Conference Summary

Higgs Couplings 2014

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Physikalisches Institut
Universität Freiburg / Germany
At this conference more than 30 talks were given

I do not attempt to summarize all results in detail and I had to make a selection; I would in no way be capable of giving justice and fair credit to the fantastic amount of work presented during the last days.

My apologies to those speakers whose results I have omitted. It is not intended as a reflection of the relative importance!

---

*Helmut Schmidt, German Chancellor, 1974-1982*

„Wer Visionen hat, sollte zum Arzt gehen“
In 2012 the Higgs boson was like …

……a newborn child in the particle family;

After a long and painful way to discovery the world celebrated the arrival of a

“Higgs-like particle”
After a huge effort from many people over a long time, we arrived at physics analysis.
$H \to \gamma \gamma$ (historical mode)
Evolution of the excess with time
Evolution of the excess with time
GAUGE AND HIGGS BOSONS

\[ \eta^{(PC)} = 0.1(1-\cdots) \]

\( J = 1 \)

Charge = \( \pm 1 \) e
Mass \( m = 80.385 \pm 0.015 \) GeV
\( m_{Z} - m_{W} = 10.4 \pm 1.6 \) GeV
\( m_{W^{+}} - m_{W^{-}} = -0.2 \pm 0.6 \) GeV
Full width \( \Gamma = 2.085 \pm 0.042 \) GeV
\( \langle N_{Z}^{a} \rangle = 15.70 \pm 0.35 \)
\( \langle N_{W^{\pm}} \rangle = 2.26 \pm 0.19 \)
\( \langle N_{W} \rangle = 0.92 \pm 0.14 \)
\( \langle N_{\text{charged}} \rangle = 19.39 \pm 0.08 \)

\( m = 0 \) [4]
SU(3) color octet

\[ \eta^{(P)} = 0(1-\cdots) \]

\( m = 0 \) [4]
SU(3) color octet

Z

\( J = 1 \)

Charge = 0
Mass \( m = 91.1876 \pm 0.0021 \) GeV [5]
Full width \( \Gamma = 2.4952 \pm 0.0023 \) GeV
\( \Gamma(e^+e^-) = 83.984 \pm 0.086 \) MeV [6]
\( \Gamma(\text{invisible}) = 499.0 \pm 1.5 \) MeV [6]
\( \Gamma(\text{hadrons}) = 1744.4 \pm 2.0 \) MeV
\( \Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.0009 \pm 0.0028 \)
\( \Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) = 1.0019 \pm 0.0032 \) [7]

Higgs Bosons — \( H^0 \) and \( H^\pm \)

\( H^0 \) Mass \( m = 125.9 \pm 0.4 \) GeV

\( H^0 \) signal strengths in different channels [8]

Combined Final States = 1.07 \pm 0.26 \quad (S = 1.4)
\( WW^* \) Final State = 0.88 \pm 0.33 \quad (S = 1.1)
\( ZZ^* \) Final State = 0.89 \pm 0.20 \quad (S = 1.1)
\( \gamma \gamma \) Final State = 1.65 \pm 0.33
\( bb \) Final State = 0.5 \pm 0.7
\( \tau^+\tau^- \) Final State = 0.1 \pm 0.7

\( H^0 \)
Steve Meyers (early 2012):

“The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics.”
Key ingredients to this success story

1. The accelerator

- World record on instantaneous luminosity on 22. April 2011: \( 4.7 \times 10^{32} \) cm\(^{-2}\) s\(^{-1}\) (Tevatron record: \( 4.0 \times 10^{32} \) cm\(^{-2}\) s\(^{-1}\))

- 2012: regularly above \( 6 \times 10^{33} \) cm\(^{-2}\) s\(^{-1}\)}
The key ingredients to this success story

1. The accelerator
2. The detectors

- Working channels > 99%
- Data recording efficiency ~93-94%
- Data quality
- Speed of data analysis
- Had to cope with high luminosity
The key ingredients to this success story

1. The accelerator

2. The detectors

3. Theory, including advances in Monte Carlo simulation
• The overwhelming progress in (N)NLO calculations for signal and background processes

• Improved Monte Carlos simulations
  ALPGEN, MC@NLO, POWHEG, SHERPA, …

• The “Higgs cross section group”
  A big success story!!

* Central values for the production processes
* Theoretical uncertainties
* Differential distributions
* Guidance / benchmark scenarios on coupling measurements
* Guidance in spin/CP measurements
• The overwhelming progress in (N)NLO calculations for signal and background processes

• Improved Monte Carlos simulations
  ALPGEN, MC@NLO, POWHEG, SHERPA, ...

• The Higgs “cross section group”
  A big success story!!

  * Central values for the production processes
  * Theoretical uncertainties
  * Differential distributions
  * Guidance / benchmark scenarios on coupling measurements
  * Guidance in spin/CP measurements
The key ingredients to this success story

1. The accelerator

2. The detectors

3. Theory, including advances in Monte Carlo simulation
   - Multivariate Techniques (Neutral networks, Boosted Decision Trees, …) \(\leftarrow\) Tevatron
   - Data-driven background estimates, control region fits \(\leftarrow\) Tevatron

4. Analysis Techniques
   - Statistical methods (profile likelihood methods)
   - Energy flow techniques
Where do we stand after two years?

What aspects of the Higgs boson have we learned about in the last two years?

- Clear signals in bosonic decays
- Differential cross-section measurements
- Signals in fermionic decays
- Higgs boson profile:
  - Precision mass measurements
  - Extensive coupling measurements
  - Off-shell behaviour
  - Discrete quantum numbers (spin, CP)
- Search for brother or sister particles, i.e. additional Higgs bosons
Couplings to boson

LHC analysis + “Signal seen”

Categorisation in all channels

- Information on production mode
- Couplings
Signals in the bosonic decay modes

A. Calandri
A. Massironi

5.7$\sigma$

$\sigma$
Categorisation, example \( H \rightarrow ZZ^* \rightarrow 4l \) decays

Event categorization:

**ATLAS**

- **4l selection**
  - \( H \rightarrow ZZ^* \rightarrow 4l \)
  - BDT vs mass

**BDT variables:**
- \( P_T(4l) \)
- \( \eta(4l) \)
- Matrix Element Discriminant

- **High mass two jets**
  - VBF enriched
  - \( W(\rightarrow jj)H, Z(\rightarrow jj)H \)

- **Low mass two jets**
  - VH enriched
  - \( W(\rightarrow lv)H, Z(\rightarrow ll)H \)

- **Additional lepton**
  - \( gF \)
  - \( ggF \) enriched

- **ATLAS Simulation**
  - \( H \rightarrow ZZ^* \rightarrow 4l \)
  - \( t\bar{t} = 7 \text{ TeV} \), \( \mathcal{L} = 4.8 \text{ fb}^{-1} \)
  - \( t\bar{t} = 8 \text{ TeV} \), \( \mathcal{L} = 20.3 \text{ fb}^{-1} \)
Matrix-element / multivariate analysis techniques

**MELA: Matrix Element Likelihood Analysis:**
uses kinematic inputs for
signal to ZZ background discrimination
\[ \{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\} \]

\[
MELA = \left[ 1 + \frac{P_{bkg}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{P_{sig}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})} \right]^{-1}
\]

\[ M_{4\ell} = 121.5 - 130.5 \text{ GeV} \]

**Colours are signal + BG**

**Colours are BG only**
H → WW → lν lν signals

A. Calandri
A. Massironi
Summary of “final” Run-1 results

<table>
<thead>
<tr>
<th>H → γγ</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>m [GeV]</td>
<td>126.0 ± 0.50</td>
<td>124.70 ± 0.34</td>
</tr>
<tr>
<td>μ</td>
<td>1.17 ± 0.27</td>
<td>1.14 ± 0.26</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>H → ZZ* → 4l</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>m [GeV]</td>
<td>124.51 ± 0.52</td>
<td>125.6 ± 0.45</td>
</tr>
<tr>
<td>μ</td>
<td>1.44 ± 0.40</td>
<td>0.93 ± 0.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>H → WW* → lνlν</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>m [GeV]</td>
<td>125.5*</td>
<td>125 ± 4</td>
</tr>
<tr>
<td>μ</td>
<td>0.99 ± 0.31</td>
<td>0.72 ± 0.20</td>
</tr>
</tbody>
</table>

- Signals established with high significance in both experiments
- Signal strengths appear to be well consistent with the Standard Model expectations (high γγ signal yields “normalized”)
- Clear evidence in VBF sub-categories (later)
- Differential distributions measured (later)
- Mass determined with high precision (later)

* non-final results yet, publication in preparation
**Couplings to fermions?**

- Search for $H \rightarrow \tau\tau$ and $H \rightarrow bb$ decays
- Search for the rare $H \rightarrow \mu\mu$ decay

![Decay Diagram](image)

$H$ $\rightarrow$ $b$, $\tau^-$, $\mu^-$

$\overline{b}$, $\tau^+$, $\mu^+$
Search for $H \rightarrow \tau \tau$ decays

- A challenging analysis, focus on VBF and “boosted” topologies
- Multivariate analysis in ATLAS
- Complex models to estimate backgrounds
  (embedding of $Z \rightarrow \tau \tau$ events, use of control regions, e.g. 0-jet category)
- Complex fit models
Clear evidence for $H \to \tau \tau$ decays in both experiments

Signal strength (all sub-channels):

**ATLAS:** $\mu = 1.4^{+0.5}_{-0.4}$

**CMS:** $\mu = 0.78 \pm 0.27$

$m_H = 122 \pm 7$ GeV
Search for $H \rightarrow bb$ decays

- All what was said for $H \rightarrow \tau\tau$ applies here as well; (challenges, categorization, background normalization, complexity of the fit,… frustration of students,… )
Hints / evidence for $H \rightarrow bb$ decays

Signal strength (all sub-channels):

CMS: $\mu = 1.0 \pm 0.5$

ATLAS: $\mu = 0.51^{+0.40}_{-0.37}$
Hints / evidence for $H \to bb$ decays

Signal strength (all sub-channels):

**CMS:** $\mu = 1.0 \pm 0.5$

**ATLAS:** $\mu = 0.51^{+0.40}_{-0.37}$
Results on the search for $H \rightarrow \mu\mu$

$m_H = 125$ GeV:

- Observed 95% CL:  
  - ATLAS: $7.0 \sigma_{SM}$  
  - CMS: $7.4 \sigma_{SM}$

- Expected (no Higgs):  
  - ATLAS: $7.2 \sigma_{SM}$  
  - CMS: $5.1 \sigma_{SM}$

No evidence for “universal” fermion couplings
Summary of “final” Run-1 results of signal strength

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>m [GeV]</th>
<th>( \mu )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \gamma\gamma )</td>
<td>126.0 ± 0.50</td>
<td>1.17 ± 0.27</td>
<td>124.70 ± 0.34</td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* \rightarrow 4l )</td>
<td>124.51 ± 0.52</td>
<td>1.44+0.40-0.34</td>
<td>125.6 ± 0.45</td>
</tr>
<tr>
<td>( H \rightarrow WW^* \rightarrow l\nu l\nu )</td>
<td>125.5*</td>
<td>0.99+0.31-0.28</td>
<td>125 ± 4</td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>-</td>
<td>1.4+0.5-0.4</td>
<td>122 ± 7</td>
</tr>
<tr>
<td>( H \rightarrow bb )</td>
<td>-</td>
<td>0.51+0.40-0.37</td>
<td>-</td>
</tr>
</tbody>
</table>

* non-final results yet, publication in preparation
Differential cross-section measurements

- First fiducial, differential cross-section measurements in bosonic channels
- Good agreement within present experimental and theoretical uncertainties, (… except normalization?)

- Large future potential: probe Higgs boson kinematics, jet activity, VBF contributions, spin-CP nature, …
  → could become the “common ground” between experiment and theory for future measurements
Differential cross-section measurements (cont.)

**ATLAS**

- **data**
- **syst. unc.**
- $gg\rightarrow H$ (MINLO HJ+PS) + $XH$
  - $K_{eff} = 1.54$
- $XH = VBF + VH + t\bar{t}H$

$H \rightarrow \gamma\gamma$, $S = 8$ TeV

$\int L dt = 20.3$ fb$^{-1}$

$N_{jets} \geq 0$

$ATLAS$

$H \rightarrow ZZ' \rightarrow 4l$

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

$gg\rightarrow H$ (MINLO HJ+PS) + $XH$

$gg\rightarrow H$ (Powheg+PS) + $XH$

$XH = VBF + VH + t\bar{t}H$

G. Artoni
The Higgs Boson Profile
The Higgs Boson Profile

<table>
<thead>
<tr>
<th>Channel/Measurement</th>
<th>$\gamma\gamma$</th>
<th>ZZ</th>
<th>WW</th>
<th>$t\bar{t}$</th>
<th>bb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Couplings</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Off-shell Behaviour</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Spin-Parity</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

Significant contribution of this channel to the measurement
Measurement of the Higgs-boson mass

- Huge calibration effort by both collaborations to fix the lepton (e, $\mu$) and photon energy scales as function of $p_T$ and $\eta$
- Impressive accuracy reached (high statistics Z, Y, J/ψ samples, high performance tracking detectors, redundancy (ATLAS muon system))

Impressive accuracy reached

0.1 – 0.3%

(huge effort)
Measurement of the Higgs-boson mass

ATLAS: $m_H = 125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)}$ \; GeV

CMS: $m_H = 125.03^{+0.26}_{-0.27} \text{ (stat)}^{+0.13}_{-0.15} \text{ (syst)}$ \; GeV

- Systematic uncertainties reduced by a factor of ~3
- $m_{4l}$ and $m_{\gamma\gamma}$ as independent nuisance parameters
- $e/\gamma$ energy scale fully correlated

Compatibility between channels $2.0\sigma$ (ATLAS) and $1.6\sigma$ (CMS)

Future: further reduction of statistical and systematic uncertainties!
“modest requirements” from theory side; but parametric uncertainty in Higgs sector, e.g. branching ratios at 125 GeV
Towards Higgs Boson Couplings
Gluon fusion versus vector boson fusion

ATLAS + CMS:
Evidence for all Higgs boson production modes
$H \rightarrow \gamma \gamma$ VBF candidate event

$E_T(\gamma_1) = 80.1 \text{ GeV}, \eta = 1.01$
$E_T(\gamma_2) = 36.2 \text{ GeV}, \eta = 0.17$
$m_{\gamma \gamma} = 126.9 \text{ GeV}$

$E_T(\text{jet}_1) = 121.6 \text{ GeV}, \eta = -2.90$
$E_T(\text{jet}_2) = 82.8 \text{ GeV}, \eta = 2.72$
$m_{jj} = 1.67 \text{ TeV}$
Higgs boson couplings

- Production and decay involve several couplings

Production:

Decays: e.g. $H \to \gamma\gamma$ (good example)
(Decay widths depends on W and top-coupling, destructive interference)

- Benchmarks defined by LHC cross section working group (leading-order tree-level framework):
  - Signals observed originate from a single resonance;
    (mass assumed here is 125.5 GeV)
  - Narrow width approximation: $\to$ rates for given channels can be decomposed as:
    \[
    \sigma \cdot B (i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}
    \]
    i, f = initial, final state
    $\Gamma_i, \Gamma_H$ = partial, total width
  - Modifications to coupling strength are considered (coupling scale factors $\kappa$),
    tensor structure of Lagrangian assumed as in Standard Model

\[\begin{align*}
\text{Production:} & \\
\text{Decays:} & \\
\text{Benchmarks:} &
\end{align*}\]
Fermion vs. vector-boson coupling scale factors
- in the LO $\kappa$-framework-

- Good agreement with Standard Model expectation

- Degeneracy between rel. sign broken by $H \rightarrow \gamma\gamma$
Summary of ATLAS results for various scenarios

**ATLAS Preliminary**

$m_H = 125.5$ GeV

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter value</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_V, k_F$</td>
<td>$\kappa_V = 1.15_{-0.08}^{+0.08}$</td>
<td>$\kappa_F = 0.99_{-0.17}^{+0.08}$</td>
</tr>
<tr>
<td>$\lambda_{FV, FW}$</td>
<td>$\lambda_{FW} = 0.86_{-0.12}^{+0.14}$</td>
<td>$\lambda_{FW} = 0.94_{-0.29}^{+0.14}$</td>
</tr>
<tr>
<td>$\lambda_{WZ', FZ', ZF}$</td>
<td>$\lambda_{WZ} = 0.12_{-0.14}^{+0.15}$</td>
<td>$\lambda_{WZ} = 0.29_{-0.14}^{+0.15}$</td>
</tr>
<tr>
<td>$\lambda_{W', W}$</td>
<td>$\lambda_{W'} = 0.10_{-0.08}^{+0.08}$</td>
<td>$\lambda_{W'} = 0.10_{-0.08}^{+0.08}$</td>
</tr>
<tr>
<td>$\lambda_{g, g}$</td>
<td>$\lambda_{g} = 1.08_{-0.13}^{+0.15}$</td>
<td>$\lambda_{g} = 1.19_{-0.12}^{+0.15}$</td>
</tr>
<tr>
<td>$p_{SM} = 10%$</td>
<td>$p_{SM} = 10%$</td>
<td>$p_{SM} = 15%$</td>
</tr>
<tr>
<td>$\mu = 1.08_{-0.13}^{+0.15}$</td>
<td>$\mu = 1.19_{-0.12}^{+0.15}$</td>
<td>$\mu = 1.08_{-0.13}^{+0.15}$</td>
</tr>
</tbody>
</table>

Fermion and vector boson scale factors

Test of custodial symmetry

Up- to down-type quark couplings

Lepton / quark couplings

Contributions to ggF production and gg decay loops

Invisible and undetectable decays

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

$\sqrt{s} = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$
Summary of the fits of six benchmarks models probing:

- Fermions and vector bosons.
- Custodial symmetry.
- Up/down fermion coupling ratio.
- Lepton/quark coupling ratio.
- BSM in loops: gluons and photons.
- Extra width: $BR_{BSM}$.

No significance deviations from SM.

$\lambda_{xy} = \kappa_x / \kappa_y$
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{gZ}$</td>
<td>$0.0^{+2.2}_{-0.0}$</td>
<td>$0.0^{+2.2}_{-0.0}$</td>
</tr>
<tr>
<td>$\lambda_{WZ}$</td>
<td>$0.80^{+0.15}_{-0.14}$</td>
<td>$0.80^{+0.15}_{-0.14}$</td>
</tr>
<tr>
<td>$\lambda_{bZ}$</td>
<td>$0.3^{+0.4}_{-0.3}$</td>
<td>$0.3^{+0.4}_{-0.3}$</td>
</tr>
<tr>
<td>$\lambda_{rZ}$</td>
<td>$0.90^{+0.22}_{-0.18}$</td>
<td>$0.90^{+0.22}_{-0.18}$</td>
</tr>
<tr>
<td>$\lambda_{gZ}$</td>
<td>$0.73^{+0.22}_{-0.16}$</td>
<td>$0.73^{+0.22}_{-0.16}$</td>
</tr>
<tr>
<td>$\lambda_{tg}$</td>
<td>$0.0^{+12.2}_{-0.0}$</td>
<td>$0.0^{+12.2}_{-0.0}$</td>
</tr>
<tr>
<td>$\lambda_{gz}$</td>
<td>$1.18^{+0.17}_{-0.16}$</td>
<td>$1.18^{+0.17}_{-0.16}$</td>
</tr>
<tr>
<td>$\lambda_{tZ}$</td>
<td>$0.16^{+0.22}_{-0.18}$</td>
<td>$0.16^{+0.22}_{-0.18}$</td>
</tr>
<tr>
<td>$\lambda_{bg}$</td>
<td>$0.3^{+0.4}_{-0.3}$</td>
<td>$0.3^{+0.4}_{-0.3}$</td>
</tr>
<tr>
<td>$\lambda_{WZ}$</td>
<td>$0.80^{+0.15}_{-0.14}$</td>
<td>$0.80^{+0.15}_{-0.14}$</td>
</tr>
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</table>

- Coupling scale factors to $W, Z, t, b,$ and $\tau$ are treated independently;
- Effective scale factors for the $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ loops
- Only ratios of couplings accessible
Spin and CP

- If Standard Model Higgs boson: \( J^p = 0^+ \)
  \[ \Rightarrow \] strategy is to falsify other hypotheses (0\(^-\), 1\(^-\), 1\(^+\), 2\(^-\), 2\(^+\))

Spin 1: dis-favoured by observed \( H \rightarrow \gamma\gamma \) decays, Landau-Yang theorem

Spin 2: consider graviton-like tensor, equivalent to a Kaluza-Klein graviton

- Angular distributions of final state particles show sensitivity to spin
Result on different $J^{CP}$ hypothesis tests

**ATLAS**

- $H \rightarrow \gamma \gamma$
  - $\sqrt{s} = 8$ TeV, $\mathcal{L}_{\text{ddt}} = 20.7$ fb$^{-1}$

- $H \rightarrow ZZ^* \rightarrow 4l$
  - $\sqrt{s} = 7$ TeV, $\mathcal{L}_{\text{ddt}} = 4.6$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV, $\mathcal{L}_{\text{ddt}} = 20.7$ fb$^{-1}$

- $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ or $\mu\nu\mu\nu$
  - $\sqrt{s} = 8$ TeV, $\mathcal{L}_{\text{ddt}} = 20.7$ fb$^{-1}$

- $CL_s$ expected assuming $J^P = 0^+$
- $\pm 1 \sigma$

Are theorists satisfied? Can we stop looking at spin-2 models?
Phenomenology of anomalous couplings: spin 0

- Interaction between a spin 0 Higgs and two gauge bosons $V_1$, $V_2$ ($Z$, $W$, $\gamma$, $g$), expansion up to $q^2$

- $q^4$ and higher orders not considered assuming small anomalous couplings

$$A(HV_1V_2) \sim \left[ a_1 V_1 V_2 + \kappa_1 V_1 V_2 q_{V_1}^2 + \kappa_2 V_1 V_2 q_{V_2}^2 \right] \left( \Lambda_1 V_1 V_2 \right)^2$$

- $\Lambda_1$ term 
  leading momentum expansion

- $a_2$ term 
  CP even state

- $a_3$ term 
  CP odd state

- SM value for couplings

<table>
<thead>
<tr>
<th>Couplings</th>
<th>$a_1$</th>
<th>$q^2/\Lambda_1^2$</th>
<th>$a_2$</th>
<th>$a_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HZZ(WW)</td>
<td>2</td>
<td>$10^{-3} - 10^{-2}$</td>
<td>$10^{-3} - 10^{-2}$</td>
<td>$&lt; 10^{-10}$</td>
</tr>
<tr>
<td>HZ$\gamma$</td>
<td>-</td>
<td>$10^{-3} - 10^{-2}$</td>
<td>$\sim 0.0035$</td>
<td>$&lt; 10^{-10}$</td>
</tr>
<tr>
<td>$H\gamma\gamma$</td>
<td>-</td>
<td>-</td>
<td>$\sim -0.004$</td>
<td>$&lt; 10^{-10}$</td>
</tr>
</tbody>
</table>

- Measurements

  1) hypothesis test, pure $O^-$ ($a_3$), $O_h^+$ ($a_2$) states 
  - CMS: 99.9% ($O^-$), 95% CL ($O_h^+$)
  - ATLAS: 97.8% CL ($O^-$)

  2) measure 11 anomalous couplings 
  (10 in CMS-PAS-HIG-14-014 + 1 new)

References:

CMS results: HWW, HZγ, Hγγ anomalous couplings

- $a_i$, real, $\phi_i=0, \pi$
- Consistent with SM
- $H\rightarrow 4l$ from pure $HZγ^*$, $Hγγ$ excluded at $>99.99\%$ CL

More plots for all the other parameters in backup
• A good start to investigate the CP-structure
• Limited by number of events
• Potential in Run-2, including fermionic channels
Off-shell cross sections, Higgs boson width

In the resonance region the “on-shell” cross section is dominated by the width.

\[ \sigma_{i \rightarrow X \rightarrow f}^{on} \sim \frac{g_i^2 g_f^2}{\Gamma_X} \]

Away from the resonance region, the “off-shell” cross section does not depend on the width.

\[ \sigma_{i \rightarrow X \rightarrow f}^{off} \sim g_i^2 g_f^2 \]
Interesting Idea

- Off-shell cross sections can be used to constrain the couplings (ATLAS $\mu$-off-shell < 6.7)
- Bounds on width obtained by rescaling the SM $\rightarrow$ sensitivity to values of 5-7 SM values
- Future: improved calculations in off-shell region needed interpretation in Effective Field Theory?
Additional Higgs Bosons?

- All canonical searches (\( \phi \rightarrow \tau\tau \), \( \phi \rightarrow bb \), \( H^+ \rightarrow \tau\nu \), .... done)
- Additional searches for exotic decays, e.g. \( h \rightarrow \tau\mu \) started
- Change in interpretation paradigm: \( h(125\text{ GeV}) \) Higgs boson should be taken into account in model interpretations, e.g. MSSM

- Explicit prediction for three neutral Higgs bosons:

  - Note: \( h(125) \) has been observed!

- With increasing sensitivity new statistical interpretation is needed: “1 Higgs vs 3 Higgses.”
Limits on cross sections

R. Wolf
M. Hoffmann

φ → ττ

sensitivity to h(125) GeV at ~2.5σ

H⁺ → τν

Upper limits on
Br(t → bH⁺) × Br(H⁺ → τν)
- 1.3% - 0.23%

Upper limits on
σ(pp → tH⁺ + X) × Br(H⁺ → τν)
- 0.76 pb - 4.5 fb
• Search for heavy object $H \rightarrow \gamma\gamma$

• Search for heavy object $H \rightarrow hh \rightarrow \gamma\gamma bb$
  (several channels combined)

($m_x = 300 \text{ GeV} \sim 2.1\sigma$ after look-elsewhere)
Complete Set of Benchmark Scenarios (arXiv:1302.7033)

BR(h → γγ) enhanced

BR(h → ττ) reduced

BR(gg → h) reduced

MSSM interpretations
Vector Boson Fusion / Scattering

- Important to understand electroweak symmetry breaking → B. Jäger
- First “beautiful” experimental results appear → N. Chanon
  - Like-sign WW scattering, evidence for el.weak contributions → potential for 5σ observation in Run-2
- Exclusive $\gamma\gamma \rightarrow WW$ production gives so far best limits on $WW\gamma\gamma$ coupling → Important research field in Run-2 and HL-LHC
Theory
Many interesting theory talks presented at this workshop

- It seems that the theoretical progress keeps pace with experimental progress;

- Important work on the (N)NLO front
  - Approximate $N^3LO$ calculation of gluon-fusion progress $\Rightarrow$ S. Forte
  - NLO and NNLO calculation for Higgs boson pair production $\Rightarrow$ M. Steinhauser
  - NLO calculations for vector boson scattering $\Rightarrow$ B. Jäger

- Progress in Resummation, Higgs $p_T$ spectrum
  - HRws (treatment of heavy quarks) $\Rightarrow$ M. Grazzini
  $\Rightarrow$ A. Vicini

- Exclusive Jet bins / Jet veto efficiencies $\Rightarrow$ A. Banfi

- Off shell cross sections, Interferometry $\Rightarrow$ C. Williams
  $\Rightarrow$ S. Hoeche

- Higgs mass and potential, UV behaviour, naturalness $\Rightarrow$ W. Skiba
• Continuous progress on theoretical calculations; $N^3NLO$ (Anastasiou et al, 2014) and $N^3LL$ resummation (almost) (Bonvini et al).

- Uncertainties might decrease slowly ($\mu_R, \mu_F, \text{pdf}, \alpha_s$)
- Inclusion of top and bottom mass effects at NNLO+NNLL desirable in HRes ($p_T^H$)

Future: would be nice to come up with an updated “cross-section recommendation” and the related uncertainties at 8 and 13 TeV

→ Higgs cross section working group

→ Experiments: measurement of unfolded differential distributions ($P_T^H$ et al.. is essential to validate / test also Monte Carlo modelling)
Jet Vetos and Substructure

- Experimental motivation is very clear;
- Split into jet bins
  → increase of sensitivity
  → separate background components
    (data-driven estimates)

- Resummation of large logarithms needed to reduce uncertainties on jet-veto efficiencies, but uncertainties are still sizeable at NNLO+NNLL;
- Inclusion of top- and bottom-mass effects slightly increases uncertainty

- Boosted Jets (important for Run 2):
  New insights from analytical resummation methods
  → potential for improved tools / taggers
• Higgs Boson Couplings Beyond the Standard Model
  Effective Field theory approach as a model-independent approach
to study deviations from the SM

• Global Fits to Higgs signal strength and couplings

→ E. Massó

→ D. Lópes-Val

→ We (experimentalists and theorists) need an interface / dictionary
Analysis Tools

- Tools to describe BSM Higgs boson production
  - MSSM and beyond, e.g. general 2HDM
  - Anomalous couplings
  - Include effective Field theory approach

- Matrix element methods in Higgs phenomenology

- B-tagging at high luminosity

- Top taggers / Boosted jets

→ A. Vicini

→ M. Spannovsky

→ D. Jennens, S. Zenz
Future Colliders

- Several talks on Higgs boson potential at future colliders
- Higgs couplings at future hadron colliders I. Law
- Higgs couplings at future lepton colliders ILC K. Fujii
- Experimental studies of hh production J. Alison
  Higgs boson self coupling
- Future precision Higgs measurement an EW observables B. Hennig

A personal view:
- Important to explore full LHC potential in medium and log term (Run-2, HL-LHC)
- Potential of HL-LHC need to be better understood, more work to be done,
  e.g. Higgs boson self coupling
  high priority issues: Higgs profile, Vector boson scattering, Searches … Higgs portal
- Decision on next machine will depend on Run-2 outcome, …
Towards Run-2

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma, \gamma\gamma^*$
- Muons $\mu\mu$
- LFV $\mu\tau, e\tau$

Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with $H$ in the final state (ZH, WH, HH)

$H^0$

…and More!
- FCNC top decays
- Di-Higgs production
- Trilinear couplings prospects
- Etc…

One of the first goals: focus our efforts to extract most of the physical content of our data!
Maximization of Physics Output and Interpretation requires a close collaboration between experimentalists and theorists

The Higgs cross section working group must continue to play a key rôle:

- Predictions of cross sections
- Related uncertainties!
- PDF uncertainties must be addressed (how much can they be reduced if LHC data are included)
- Differential distributions
- Framework for CP-mixture
- Effective Field theory approach!
- Further interfaces might also be discussed there (unfolded fiducial cross-section)
THANKS to the Organizers of the Conference for the fantastic meeting!
In particular to Giampiero and Chiara

… and to all Speakers for presenting such a wealth of interesting and exiting results!