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Outline

Lecture I
- Introduction : Elements of history
- Elements of SM Higgs theory
- Precision EW tests
- The discovery of the Higgs boson
- An (early) experimental profile of the Higgs boson: The discovery channels

Lecture II
- An (early) experimental profile of the Higgs boson: All Final States (Fermion modes)
- The Higgs width
- Rare decay modes
- Rare production modes
- Combined measurements

Lecture III
- Implications of the discovered state
- Search for BSM Higgs and extended sectors
- New trends
- Future Higgs programs
The Discovery channels beyond discovery
Differential, Fiducial and Unfolded cross section

\[ n_s = \sigma \times Br \times A \times \varepsilon \times L \]

Interpretation of an observed number of events of a given signal S

“Total cross section”: an estimate of the an acceptance (given by theory) is needed to perform the measurement

\[ \sigma Br = \frac{n_s}{A \times \varepsilon \times L} \]

“Fiducial”: means that the measurement is given for a specific acceptance

\[ \sigma Br \times A = \frac{n_s}{\varepsilon \times L} \]

To be most useful the acceptance definition should be as close as possible to the reconstructed cuts.
“Unfolded” : how to estimate the particle level distribution from a measured distribution “smeared” by detector effects. Typically done using MC, the subtlety is to make this estimate independent of the MC model itself and only on the detector effects.

Why bother?

- Compare with theory
- Compare between experiments with different responses
Differential, Fiducial and Unfolded cross section

- Higgs results in general rely on the prediction of Higgs transverse momentum or jet multiplicities: Important to measure it.
- Direct tests of the production (sensitive e.g. to new physics)

\[ H \rightarrow 4l \]


\[ H \rightarrow \gamma\gamma \]

JHEP 09 (2014)
Combined Differential Cross sections

Inclusive cross section (Acceptances assume SM production) – Absolute(Comparison with several State of the Art MCs and XS calculations)

(Publication in preparation)

\[ \frac{d\sigma}{dp_T^H} \text{ [pb/GeV]} \]

\[ ATLAS \text{ Preliminary } pp \rightarrow H \]

\[ ATLAS \text{ Preliminary } pp \rightarrow H \]

\[ \sigma \text{ [pb]} \]

\[ N_{\text{Jets}} \]

\[ \text{Compatibility probability } \sim \text{few permil level (mostly due to the overall normalisation)} \]
Combined Differential Cross sections

Inclusive cross section (Acceptances assume SM production) – Absolute(Comparison with several State of the Art MCs and XS calculations)

(Publication in preparation)

ATLAS Preliminary \( pp \rightarrow H \)

\( \frac{1}{\sigma} \frac{d\sigma}{dp_T^H} [1/{\text{GeV}}] \)

[Graph showing the ratio of differential cross sections with various theoretical and experimental inputs.]

More compatible
\[ \sigma(\text{Data, } pp \rightarrow H) = 33.0 \pm 5.3 \text{ (stat)} \pm 1.6 \text{ (syst) pb} \]

\[ \sigma(\text{Data, } gg \rightarrow H) = 30.0 \pm 5.5 \text{ pb} \]

\[ \sigma(\text{LHC Higgs XS WG, } gg \rightarrow H) = 19.1 \pm 2.0 \text{ pb} \]
**Breakthrough!!**

\[ \sigma(pp \rightarrow H, \ m_H = 125.4 \text{ GeV}) \]

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma_{ggF} + \sigma_{XH} )</th>
<th>( \sigma_{XH} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \gamma\gamma )</td>
<td>( 3.0 \pm 0.1 \text{ pb} )</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* \rightarrow 4l )</td>
<td>( 3.0 \pm 0.1 \text{ pb} )</td>
<td></td>
</tr>
</tbody>
</table>

\[ \sigma(\text{Data, } pp \rightarrow H) = 33.0 \pm 5.3 \text{ (stat)} \pm 1.6 \text{ (syst)} \text{ pb} \]

\[ \sigma(\text{Data, } gg \rightarrow H) = 30.0 \pm 5.5 \text{ pb} \]

\[ \sigma(\text{LHC Higgs XS WG, } gg \rightarrow H) = 19.1 \pm 2.0 \text{ pb} \]
Recent Important News

**N3LO Inclusive Higgs Production Achieved**

Development of sophisticated numerical/computational methods.

\[ \sqrt{s} = 13 \text{TeV} \]

*B. Mistelberger @ Moriond QCD (2015)*

Other uncertainties now become important (PDFs, treatment of EW, heavy-top approximation, top-bottom interference in loops...).
PDF Uncertainties

PDF (+ $\alpha_s$) Uncertainties dominant in particular with recent N3LO Calculation

Situation likely to change ...

Gluon density

Very recent developments ...

<table>
<thead>
<tr>
<th></th>
<th>CT14</th>
<th>MMHT2014</th>
<th>NNPDF3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_H$ (pb)</td>
<td>42.68</td>
<td>42.70</td>
<td>42.97</td>
</tr>
<tr>
<td>Error (%)</td>
<td>+2.0%</td>
<td>+1.3%</td>
<td>+1.9%</td>
</tr>
<tr>
<td>Error (%)</td>
<td>-2.4%</td>
<td>-1.8%</td>
<td>-1.9%</td>
</tr>
</tbody>
</table>
Wide Overview of Measurements

Past decade tremendous progresses in theory calculations and simulation “Next-to... revolution”

Processes are simulated to an unprecedented level of accuracy

Number of events selected in full 2010-2012 dataset

- $W (l\nu) \sim 100 \ M$
- $Z (l\bar{l}) \sim 10 \ M$
- $tt (l+X) \sim 0.4 \ M$
  (top factory)

- Test Standard Model predictions at 7 and 8 TeV
- Calibrate the detector
A More Complex Discovery Mode
Jets and MET

Another important (r)evolution: Jet algorithms

- Fastjet: IR and collinear safe computable
- PU subtraction
- Boosted techniques (discussed in top lecture)
Jet Energy Scale

Jet Energy Calibration at **Percent level**
Achieved *in situ*

**Astonishing Precision !**
Boosted Jets

Important developments used extensively at Run 1, increasingly important at Run 2

HEP Top Tagger: Reconstruction of the top jets in $t\bar{t}$ events

High pT W and Z cross section: Measurement of the W and Z production cross sections in a boosted regime
A discovery channel of a different kind...

- Intricate analysis
- Moderate s/b ratio starting from approximately 1.5 and reaching more than 10.
- Poor mass resolution

\[ H \rightarrow WW^{(*)} \rightarrow l\nu l\nu \]

ATLAS
\[ Z = 6.1 \ (5.8) \ \sigma \]

CMS
\[ Z = 4.0 \ (5.0) \ \sigma \]
Systematics (in particular TH systematics) play a very important role

<table>
<thead>
<tr>
<th>Source</th>
<th>Observed $\mu = 1.08$</th>
<th>Observed $\mu_{\text{rej}} = 1.01$</th>
<th>Observed $\mu_{\text{VBF}} = 1.27$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Error + / -</td>
<td>Plot of error (scaled by 100)</td>
<td>Error + / -</td>
</tr>
<tr>
<td>Data statistics</td>
<td>0.16 / 0.15</td>
<td>-</td>
<td>0.19 / 0.19</td>
</tr>
<tr>
<td>Signal regions</td>
<td>0.12 / 0.12</td>
<td>-</td>
<td>0.14 / 0.14</td>
</tr>
<tr>
<td>Profilled control regions</td>
<td>0.10 / 0.10</td>
<td>-</td>
<td>0.12 / 0.12</td>
</tr>
<tr>
<td>Profilled signal regions</td>
<td>- / -</td>
<td>-</td>
<td>0.03 / 0.03</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.04 / 0.04</td>
<td>-</td>
<td>0.05 / 0.06</td>
</tr>
<tr>
<td>Theoretical systematics</td>
<td>0.13 / 0.11</td>
<td>-</td>
<td>0.17 / 0.14</td>
</tr>
<tr>
<td>Signal $H \to WW^* \ell\ell$</td>
<td>0.05 / 0.04</td>
<td>-</td>
<td>0.05 / 0.03</td>
</tr>
<tr>
<td>Signal ggF normalization</td>
<td>0.06 / 0.05</td>
<td>-</td>
<td>0.09 / 0.06</td>
</tr>
<tr>
<td>Signal ggF acceptance</td>
<td>0.05 / 0.04</td>
<td>-</td>
<td>0.06 / 0.05</td>
</tr>
<tr>
<td>Signal VBF normalization</td>
<td>0.01 / 0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Signal VBF acceptance</td>
<td>0.02 / 0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Background $WW$</td>
<td>0.06 / 0.06</td>
<td>-</td>
<td>0.08 / 0.08</td>
</tr>
<tr>
<td>Background top quark</td>
<td>0.03 / 0.03</td>
<td>-</td>
<td>0.04 / 0.04</td>
</tr>
<tr>
<td>Background misid. factor</td>
<td>0.05 / 0.05</td>
<td>-</td>
<td>0.06 / 0.06</td>
</tr>
<tr>
<td>Others</td>
<td>0.02 / 0.02</td>
<td>-</td>
<td>0.02 / 0.02</td>
</tr>
<tr>
<td>Experimental systematics</td>
<td>0.07 / 0.06</td>
<td>-</td>
<td>0.08 / 0.07</td>
</tr>
<tr>
<td>Background misid. factor</td>
<td>0.03 / 0.03</td>
<td>-</td>
<td>0.04 / 0.04</td>
</tr>
<tr>
<td>Bkg. $Z/\gamma^* \to ee, \mu\mu$</td>
<td>0.02 / 0.02</td>
<td>-</td>
<td>0.03 / 0.03</td>
</tr>
<tr>
<td>Muons and electrons</td>
<td>0.04 / 0.04</td>
<td>-</td>
<td>0.05 / 0.04</td>
</tr>
<tr>
<td>Missing transv. momentum</td>
<td>0.02 / 0.02</td>
<td>-</td>
<td>0.02 / 0.01</td>
</tr>
<tr>
<td>Jets</td>
<td>0.03 / 0.02</td>
<td>-</td>
<td>0.04 / 0.03</td>
</tr>
<tr>
<td>Others</td>
<td>0.03 / 0.02</td>
<td>-</td>
<td>0.03 / 0.03</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>0.03 / 0.03</td>
<td>-</td>
<td>0.03 / 0.02</td>
</tr>
<tr>
<td>Total</td>
<td>0.22 / 0.20</td>
<td>-</td>
<td>0.27 / 0.25</td>
</tr>
</tbody>
</table>
In particular background systematic uncertainties play an important role (*which affect the significances* described above)

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Pre-fit $\Delta \mu$</th>
<th>Post-fit $\Delta \mu$</th>
<th>Plot of post-fit $\pm \Delta \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW$, generator modeling</td>
<td>$-0.07$ $+0.07$ $-0.05$ $+0.05$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF $H$, QCD scale on total cross section</td>
<td>$-0.04$ $+0.05$ $-0.04$ $+0.05$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top quarks, generator modeling on $\alpha_{top}$</td>
<td>$+0.03$ $-0.04$ $+0.03$ $-0.03$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Misid. of $\mu$, OC uncorrelated corr. factor $\alpha_{misid}$, 2012</td>
<td>$-0.03$ $+0.04$ $-0.02$ $+0.03$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Misid. of $e$, OC uncorrelated corr. factor $\alpha_{misid}$, 2012</td>
<td>$-0.03$ $+0.03$ $-0.02$ $+0.03$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated luminosity, 2012</td>
<td>$-0.02$ $+0.03$ $-0.02$ $+0.03$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF $H$, PDF variations on cross section</td>
<td>$+0.02$ $-0.03$ $+0.02$ $-0.03$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF $H$, QCD scale on $n_j \geq 2$ cross section</td>
<td>$+0.02$ $-0.03$ $+0.01$ $-0.03$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon isolation efficiency</td>
<td>$-0.02$ $+0.02$ $-0.02$ $+0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF $H$, UE/PS</td>
<td>$-0.02$ $+0.02$ $-0.02$ $+0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF $H$, PDF variations on acceptance</td>
<td>$-0.02$ $+0.02$ $-0.02$ $+0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale, $\eta$ intercalibration</td>
<td>$-0.02$ $+0.02$ $-0.02$ $+0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VV, QCD scale on acceptance</td>
<td>$-0.01$ $+0.02$ $-0.01$ $+0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF $H$, UE/PS</td>
<td>$-0.02$ $-0.02$ $-0.02$ $-0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light jets, tagging efficiency</td>
<td>$+0.01$ $-0.02$ $+0.01$ $-0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Misid. $jj$, correction on $\alpha_{misid}$</td>
<td>$+0.01$ $-0.02$ $+0.01$ $-0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron isolation efficiency</td>
<td>$-0.01$ $+0.02$ $-0.01$ $+0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Misid. of $\mu$, closure on $\alpha_{misid}$, 2011</td>
<td>$-0.01$ $+0.02$ $-0.01$ $+0.01$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron identification eff. on $p_{T} &gt; 20$ GeV, 2012</td>
<td>$-0.01$ $+0.02$ $-0.01$ $+0.02$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF $H$, QCD scale on $\epsilon_1$</td>
<td>$-0.01$ $+0.02$ $-0.01$ $+0.02$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*NNLO Done (need fiducial and differential)!

*Discovery with help from Theory*
Combining Bosonic Modes to Measure Higgs Properties
$J^{PC}$

- The observed rates in the diboson channels already a lot of information:
  - Observation in the diphoton channel $J \neq 1$
  - Observation in WW and ZZ channels disfavor the CP-Odd hypothesis (can occur through loops)

- Spin hypothesis tests (difficult model spin 2) – Combination of ZZ, WW and $\gamma\gamma$

$$\mathcal{L}_2 = \frac{1}{\Lambda} \left[ \sum_V \kappa_V X^{\mu \nu} \mathcal{T}_{\mu \nu}^V + \sum_f \kappa_f X^{\mu \nu} \mathcal{T}_{\mu \nu}^f \right]$$

Coupling to energy-momentum tensor

$p_T [125,300] \text{ GeV}$
CP Mixing

- Spin 0 effective model

\[ L_0^V = \left\{ c_\alpha \kappa_{\text{SM}} \left[ \frac{1}{2} g_{HZ} Z^\mu Z_\mu + g_{HWW} W^+_\mu W^-_{-\mu} \right] \right. \]
\[ - \frac{1}{4} \Lambda \left[ c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} Z^{\mu\nu} \right] \]
\[ - \frac{1}{2} \Lambda \left[ c_\alpha \kappa_{HWW} W^{+}_{\mu\nu} W^{-}_{-\mu\nu} + s_\alpha \kappa_{AWW} W^{+}_{\mu\nu} W^{-}_{-\mu\nu} \right] \left\} X_0 \right. \]

(Use e.g. optimal observables in 4l channel)
Both ATLAS and CMS find that the observed Higgs boson is compatible with a standard CP-even
The Higgs Natural Width

Problem at the LHC: Measure only cross sections times branching fractions in specific modes !!

The total width can be scaled at will (with an undetected part) and be compensated by the scaling of the couplings in the observed modes.
\Gamma_{SM} = 4.2 \text{ MeV} \quad \text{Is small therefore small couplings to the Higgs can be easily visible: tool for discovery!}
Exploring the far Off-Shell signal strength
And constraints on the Higgs boson width

Probing the Higgs boson as a propagator:


Off Shell Higgs coupling properties Measurement

Study the Higgs boson as a propagator

Why is it interesting?

- If the coupling properties of the Higgs boson are known on mass shell (in particular the width of the Higgs: Probe e.g. the running of the Higgs coupling to gluons.

- If we assume that the running does not have large contributions from new physics at higher mass scales: Probe of the width.
Intricacies...

Study the Higgs boson as a propagator

Needs to be known to a high precision level. Latest NLO estimate (Melnikov and Dowling TTP-15-009)

... and the interference

... but wait there is a way larger background (also needing to be accurately, in particular with EW corrections)!
Exploring the High mass region in 4l and 2l2v

Need to use as much information as possible e.g. Matrix Element
CLs limits on Off-Shell signal strength

Agnostic to k-factor!

R=1 Approximately verified in the soft collinear approximation and latest calculations

95% CL limit obs. (exp.)

$\mu_{\text{OffShell}} < 6.7 \ (8.1)$
γ\text{H}/γ_H^{SM} < 5.5 (8.0)

Assuming: \((\kappa_g^2 \kappa_V^2)_{\text{OnShell}} = (\kappa_g^2 \kappa_V^2)_{\text{OffShell}}\)

95% CL limit obs. (exp.)
\(\Gamma_H/\Gamma_H^{SM} < 5.5 (8.0)\) ~23 MeV

Precision currently statistically limited
Exploring the Fermion Sector in Complex Final States
## Panorama of Main Higgs Analyses

<table>
<thead>
<tr>
<th>Channel categories</th>
<th>ggF</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>γγ</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ZZ (llll)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>WW (lllν)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ττ</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>bb</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Zγ and γγ*</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>μμ and ee</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Invisible</td>
<td>✓   (monojet)</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
Reconstructing Taus

**Tau reconstruction**

Typical numbers:
- Efficiency ~50%
- Background efficiency ~2%

*ATLAS Preliminary*  
2012 Simulation

**Splendid visible mass spectrum (CMS)**
A Very Important Observation...

(Mostly) VBF $H \rightarrow \tau\tau$

- Control of background through embedding (of taus in dimuon data events)
- Moderate s/b ratio starting from a few percent to approximately 1

ATLAS

$Z = 4.5 \ (3.5) \ \sigma$

CMS

$Z = 3.2 \ (3.7) \ \sigma$
Tagging b-jets

Performant tagging algorithms using the impact parameter and reconstructed secondary vertex information. Only one quick (important) comment:

**Challenge**: Controlling the efficiency in data at high transverse momentum!
Cornering the b Yukawa Coupling

**VH production with \( H \rightarrow bb \)** (VBF possible)

- Analysis using the boost (without substructure)
- Moderate s/b ratio starting from approximately few percent to approximately 30%

Tevatron: \( \mu = 1.6 \pm 0.7 \) (~2.3 sigma)

ATLAS
\[ Z = 1.4 \pm (2.6) \sigma \]

CMS
\[ Z = 2.1 \pm (2.1) \sigma \]
Boosted Analyses (without substructure)

Simulation of $p_T (V)$ is critical

Our precision will initially rely significantly on the simulation, will move to state-of-the-art MC for Run-2
Cornering (directly) the top Yukawa coupling

Analysis strategy

- 2 channels $t(lvb)t(qqb)H(bb)$ and $t(lvb)t(lvb)H(bb)$
- Challenging $tt$+jets background...
- $tt$+jets and $tt$+HF tamed

$ttH(bb)$

**ATLAS**

Preliminary Simulation

$m_t = 125$ GeV

$\sqrt{s} = 8$ TeV

Single lepton
Profiling Paradigm: why it matters?

<table>
<thead>
<tr>
<th>System</th>
<th>Signal 5 jets, ≥ 6 jets, ≥ 6 jets, ≥ 4 b-tags</th>
<th>3 b-tags</th>
<th>≥ 4 b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}H$ (125)</td>
<td>$11 \pm 1 \pm 9$</td>
<td>$69 \pm 3 \pm 57$</td>
<td>$28 \pm 2 \pm 23$</td>
</tr>
<tr>
<td>$t\bar{t} + \text{light}$</td>
<td>$78 \pm 9$</td>
<td>$2380 \pm 130$</td>
<td>$78 \pm 11$</td>
</tr>
<tr>
<td>$t\bar{t} + c\bar{c}$</td>
<td>$45 \pm 12$</td>
<td>$750 \pm 190$</td>
<td>$75 \pm 19$</td>
</tr>
<tr>
<td>$t\bar{t} + b\bar{b}$</td>
<td>$149 \pm 20$</td>
<td>$1160 \pm 170$</td>
<td>$300 \pm 40$</td>
</tr>
<tr>
<td>$t\bar{t} + V$</td>
<td>$3.3 \pm 1.0$</td>
<td>$44 \pm 13$</td>
<td>$8.9 \pm 2.7$</td>
</tr>
<tr>
<td>non-$t\bar{t}$</td>
<td>$23.2 \pm 2.5$</td>
<td>$218 \pm 23$</td>
<td>$18.8 \pm 2.2$</td>
</tr>
<tr>
<td>Total</td>
<td>$309 \pm 11$</td>
<td>$4620 \pm 80$</td>
<td>$507 \pm 27$</td>
</tr>
<tr>
<td>Data</td>
<td>283</td>
<td>4671</td>
<td>516</td>
</tr>
</tbody>
</table>

Light rejection crucial

13% Irreducible not critical
Cornering (directly) the top Yukawa coupling

$ttH(bb)$
Cornering the top Yukawa coupling

\[ t(t)H(\gamma\gamma) \]

**Leptonic channel**

**Hadronic channel**

**Analysis reinterpretation**

Inclusive \( \gamma\gamma \) limit from process assuming \( \kappa_W = 1 \)

\[ tH \] contribution at negative \( \kappa_t \)

\[ \propto 3.3 \times \kappa_W^2 - 5.1 \times \kappa_t \kappa_W + 2.8 \times \kappa_t^2 \]

95% CL exclusion \( -\infty, 1.3] \cup [8.1, +\infty[ \)

\[ ( -\infty, 1.2] \cup [7.9, +\infty[ \)
Cornering (directly) the top Yukawa coupling

Very complex final state that requires a thorough control of the background (as well)

\[ ttH(ML) \]

- Uses decays of W’s and taus
- Essentially 4W’s and 2b’s in the final state
- All possible combinations
Cornering (directly) the top Yukawa coupling

Very complex final state that requires a thorough control of the background (as well)

\( ttH(ML) \)

- Analysis much more vulnerable to irreducible \( ttV \) background
- Determination of fakes is delicate and important
- An excess is observed in both experiments in the SS 2-leptons channel

Back of the enveloppe: \( 2.3^{+0.7}_{-0.6} \) (Still roughly 2 sigma high)

\( 2.9^{+1.1}_{-0.9} \) \( Z = 2.1 \sigma \) From SM
Rare Decays and Rare Production modes
Rare Decays

\( \mu^+ \mu^- \)

\( \sigma . \text{Br} < 7.0 \times (7.2) \sigma . \text{Br}_{\text{SM}} \)

Universal couplings

\( \sim 260 \) times SM

\( e^+ e^- \)

\( \sigma . \text{Br} < 3.7 \times 10^5 \sigma . \text{Br}_{\text{SM}} \)

**ATLAS**

\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 24.8 \text{ fb}^{-1} \]

\[ \sqrt{s} = 8 \text{ TeV} \]

**CMS**

\[ \int L dt = 4.5 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \]

\[ \int L dt = 20.3 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \]
Strong Constraints on \( Br(H \rightarrow e\mu) < O(10^{-8}) \) from \( \mu \rightarrow e\gamma \)

Less on \( Br(H \rightarrow \tau\mu) \)

Observed limit: 1.6% (0.7% expected)
Sensitivity to Light Quark Modes?

Decays to a Meson and a photon

![Diagram showing H decay to q and q̄](image)

**Final State**

potential sensitive to **strange** Yukawa

\[ \Gamma \sim |11.9 - 1.04k_c|^2 \]

Current upper bound: 0.1 – 0.2 %

![Graph showing 95% CL upper limit on branching fraction for H/Z → QY](image)
Invisible Decays

Very small expected SM signal

\[ Br(H \rightarrow \text{invisible}) \]

VH Production
Observed limit 95% CL: approximately 60%

VBF Production
Observed limit 95% CL: approximately 30%

Indirect limit from standard combination (assuming Standard couplings to Standard fields)
Observed limit 95% CL: approximately 30%

Searches sensitive to Dark Matter
(if it couples to the Higgs boson and if it is light enough)
Rare Production Modes

Flavor changing neutral current decays of the top quark

Single top associated production

Tree level interference between W and top

Various decay channels of the Higgs boson (gg, bb)

Limits on $\text{Br}(t \rightarrow Hq)$

SM Branching $\sim 10^{-15}$

$\text{Br}(t \rightarrow cH) < 0.79 \ (0.51)\%$

$\text{Br}(t \rightarrow Hq) \propto 3.3 \times \kappa_W^2 - 5.1 \times \kappa_t \kappa_W + 2.8 \times \kappa_t^2$

Allows to further constrain the top Yukawa coupling, in particular to exclude a negative relative sign

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<table>
<thead>
<tr>
<th>Channel categories</th>
<th>ggF</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
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<tr>
<td>Invisible</td>
<td>✓ (monojet)</td>
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## The Observed Part of the Landscape

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</tbody>
</table>

( monojet)
Combination Master Formula

Parameterize the signal yields as a function of these parameters
(assuming narrow width approximation)

\[ n^c_s = \mu \sum_{i \in \{\text{productions}\}} \sum_{f \in \{\text{decays}\}} \mu^i \sigma^i_{SM} \times A^{ifc} \times \varepsilon^{ifc} \times \mu^f \text{Br}^f \times L^c \]
Naïve interpretation, simple example, VBF production in the WW decay channel:

\[
\mu^f = \frac{\kappa_V^2}{\kappa_H^2}
\]

\[
\kappa_H^2 = \frac{\sum \Gamma_f}{\Gamma_{SM}} = 0.75 \times \kappa_F^2 + 0.25 \times \kappa_V^2
\]

Assuming no BSM width

Two fundamental options:

1. Allow BSM fields in the decay: \( \kappa_H \) free parameter (typically cannot constrain the couplings to SM particles in this case)

2. Allow BSM particles in the loops or resolve the loops assuming SM fields only

\[
\kappa_g^2 \propto 1.06 \kappa_l^2 - 0.07 \times \kappa_t \kappa_b + 0.01 \times \kappa_b^2
\]
Higgs Production Modes

\[ \kappa \text{ for } m_H = 125.5 \text{ GeV} \]

\[ \mathcal{K}_g^2 \propto 1.06 \mathcal{K}_t^2 - 0.07 \times \mathcal{K}_t \mathcal{K}_b + 0.01 \times \mathcal{K}_b^2 \]

Gluon fusion process
NNnLO \(\sim O(10\%)\)
~0.5 M events produced

\[ \mathcal{K}_q^2 \propto \mathcal{K}_V^2 \]
Vector Boson Fusion
NNLO TH uncertainty \(\sim O(5\%)\)
Two forward jets and a large rapidity gap
~40 k events produced

\[ \mathcal{K}_W^2 \propto \mathcal{K}_V^2 \]
W and Z Associated Production
NNLO TH uncertainty \(\sim O(5\%)\)
~20 k events produced

\[ \mathcal{K}_b^2 \]
B-quark Assoc. Prod.
~5 k evts produced

\[ \mathcal{K}_t^2 \]
Top Assoc. Prod.
~3 k evts produced

\[ \propto 3.3 \times \mathcal{K}_W^2 - 5.1 \times \mathcal{K}_t \mathcal{K}_W + 2.8 \times \mathcal{K}_t^2 \]

And more e.g. \(gg\) to \(VH\)...
**Higgs Decay Channels**

- Dominant: $bb$ (57%) $\propto K_b^2 / K_H^2$
- $WW$ channel (22%) $\propto K_W^2 / K_H^2$
- $\tau\tau$ channel (6.3%) $\propto K_{\tau}^2 / K_H^2$
- The $\mu\mu$ channel (0.02%) $\propto K_{\mu}^2 / K_H^2$
- $ZZ$ channel (3%) $\propto K_Z^2 / K_H^2$
- $cc$ channel (3%) $\propto K_c^2 / K_H^2$
- The $\gamma\gamma$ channel (0.2%) $\propto K_{\gamma}^2 / K_H^2$

- The $Zg$ (0.2%) $\kappa_{Z\gamma} \propto 1.12 \times K_W^2 - 0.15 \times K_t K_W + 0.03 \times K_t^2$

$\kappa_{\gamma} \propto 1.6 \times K_W^2 - 0.7 \times K_t K_W + 0.1 \times K_t^2$

(when assuming no BSM charged in the loop)
Overall Signal Strengths

Probing Consistency with Standard Model Higgs

**ATLAS**

\[ \mu = 1.18 \pm 0.10 \ (\text{stat}) ^{+0.08}_{-0.07} \ (\text{th}) \pm 0.07 \ (\text{syst}) \]

**CMS**

\[ \mu = 1.00 \pm 0.09 \ (\text{stat}) ^{+0.08}_{-0.07} \ (\text{th}) \pm 0.07 \ (\text{syst}) \]
**ATLAS** Preliminary

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

**Input measurements**

\[ n_s^c = \mu \left( \sum_{i \in \{ \text{processes} \}} \mu^i \sigma_{SM}^i \times A_{bc}^i \times \epsilon_{ic} \right) \times \mu^f Br_f \times L^c \]

### Strengths in the Main Categories

#### Independent fit of each channel

- **H → γγ**
  - Overall: \( \mu = 1.17^{+0.20}_{-0.22} \)
  - ggF: \( \mu = 1.32^{+0.03}_{-0.04} \)
  - VBF: \( \mu = 0.88^{+0.02}_{-0.03} \)
  - Wt: \( \mu = 1.04^{+0.02}_{-0.03} \)
  - Zh: \( \mu = 0.53^{+0.02}_{-0.03} \)

- **H → ZZ^***
  - Overall: \( \mu = 1.44^{+0.06}_{-0.08} \)
  - ggF: \( \mu = 1.70^{+0.05}_{-0.06} \)
  - VBF: \( \mu = 0.31^{+0.05}_{-0.06} \)
  - VbF: \( \mu = 0.31^{+0.05}_{-0.06} \)

- **H → WW^***
  - Overall: \( \mu = 1.17^{+0.06}_{-0.08} \)
  - ggF: \( \mu = 0.98^{+0.06}_{-0.08} \)
  - VBF: \( \mu = 1.29^{+0.06}_{-0.08} \)
  - WH: \( \mu = 3.02^{+0.04}_{-0.05} \)
  - Zt: \( \mu = 3.02^{+0.04}_{-0.05} \)

- **H → ττ**
  - Overall: \( \mu = 1.43^{+0.08}_{-0.10} \)
  - ggF: \( \mu = 2.01^{+0.08}_{-0.10} \)
  - VBF: \( \mu = 1.24^{+0.08}_{-0.10} \)

- **VH → VbF**
  - Overall: \( \mu = 0.52^{+0.06}_{-0.08} \)
  - WH: \( \mu = 1.50^{+0.06}_{-0.08} \)
  - Zt: \( \mu = 0.06^{+0.02}_{-0.03} \)

- **H → μμ**
  - Overall: \( \mu = 0.73^{+0.07}_{-0.08} \)

- **H → Zμ**
  - Overall: \( \mu = 2.74^{+1.01}_{-1.02} \)

- **ttH**
  - tH: \( \mu = 1.3^{+0.1}_{-0.1} \)
  - Multiphoton: \( \mu = 2.5^{+0.1}_{-0.1} \)
  - γγ: \( \mu = 1.3^{+0.1}_{-0.1} \)

#### Combined

- \( \mu = 1.18^{+0.15}_{-0.14} \)

**Overall**

- \( \mu = 1.3^{+0.1}_{-0.1} \)
  - ggF: \( \mu = 1.3^{+0.1}_{-0.1} \)
  - VBF: \( \mu = 1.3^{+0.1}_{-0.1} \)
  - WH: \( \mu = 1.3^{+0.1}_{-0.1} \)
  - Zt: \( \mu = 1.3^{+0.1}_{-0.1} \)

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

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
Production Strengths or Cross Sections

\[ n_s^c = \mu \left( \sum_{i \in \{\text{processes}\}} \mu^i \sigma_{SM}^i \times A^{inc} \times \epsilon^{ic} \right) \times \mu^f \text{Br}^f \times L^c \]

Combination of all channels assuming SM branchings

Clear evidence of production in the two main modes
Overview of Cross Sections

Standard Model Total Production Cross Section Measurements

- **Theory**
- **Observed**

**LHC pp \(\sqrt{s} = 7\) TeV
- **Theory**
- **Observed** 4.5 – 4.9 fb \(^{-1}\)

**LHC pp \(\sqrt{s} = 8\) TeV
- **Theory**
- **Observed** 20.3 fb \(^{-1}\)

**Summary**
- **ATLAS** Preliminary
- **Run 1** \(\sqrt{s} = 7, 8\) TeV

**Standard Model Total Production Cross Section Measurement Status:** March 2015

**Run Parameters:**
- **LHC pp**
  - **Run 1**
    - \(\sqrt{s} = 7, 8\) TeV
Coupling to SM Spectra with Assumptions

Assuming no BSM in the loops or in the decay, testing couplings to SM particles

What are the assumptions?

- No BSM width
- No BSM in the loops
- All boson couplings scaled equally
- All fermion couplings scaled equally

Measurements very compatible with SM hypothesis
Higgs Couplings

Most General Fit

(By definition independent of width and no assumption on the loops)

- Direct coupling to the Z
- Custodial Symmetry
- Direct coupling to the top (through ttH production channels)
- Direct coupling to b quarks (Through mainly VH channels)
- Direct coupling to $\tau$ (through VBF production)
- Non-universality of Yukawa couplings

$\kappa_Z = 1.18 \pm 0.16$

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

$\lambda_{WZ} \in [-1.04, -0.81]$

$\lambda_{tg} \in [-1.70, -1.07]$

$\lambda_{bZ} = 0.60 \pm 0.27$

$\lambda_{tZ} = 0.99^{+0.23}_{-0.19}$

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

$\lambda_{YZ} = 0.90 \pm 0.15$

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

$m_H = 125.36$ GeV

Parameter value
Higgs boson couplings

Absolute couplings measurements under specific conditions:

- Standard only width
- Unitarity constraint on the coupling to vector bosons
- Use of Off-shell couplings measurements*

*Requires constraint of equal OffShell and OnShell Higgs couplings
Taste of Combination (and More)

**Higgs coupling measurements:**
- $K_V = 0.99 \pm 0.08$
- $K_F = 1.01 \pm 0.17$

- **Combined result:**
  - $K_V = 1.03 \pm 0.02$
  - ($\lambda = 3$ TeV) [1303.1812]
  - implies NP-scale of $\Lambda \geq 13$ TeV

Taste of future programs using EFT (Still to be defined) to combine EW measurements, Higgs, top, dibosons, etc...

R. Kogler @ Moriond EW
Summary

- A very vast new Higgs landscape
- A large amount of it already started to be investigated
- Still completely open for future investigation in quest for precision
- Emphasis: importance of theory input (for both the background and the signal predictions)
- All results very compatible with the Standard Model expectation...

But Where Is Everybody?

Nima Arkani Hamed