high $p_{T}$</td>
<td>1.64</td>
<td>0.89</td>
</tr>
<tr>
<td>Conv. transition</td>
<td>2.41</td>
<td>0.85</td>
</tr>
</tbody>
</table>

$m_H = 125.98 \pm 0.42\text{(stat)} \pm 0.28\text{(syst)} \text{ GeV}$

Combined mass:

- Similarly to coupling analysis, fit 2-dim PDF:
  \[ P_{\text{bkg}}(m_{4\ell}, O_{\text{BDT}_{ZZ^*}}) \]

- $Z$ mass constraint improves resolution by 15%

$m_H = 124.51 \pm 0.52 \text{ (stat)} \pm 0.06 \text{ (syst)} \text{ GeV}$

Electron energy scale $\sigma$: 0.03 $\div$ 0.2% (40 GeV)

Muon momentum scale $\sigma$: 0.04% $\div$ 0.2%
H to WW (ggF/VBF)

- Categories in **n. jets**, Diff.Flav/SameFlav leptons, VFB/ggF enriched, \(p_T\) of the sub-leading lepton and \(m(ll)\).

- Fit to \(m_T\) (BDT) discriminant for ggF (VBF) mode

- One normalization factor per control region (CR)
  - Avoids risk of “overprofiling”.

**e.g. WW CR**

Revert \(m(ll)\) cut

In \(n_j=0\), choose [55,110] GeV

Minimize theory extrapolation!
Results

\[ \mu_{ggF} = 1.02 \pm 0.19 = 1.02 \pm 0.29 \]

\[ \mu_{VBF} = 1.27 \pm 0.44 = 1.27 \pm 0.53 \]

\[ \text{(stat.)} \quad \text{(syst.)} \]

**Combined:**

\[ \mu = 1.09 \pm 0.23 \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
<th>Plot of error (scaled by 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data statistics</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Theoretical systematics</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>Signal ( H \rightarrow WW^* ) ( B )</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Signal ggF cross section</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>Signal ggF acceptance</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Background WW</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Experimental systematics</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>0.23</td>
<td>0.21</td>
</tr>
</tbody>
</table>

**Signal cross-section**

dominant systematics, but **signal acceptance** (esp. VBF) and **WW background** extrapolation also important

**3σ evidence for VBF production**

(2.1 expected)

- **Leading experimental uncertainties** lepton efficiency and misid. rate (and jet energy scale for VBF)
VH to WW (multi-lepton)

4 leptons

3 leptons

2 OS leptons

2 SS leptons

SS = same sign, OS = opposite sign

- Categories depending on number of leptons and jets
  - Sub-categories depending on number of same flavor opposite sign leptons
  - VV, VVV (V=W,Z,γ) are the main backgrounds, in add. top and Z/W +jets in the 2 lepton channels

- Results:
  
  \[
  \mu_{WW}^{\text{WH}} = 2.1^{+1.5}_{-1.3} \ (\text{stat.})^{+1.6}_{-0.9} \ (\text{sys.}), \quad \mu_{ZH}^{\text{WH}} = 4.9^{+3.7}_{-2.7} \ (\text{stat.})^{+1.7}_{-1.0} \ (\text{sys.})
  \]
  
  \[
  \mu_{HH}^{\text{WW}} = 2.9^{+1.2}_{-1.1} \ (\text{stat.})^{+0.8}_{-0.6} \ (\text{sys.})
  \]

- Combined with the ggF and VBF channels, helps constraining the fermionic coupling.
H to $\tau\tau$

- Direct probe of **fermionic couplings** (as H to bb)
- **Three** channels, **two** main categories:
  - VBF, **Boosted** ($\sim$ggF with $pT(H)>100$ GeV)
- **BDT** with main discriminant: $m(\tau\tau)$ mass

- **4.5$\sigma$** evidence for tau Yukawa coupling! (3.4$\sigma$ expected)

**Source of Uncertainty** | **Uncertainty on $\mu$**
--- | ---
Signal region statistics (data) | $+0.27$ $-0.26$
Jet energy scale | $\pm 0.13$
Tau energy scale | $\pm 0.07$
Tau identification | $\pm 0.06$
Background normalisation | $\pm 0.12$
Background estimate stat. | $\pm 0.10$
BR ($H \to \tau\tau$) | $\pm 0.08$
Parton shower/Underlying event | $\pm 0.04$
PDF | $\pm 0.03$
Total sys. | $+0.33$ $-0.26$
Total | $+0.43$ $-0.37$

**Combined**

**Jet energy scale:** especially forward/central eta inter-calibration

**Background normalization** (esp. Z to $\tau\tau$ and top)

[arXiv:1501.04943]
**VH to Vbb**

- **BR(H to bb) ~60%**: leading contribution to Higgs width

**Categorization**
- **Two** pT(W/Z) regions (<120, >120 GeV)
- **Four** b-tag regions (1-tag + 3 x 2-tag)
- **Two** jet bins (2 and 3 jets)
- Use b-tagging discriminant (MV1c)

**Fit variables:**
- **1-tag**: MV1c
- **2-tag**: BDT (esp. mass(bb), pT(V), MV1c)

- **1.4σ excess (2.5σ exp.), excluded 1.2xSM**

**Jet energy scale and b-tagging**

**Theory modeling of backgrounds dominant (esp. W+bb, W+bl)**
Off-shell coupling analysis

- Measure the Higgs boson signal strength for $m(ZZ/WW) \gg 2 m_{Z/W}$
- Can look for coupling deviation from SM at high energies $\hat{s}$!

**Three channels** considered:

**ZZ → 4ℓ**

![ZZ → 4ℓ](image)

220 GeV < $m_{4\ell}$ < 1000 GeV

**ZZ → 2ℓ 2ν**

![ZZ → 2ℓ 2ν](image)

380 GeV < $m_{ZZ}^{ZZ}$ < 1000 GeV

**WW → eνμν**

![WW → eνμν](image)

$R_8 = \sqrt{m_{\ell\ell}^2 + \left(0.8 m_{WW}^{WW}\right)^2} > 450$ GeV

- $p_T(VV)$ distribution for signal only known to $\sim$LO
- Reduce $p_T(VV)$ dependence: ME method (no BDT), no jet binning, $R_8$ variable
Results

Off-shell signal strength ($\mu_{\text{off-shell}}$)

1. Assume SM ratio of $gg$ to $H^*$ w.r.t. VBF signal strength ($\mu_{\text{off-shell}}^{gg \rightarrow H^*} / \mu_{\text{off-shell}}^{VBF} = 1$), measure common $\mu_{\text{off-shell}}$

2. Assume SM off-shell VBF cross section, measure $\mu_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow VV}$

<table>
<thead>
<tr>
<th>$R_{H^*}^B$</th>
<th>Observed</th>
<th>Median expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$\mu_{\text{off-shell}}$</td>
<td>5.1</td>
<td>6.2</td>
</tr>
<tr>
<td>$\mu_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow VV}$</td>
<td>3.3</td>
<td>6.7</td>
</tr>
</tbody>
</table>

95% CL upper limits

Combine with on-shell analysis

$\mu_{\text{off-shell}}(\hat{s}) \equiv \kappa_{g,\text{off-shell}}(\hat{s}) \cdot \kappa_{V,\text{off-shell}}^2(\hat{s})$

$\mu_{\text{on-shell}} = \frac{\kappa_{g,\text{on-shell}} \cdot \kappa_{V,\text{on-shell}}^2}{\Gamma_H / \Gamma_{H}^{\text{SM}}}$

3. Assume $\kappa_{g,\text{on-shell}} \cdot \kappa_{V,\text{on-shell}} \leq \kappa_{g,\text{off-shell}} \cdot \kappa_{V,\text{off-shell}}$ and determine upper limit on $\Gamma_H / \Gamma_{H}^{\text{SM}}$

4. Assume $\kappa_V = \kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}$. Determine $R_{gg} = \kappa_{g,\text{off-shell}}^2 / \kappa_{g,\text{on-shell}}^2$.

- Measure as a function of unknown K-factor ratio $R_{H^*}^B = \frac{K(gg \rightarrow VV)}{K(gg \rightarrow H^* \rightarrow VV)}$
- Systematics worsens limits by 30%
- Interference term, scale variations on signal K factor, PDF/scale variations of $qq$ to $VV$

$R_{H^*}^B = 1$

$\Gamma_H / \Gamma_{H}^{\text{SM}} < 5.5$ (8.0 exp)

$R_{gg} = \kappa_{g,\text{off-shell}}^2 / \kappa_{g,\text{on-shell}}^2 < 6.0$ (9.0 exp)
Higgs to invisible

VBF

- 2 jets from VBF signature + high missing $E_T$ (>150 GeV)

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield ± Stat ± Syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH Signal</td>
<td>20 ± 5.5 ± 9.7</td>
</tr>
<tr>
<td>VBF Signal</td>
<td>286 ± 5 ± 49</td>
</tr>
<tr>
<td>$Z \rightarrow \nu\nu$+jets</td>
<td>339 ± 22 ± 13</td>
</tr>
<tr>
<td>$W \rightarrow \ell\nu$+jets</td>
<td>237 ± 17 ± 18</td>
</tr>
<tr>
<td>Multijet</td>
<td>1.9 ± 2.4</td>
</tr>
<tr>
<td>Other Backgrounds</td>
<td>0.4 ± 0.2 ± 0.3</td>
</tr>
<tr>
<td>Total Background</td>
<td>578 ± 38 ± 30</td>
</tr>
<tr>
<td>Data</td>
<td>539</td>
</tr>
</tbody>
</table>

- Dedicated $Z\rightarrow ll$ and $W\rightarrow l\nu$ control regions (CRs), emulating missing $E_T$

- Simultaneous fit to yields in signal and $Z$+jets and $W$+jets control regions.

$\text{BR}(H \rightarrow \text{invisible}) < 29\% @ 95\text{ CL (35\% exp)}$

VH

- Two signatures:
  - $ZH$ to $\ell\ell + \text{invisible}$
    - $\text{BR}(H \rightarrow \text{invisible}) < 75\% @ 95\text{ CL (62\% exp)}$
  - $W/ZH$ to $jj + \text{invisible}$
    - Includes ggF contamination
    - $\text{BR}(H \rightarrow \text{invisible}) < 78\% @ 95\text{ CL (86\% exp)}$

- Alternatively, set limits on $\sigma \times \text{BR}$:

$\text{BR}(H \rightarrow \text{invisible}) < 29\% @ 95\text{ CL (35\% exp)}$
Spin/CP: testing spin-2 EFT

Graviton-like

\[ L_2^p = \sum_{p=V,f} -\frac{1}{\Lambda^2} \kappa_p T^p_{\mu\nu} X^\mu\nu \]

Energy momentum tensor

Particle field

Variable couplings (\(\kappa_g, \kappa_q\))

cutoff at \(p(T(H))=125/300 \text{ GeV}\)

- Strongest exclusions of alternative spin-2 hypotheses (CLs\(~0.01-1\%\)) from H to 4\(\ell\)

- **PDF**(my\(\gamma\gamma, \text{pT}_{\gamma\gamma}, \cos(\theta^*)\))

\[ |\cos(\theta^*)| = \frac{|\sinh(\Delta\eta_{\gamma\gamma})| \sqrt{2p_Y^1p_Y^2}}{\sqrt{1 + (p_Y^1/m_{\gamma\gamma})^2}} \]

\[ \Delta \phi_{\ell\ell} \text{ [rad]} \]

H to ZZ\(^*\) to 4\(\ell\)

H to WW to \(\ell\nu\ell\nu\)

WW+0 jet

ATLAS Internal

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

H → WW\(^*\) → \(\ell\nu\ell\nu + 1\) jet

\(J^f = 0^0\)

\(J^f = 2^0, k_g = k_q\)

\(J^f = 2^0, k_g = 0.5, k_q = 1\)

\(J^f = 2^0, k_g = 1, k_q = 0\)

\(J^f = 2^0, k_g = 0.1, k_q = 0\)

2 bins

10 bins

PDF(MELA, BDT\(_{ZZ}\))

PDF(BDT\(_0\), BDT\(_2\))

SM vs bkg

Spin2 vs bkg

H to \(\gamma\gamma\)

Combination → see Michael's talk

WW+1 jet

WW+1 jet sensitive to \(p(T(H))\)
Spin/CP: parity / CP mixing

Spin-0 with CP mixing

\[ \mathcal{L}_0 = \begin{cases} c_0 \kappa_{\text{SM}} \left[ \frac{1}{2} g_{\text{HZZ}} Z_\mu Z^\mu + g_{\text{HWW}} W_+ W^- \right] \\ - \frac{1}{2} \lambda \left[ c_0 \kappa_{\text{HZZ}} Z_\mu Z^\mu + S_\alpha \kappa_{A\mu} Z_\mu Z^- \right] \end{cases} \]

H to WW to \( e^+ e^- \)

Combination → see Michael’s talk

H to ZZ* to 4\( \ell \)

- Define new observables:
  \[ O_1(\kappa_{\text{HVV}}) \sim \frac{2R(\text{ME}(\kappa_{\text{HVV}}) , \text{ME}(\text{SM}))}{|\text{ME}(\kappa_{\text{HVV}})|^2} \]
  \[ O_2(\kappa_{\text{HVV}}) \sim \frac{|\text{ME}(\text{SM})|^2}{|\text{ME}(\kappa_{\text{HVV}})|^2} \]

and similarly for \( \kappa_{\text{AVV}} \tan(\alpha) \)

- Perform CP mixing scan fitting \( 0_1, 0_2 \) and BDT\( _{\text{ZZ}} \)

ATLAS Preliminary

H to ZZ* to 4\( \ell \)

- Observed
- Expected: signal strength fit to data
- Expected: SM

CP even mixture

PDFs (BDT\(_0\), BDT\(_{\text{CP}}\))

SM vs bkg SM vs CP alternative
Conclusions

- Final Run-I Higgs analyses!
- Improved sensitivity, especially to different production modes
- No significant deviations from SM so far.
- Signal strength in all production and decay modes input to coupling fits (→ Michael’s talk later today!)

**Important lessons for Run-II and beyond**

- Despite huge progress, in many cases systematics (esp. theory) dominant
  - Theory uncertainty on cross section + acceptance of Higgs signal
  - Background modeling (e.g. V+bb, tt+bb for H to bb)
- Need improved experimental and theory techniques to fully profit from improved statistical sensitivity.