Results on Higgs boson from the ATLAS experiment

Rosi Nicolaidou
CEA IRFU-SPP
On behalf of ATLAS collaboration
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Back in time (50 years ago...)
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Back in time (50 years ago...)

1964  Brout & Englert, Higgs, Gouralnik, Hagen & Kibble
1968  “Higgs” mechanism used in the Standard Model formulation
1983  Discovery of W, Z
2000  LEP: limits $m_H > 114.4$ GeV
2011  LHC: $130 < m_H < 550$ GeV, indications of $m_H \sim 125$ GeV?
Tevatron: $156 < m_H < 175$ GeV,
2012  LHC: Discovery of a new particle
2013  Nobel price

Francois Englert and Peter Higgs receive the 2013 Nobel Prize for: "the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the Atlas and CMS experiments at Cern’s Large Hadron Collider."
**LHC Run 1 (2010-2012):** In less than 3 years
- we moved from *exclusion limits* to
- *discovery* and properties measurements
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- **discovery** and properties measurements
Introduction

LHC Run 1 (2010-2012): In less than 3 years
• we moved from exclusion limits to discovery and properties measurements

31/07/2014  ICNFP 2014, Rosy Nicolaidou
Introduction

**LHC Run 1 (2010-2012):** In less than 3 years

- we moved from **exclusion limits** to **discovery** and properties measurements
Rich and extensive program
- Property measurements
  - mass, couplings, cross section, width, spin&parity
- Rare decays
  - e.g. $H \rightarrow Z \gamma$, $H \rightarrow \mu \mu$
- Searches beyond the Standard Model
  - 2HDM models, $H\pm$
- Using the Higgs as tool for discovery
  - e.g. Portal to dark matter …

List of ATLAS public Higgs results
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
~3000 scientists
178 Institutes
38 Countries
Outstanding performance of the LHC

**ATLAS** Preliminary

- **LHC Delivered**
- **ATLAS Recorded**
- **Good for Physics**

2012, $\sqrt{s} = 8$ TeV
- Delivered: 22.8 fb$^{-1}$
- Recorded: 21.3 fb$^{-1}$
- Physics: 20.3 fb$^{-1}$

2011, $\sqrt{s} = 7$ TeV
- Delivered: 5.46 fb$^{-1}$
- Recorded: 5.08 fb$^{-1}$
- Physics: 4.57 fb$^{-1}$
Outstanding performance of the LHC

Excellent ATLAS performance

<table>
<thead>
<tr>
<th>Luminosity fb⁻¹</th>
<th>Data taking ε%</th>
<th>data used in physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6 ( @7 TeV)</td>
<td>94%</td>
<td>90%</td>
</tr>
<tr>
<td>23.3 ( @8 TeV)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Outstanding performance of the LHC

Excellent ATLAS performance

Luminosity fb⁻¹ | Data taking ε % | Data used in physics
---|---|---
5.6 (@7 TeV) | 94% | 90%
23.3 (@8 TeV) | 90% |

Challenge ➔ high pileup rates
• Trigger, computing, reconstruction of physics objects

High performance of world wide grid computing to cope with processing of the totality of the data and simulated events

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1. Total inelastic
2. B physics
3. Jets
4. W,Z physics
5. top physics
6. Higgs physics

Background rejection very important at LHC
Testing the Standard Model at LHC

1. Total inelastic
2. B physics
3. Jets
4. W,Z physics
5. top physics
6. Higgs physics

Background rejection very important at LHC

2011+2012 data set
- W (l+X) ~ 100M events
- Z(ll) ~ 10M events
- tt(l+X) ~ 0.4 M events

- Standard Model processes and detector performance well understood
- background to Higgs physics
Higgs boson production at the LHC

Huge effort from theory to calculate cross-section at (N)NLO
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Higgs boson production at the LHC

Huge effort from theory to calculate cross-section at (N)NLO
Higgs boson production at the LHC

Huge effort from theory to calculate cross-section at (N)NLO

<table>
<thead>
<tr>
<th></th>
<th>ggF</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section</td>
<td>19.5 pb</td>
<td>1.6 pb</td>
<td>1.1 pb</td>
<td>0.1 pb</td>
</tr>
<tr>
<td>Events produced</td>
<td>~0.5 M</td>
<td>~40K</td>
<td>~20K</td>
<td>~3K</td>
</tr>
</tbody>
</table>

Gluon fusion ggF

Vector boson fusion VBF

Associated production with W, Z, top
Higgs boson decay modes

All decay modes available at ~125 GeV!
Higgs boson decay modes

All decay modes available at \( \sim125 \text{ GeV} \)!
Higgs boson decay modes

All decay modes available at \( \sim 125 \text{ GeV} \)!

<table>
<thead>
<tr>
<th>Bosonic decays</th>
<th>WW 21.5%</th>
<th>ZZ 2.6%</th>
<th>( \gamma \gamma ) 0.23%</th>
<th>( \gamma \gamma ) 0.15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermionic decays</td>
<td>bb 57.7%</td>
<td>( \tau \tau ) 6.3%</td>
<td>( \mu \mu ) 0.02%</td>
<td>cc 3%</td>
</tr>
</tbody>
</table>
## Higgs boson searches: summary table

<table>
<thead>
<tr>
<th>Channel</th>
<th>H→γγ</th>
<th>H→ZZ (4l)</th>
<th>H→WW (lvlv)</th>
<th>H→ττ</th>
<th>H→bb</th>
<th>H→Zγ</th>
<th>H→μμ</th>
<th>Invisibe</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>VBF</td>
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<td>✓</td>
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<tr>
<td>VH</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>Resonant</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Invisible</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
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<td>✓</td>
</tr>
</tbody>
</table>

Channels that were combined
Measuring the Higgs boson mass

\( H \rightarrow \gamma \gamma \) High resolution channels
Measuring the Higgs boson mass

$H \rightarrow \gamma \gamma$  

**High resolution channels**

- Rare decay ~2 %, $\sigma \times BR \sim 50$ fb ($m_H=126$ GeV)
- Two isolated photons
- Narrow resonance on top of a continuous background
- High background (γγ continuum, γ-jet, jet-jet)
- Background extrapolated from side bands in data
- Signal/Background ~0.03
- γγ resolution key ingredient of this analysis
- To increase analysis sensitivity, events are classified w.r.t their production mode and in inclusive categories with different resolution and S/B
Measuring the Higgs boson mass

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$H \rightarrow \gamma\gamma$

- $\sigma \times BR \sim 2.5 \text{ fb (}m_H \ 125 \text{ GeV)}$
- Golden channel: Simple topology of 4 isolated leptons from primary vertex
- Narrow resonance on top of smooth background
- Background from $ZZ^*$, $Z$+jets, $Z$+bb, $tt$
- Signal/Background $\sim 2$
- Use of 2D information $m_{4l}$ and a BDT to suppress $ZZ^*$ background

$H \rightarrow ZZ^* \rightarrow 4l$
Calibration in 3 steps:
• Electronics calibration
• MC based MVA regression
  • accurate material description
• In situ absolute calibration with $Z \to e^+e^-$
Improved calibration of electrons, photons

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Uncertainty on energy scale:
• Photons from H decay
  • $\sim 0.3\%$
• Electrons from 10 (45) GeV
  • 04 -1 (0.04%) %

Validation of calibration uncertainties
• Correct simulation to match resolution and momentum scale observed in data
• Corrections derived from fits to \( m_{\mu\mu} \) distributions for \( Z \rightarrow \mu\mu, J/\psi \rightarrow \mu\mu \)
Improved calibration of muons

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arXiv:1407.3935
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- Momentum scale corrections $0.04 - 0.2\%$ depending on the $\eta$ region
- Momentum scale corrections and uncertainties of the same order

arXiv:1407.3935
Measuring the Higgs boson mass

$H \rightarrow \gamma \gamma$

ATLAS

- Data
- Combined fit:
  - Signal+background
  - Background
  - Signal

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

$\Sigma$ weights / GeV
$\Sigma$ weights - fitted deg

$\Sigma_{mm} \, [GeV]$

arXiv:1406.3827
Measuring the Higgs boson mass

$H \rightarrow \gamma\gamma$

Previous measurement:
$m_H = 126.8 \pm 0.2 \text{(stat)} \pm 0.7 \text{(syst)} \text{GeV}$

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

arXiv:1406.3827
Measuring the Higgs boson mass

H → γγ

$\sum \text{weights} / \text{GeV}$

$\sum \text{weights} - \text{fitter dig}$

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New
Measuring the Higgs boson mass

Previous measurement:
\( m_H = 126.8 \pm 0.2 \text{(stat)} \pm 0.7 \text{(syst)} \text{GeV} \)

Previous measurement:
\( m_H = 124.3^{+0.6}_{-0.5} \text{(stat)}^{+0.5}_{-0.3} \text{(syst)} \text{GeV} \)

New measurement:
\( m_H = 125.98 \pm 0.42 \text{(stat)} \pm 0.28 \text{(syst)} \text{GeV} \)

New measurement:
\( m_H = 124.51 \pm 0.52 \text{(stat)} \pm 0.06 \text{(syst)} \text{GeV} \)

arXiv:1406.3827
### Measuring the Higgs boson mass

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<tr>
<th>Decay Channel</th>
<th>Mass (stat) ± (syst) GeV</th>
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<td><strong>Combined mass</strong></td>
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0.3 % precision measurement still statistical dominated
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Signal strength $\mu = \frac{\text{measured rate}}{\text{SM predicted rate}}$

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<td>$H \rightarrow \gamma\gamma$</td>
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<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$1.66 + 0.45 - 0.38$</td>
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### Measuring the Higgs boson mass

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<th>Mass (GeV)</th>
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<td>$H \rightarrow \gamma\gamma$</td>
<td>$\mu_{(<a href="mailto:mH@125.98GeV">mH@125.98GeV</a>)}^{\gamma\gamma} = 1.29 \pm 0.30$</td>
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<tr>
<td>$H \rightarrow ZZ^{*} \rightarrow 4\ell$</td>
<td>$\mu_{(<a href="mailto:mH@124.51GeV">mH@124.51GeV</a>)}^{ZZ^{*} \rightarrow 4\ell} = 1.66 + 0.45 - 0.38$</td>
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Mass difference between the two channels

$\Delta m_H = 1.47 \pm 0.72$ GeV

Compatibility @ 2 $\sigma$ level
Constraints on the H width: direct measurement

- SM H width ~ 4MeV
  - But can increase significantly by non SM contributions
- Constrained directly from the analyses in two channels
  - $H \rightarrow \gamma \gamma$
  - $H \rightarrow ZZ \rightarrow 4l$ analysis:
    - used an event-by-event convolution with the detector response line-shape technique for this measurement
- Direct measurement limited by much larger detector resolution (1-2 GeV)
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$H \rightarrow \gamma \gamma$: $\Gamma_H < 5$ GeV
(expected < 6.2 @ $\mu=1$)

$H \rightarrow ZZ^* \rightarrow 4\ell$: $\Gamma_H < 2.6$ GeV
(expected < 6.2 @ $\mu=1$)
Constraints on the H width: off-shell H→ZZ analysis

Measurements of the on-shell and off-shell cross section can constraint $\Gamma_H$

$$
\sigma_{on-shell}^{gg\rightarrow H^*\rightarrow ZZ} \sim \frac{g_{ggH(on-shell)}^2 g_{HZZ(on-shell)}^2}{\Gamma_H}
$$

$$
\sigma_{off-shell}^{gg\rightarrow H^*\rightarrow ZZ} \sim g_{ggH(off-shell)}^2 g_{HZZ(off-shell)}^2
$$

Assuming same on-shell and off-shell couplings
**Constraints on the H width: off-shell $H \rightarrow ZZ$ analysis**

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\]

Assuming same on-shell and off-shell couplings

\[
\frac{\sigma_{\text{off-shell}}^{gg\rightarrow H\rightarrow ZZ}}{\sigma_{\text{on-shell}}^{gg\rightarrow H\rightarrow ZZ}} \sim \Gamma_H
\]

---

**Contributions in the region of $m_{ZZ} > 2m_Z$ from**

- **S**: Signal,
- **B**: Background and

S-B Interference (large and negative)

Large theoretical uncertainties

- $gg\rightarrow ZZ$ known at LO: with no (N)NLO $k$ factor
**Constraints on the H width: off-shell H → ZZ analysis**

Measurements of the on-shell and off-shell cross section can constraint $\Gamma_H$

\[
\sigma_{\text{on-shell}}^{gg \to H^* \to ZZ} \sim \frac{g_{ggH(\text{on-shell})}^2}{\Gamma_H} g_{HZZ(\text{on-shell})}^2
\]

\[
\sigma_{\text{off-shell}}^{gg \to H^* \to ZZ} \sim \frac{g_{ggH(\text{off-shell})}^2}{\sigma_{\text{on-shell}}^{gg \to H \to ZZ}} g_{HZZ(\text{off-shell})}^2
\]

Assuming same on-shell and off-shell couplings

Contributions in the region of $m_{ZZ} > 2m_Z$ from S: Signal, B: Background and
S-B Interference (large and negative)

Large theoretical uncertainties
- $gg\to ZZ$ known at LO: with no (N)NLO $k$ factor

Analysis strategy
- Inclusive with no cuts in $N_{jets}$, $p_T^{ZZ}$
- Increase statistics: look at both $H \to ZZ^* \to 4l$, $llvv$

Results expressed in

\[
R_H^B = \frac{k_{gg \to ZZ}}{k_{gg \to H \to ZZ}} = [0.5, 2]
\]

- $k_{gg \to ZZ} \sim k_{gg \to H \to ZZ}$ soft-collinear approximation assumed
- Main result quoted for

\[
R_H^B = 1
\]
Constraints on the H width: off-shell $H \rightarrow ZZ$ analysis

$H \rightarrow ZZ \rightarrow 4l$


- Off peak region 220 - 1000 GeV
- ME discriminant to separate $gg \rightarrow H$ from $gg \rightarrow ZZ$ $qq \rightarrow ZZ$
- Limits on $\mu_{\text{off-shell}}$ CLs method
**Constraints on the H width: off-shell H→ZZ analysis**

**H→ZZ→4l**
- Off peak region: 220-1000 GeV
- ME discriminant to separate gg→H from gg→ZZ qq→ZZ
- Limits on μ\text{off-shell} CLs method

**H→ZZ→llvv**
- Analysis: PRL 112(2014)
- Off peak region: m_T^{ZZ} > 350 GeV
- Limits on μ\text{off-shell} CLs method
Constraints on the H width: off-shell H → ZZ analysis

\( H \rightarrow ZZ \rightarrow 4l \)
• Off peak region 220 -1000 GeV
• ME discriminant to separate gg→H
from gg→ZZ qq→ZZ
• Limits on \( \mu_{\text{off-shell}} \) CLs method

\( ATLAS\text{-CONF-2014-042} \)

\( H \rightarrow ZZ \rightarrow llvv \)
Analysis: PRL 112(2014)
• Off peak region \( m_T^{ZZ} > 350 \) GeV
• Limits on \( \mu_{\text{off-shell}} \) CLs method

Combine 4l, 2l2v to fit \( \mu_{\text{off-shell}} \)
Include low mass region (4l) results
Assuming \( g_{\text{on-shell}} = g_{\text{off-shell}} \)
From ratio \( \mu_{\text{on-shell}} / \mu_{\text{off-shell}} \rightarrow \Gamma_H \)

\[ \Gamma_H / \Gamma_H^{\text{SM}} < 5.7 \]

\( \begin{array}{|c|c|c|}
\hline
\( R_H^B \) & Observed & Expected \mu=1 \\
\hline
0.5 & 4.8 & 7 \\
1 & 5.7 & 8.5 \\
2 & 7.7 & 12 \\
\hline
\end{array} \)

31/07/2014
Can probe various H boson properties
- Spin, parity, jets, $H_{PT}$, production modes
Measure $d\sigma/dX$, $X=Pt^{H}, y^{H}, P_{T}^{jets}, N_{jets}$ ...
Design analyses with minimal model dependence
- Define fiducial region and
- Compare with various theoretical predictions
Can probe various H boson properties
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Measure $d\sigma/dX$, $X=P_{T}^{H}$, $y^{H}$, $P_{T}^{jets}$, $N_{jets}$ ...

Design analyses with minimal model dependence
- Define fiducial region and
- Compare with various theoretical predictions

**H\rightarrow ZZ\rightarrow 4l channel**

- Use standard analysis signal region $m_{H}$ [118-129]
- Fiducial cross-section: from fits to mass spectrum
- Cut and count method for differential measurement
  - Estimate bin by bin yields after background extraction and detector efficiency and resolution effects correction
- Compare three generators
  - POWHEG: used for ggF, VBF, up to NLO corrections
  - HRES2.2: up to NNLO in QCD + NNLL re-summation in ggF
  - MINLO: Multiscale improved NLO better jet related variables

**Differential Cross section**

<table>
<thead>
<tr>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWHEG: 30%</td>
</tr>
<tr>
<td>MINLO: 23%</td>
</tr>
<tr>
<td>HRES2: 16%</td>
</tr>
</tbody>
</table>

**Comparison**

| Generator | Value |
|------------|
| POWHEG: 37% |
| MINLO: 28% |
Can probe various H boson properties
• Spin, parity, jets, $H_{\text{PT}}$, production modes
Measure $d\sigma/dX$, $X=P_T^H$, $y^H$, $P_T^{\text{jets}}, N_{\text{jets}}$ …
Design analyses with minimal model dependence
• Define fiducial region and
• Compare with various theoretical predictions

H→ZZ→4l channel
• Use standard analysis signal region $m_H$ [118-129]
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  • POWHEG: used for ggF, VBF, up to NLO corrections
  • HRES2.2: up to NNLO in QCD + NNLL re-summation in ggF
  • MINLO: Multiscale improved NLO better jet related variables

Inclusive cross-section in fiducial region
\[ \sigma_{\text{fid}} = 2.11^{+0.53}_{-0.47} \text{(stat)} \pm 0.08 \text{(syst)} \text{ fb} \]

Predicted by SM
\[ \sigma_{\text{fid}}^{\text{SM}} = 1.30 \pm 0.13 \text{ fb} \]
H→γγ channel

• Signal extraction: fit m_{γγ} in each bin
• Fiducial cross-section: Standard analysis cuts and definition of 7 fid regions
  • w.r.t Njets, VBF-enriched, 1 lepton

\[ \sigma_{\text{fid}} = 43.2 \pm 9.4 (\text{stat})^{+3.2}_{-2.9} (\text{syst}) \text{ fb} \]

• Differential cross-section
  • test of 12 differential distributions \( \frac{d\sigma}{dX} \), \( X = P_T^H, y^H, P_T^{\text{jets}}, \text{Njets} \ldots \)

arXiv:1406.4222
Differential Cross section II

H→γγ channel

• Signal extraction: fit m_{γγ} in each bin
• Fiducial cross-section: Standard analysis cuts and definition of 7 fid regions
  • w.r.t Njets, VBF-enriched, 1 lepton

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• Differential cross-section
  • test of 12 differential distributions \( d\sigma/dX, X=P_T^H, y^H, P_T^{jets}, \text{Njets} \) …

1st moment of distributions = mean

Reasonable agreement with SM prediction

arXiv:1406.4222
Spin CP analysis

- SM Higgs boson has $J^P = 0^+$
- The $H \rightarrow \gamma\gamma$ decay mode excludes spin-1 possibility (Landau Yang theorem)
- Observed decay channels into $\gamma\gamma, ZZ^*, WW^*$ imply integer spin
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Studies of $J^P = 0^-,1^{\pm},2^+$ possible states performed
- $H \rightarrow ZZ^*$ for $0^-$
- $H \rightarrow WW, ZZ$ for $J=1^{\pm}$
- $H \rightarrow \gamma\gamma,ZZ^*,WW^*$ for $2^+$ (and a $2^-$ hybrid model)
- For $J^P=2^+$ a “graviton” like with minimal coupling model is used with an unknown fraction of the two production mechanisms qq and gg

Use of different discriminants per channel
- $H \rightarrow \gamma\gamma$ ($\gamma$ production angle in the $\gamma\gamma$ center-of-mass frame)
- $H \rightarrow ZZ, m_{12}, m_{34} (Z, Z^*)$, 5 angles $\theta^*, \phi, \theta_1, \theta_2$
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$J^P = 0^+$ strongly favored
$0^-,1^+,1^-,2^+$ excluded $> 97.8\%$ CL
H→ττ decays: evidence of H couplings to leptons
VBF $\tau^+\tau^-$ analysis
- 3 final states ($e\tau_h$, $\mu\tau_h$, $\tau_\tau\tau_h$)
- Challenges:
  - Huge background mainly from $Z\rightarrow\tau\tau$
  - $m_{\tau\tau}$ resolution (due to neutrinos)
    - 15-20% achieved
VBF $\tau^+\tau^-$ analysis
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Observed excess significance $4.1\sigma$
Expected @ $m_H = 125$ GeV $3.2\sigma$
Investigate if our measurements are consistent with H couplings to SM particles

- At LHC we measure \((\sigma \times Br)\)
- Strategy: Measure \((\sigma \times Br) (aa \rightarrow H \rightarrow ff)\) and test deviations on \(\sigma_{aa}, \Gamma_{ff}, \Gamma_H\)
- Basic assumption: One single narrow CP-even resonance @mH~125 GeV with the same couplings as in the SM
- Parameterize deviations with coupling scale factor \(k_a\)
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- Parameterize deviations with coupling scale factor \(k_a\)

for example

\[
\sigma \ Br_{gg \rightarrow H \rightarrow \gamma\gamma} = \frac{\sigma_{gg \rightarrow H}^{SM} \ Br_{H \rightarrow \gamma\gamma}^{SM} \ k_g^2 \ k_\gamma^2}{k_H^2}
\]

\[
k_\gamma^2 \sim 1.59k_W^2 - 0.66k_wk_t + 0.07k_t^2
\]

\[
k_g^2 \sim 1.06k_t^2 - 0.07k_tk_b + 0.01k_b^2
\]

\[
k_{VBF}^2 \sim 0.74k_W^2 + 0.26k_Z^2
\]

\[
k_H^2 \sim 0.57k_b^2 + 0.22k_W^2 + 0.09k_g^2 + 0.06k_\tau^2 + 0.03k_Z^2 + 0.03k_c^2
\]
Assuming:
- One scale factor for fermions: $k_F = k_b = k_t = k_\tau$
- One scale factor for vector bosons: $k_V = k_W = k_Z$
- No new particles in production or decay

Negative sign ($\kappa_t$ relative to $\kappa_V$) disfavored

$\kappa_V [1.07,1.23]$  $\kappa_F [0.84,1.16]$ @ 68%CL
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One scale factor for fermions $k_F = k_b = k_t = k_\tau$
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$\kappa_V [1.07,1.23]$ $k_F [0.84,1.16] @ 68\%$CL

Measuring the couplings within the benchmark framework as defined by the LHC WG
No significant deviation from SM
Probing rare decays

$H \rightarrow \mu^+\mu^-$ check lepton universality to $H$ couplings

**Analysis:**
Consider 2 production mechanisms $ggF$, VBF

Analysis “a la $H \rightarrow \gamma\gamma$” analytic background model

**Results at 95% CL:**
$\sigma \times Br < 7.0 \ (7.2)\ \sigma \times Br_{SM}$

Universal couplings ~ 260 x SM
Probing rare decays

$H \rightarrow \mu^+\mu^-$  check lepton universality to H couplings

Analysis :
Consider 2 production mechanisms $ggF$, $VBF$
Analysis “a la $H \rightarrow \gamma\gamma$“ analytic background model

Results at 95% CL:
$\sigma \times Br < 7.0$ (7.2) $\sigma \times Br_{SM}$
Universal couplings $\sim 260 \times SM$

$H \rightarrow Z\gamma$  check new BSM particles running in the loop

Analysis :
Split events in categories to increase sensitivity
Use of analytic background model “a la $\gamma\gamma$”

Results at 95% CL:
$\sigma \times Br < 11$ (9) $\sigma \times Br_{SM}$
Search for new particles that couple very weakly to SM particles except the Higgs boson→WIMPs

- Direct search for $H \rightarrow$ invisible ($E_T^{\text{miss}}$)
  - $ZH$ production, $Z \rightarrow ll/bb$
  - VBF (2 forward-back jets with large rapidity gaps)

- Indirect search: modification of couplings to photons and gluons ($k_\gamma, k_g$) due to contribution from new particles in loops

No signal candidates observed
No deviation from SM couplings
Searches beyond the SM: Higgs portal to Dark Matter

Search for new particles that couple very weakly to SM particles except the Higgs boson→WIMPs

- Direct search for $H \rightarrow \text{invisible} \left( E_{T}^{\text{miss}} \right)$
  - ZH production, $Z \rightarrow ll/bb$
  - VBF (2 for-back jets with large rapidity gaps)

- Indirect search: modification of couplings to photons and gluons ($k_{\gamma}, k_{g}$) due to contribution from new particles in loops

- Compare with direct WIMP exper. and interpret the results in terms of WIMP-nucleon scattering via $H$ boson exchange
- Assumption $Br_{\text{inv}} = Br(H \rightarrow \chi \chi)$, $m_{\chi} < m_{H}/2$

No signal candidates observed
No deviation from SM couplings

Stringent limits up to $m_{\chi} < m_{H}/2$
What do we know so far?

- ATLAS experiment has analyzed the totality of Run I data: **observation of a new particle: “the Higgs boson”**
  - Rich and extensive program of measurement of its properties defined

- Improved measurement of its mass:
  \[
  \text{ATLAS: } m_H = 125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)} \text{ GeV}
  \]
  - Consistent with SM from EW fits with no addition
  \[
  \text{In SM: } m_H = 94^{+29}_{-24} \text{ GeV}
  \]

- Compatible with spin-0\(^+\) state
  - Alternative states 0\(^-\), 1\(^\pm\), 2\(^+\) excluded at > 99% C.L

- Couplings measurements compatible with the SM prediction
  - Precision of these measurements at ≥20% level
✓ These results already rule out some models

• example: 4th generation of quarks
  o Higgs production dominant mechanism is gluon fusion induced by loops with top quarks in there;
    • if a heavier quark existed it would have increased the rate

✓ Direct searches of particles beyond the SM have been performed also
  o No signs for physics beyond the SM so far.

✓ Run I data analyses are being finalized
  o But many studies will remain statistically limited

Certainly not the end of this exciting adventure

✓ Run II period starting at 2015 with more statistics and at higher energy will allow us to do more precise studies