Discovery of the Higgs boson in ATLAS at the LHC

Aleandro Nisati
INFN-Roma, Universita di Roma “La Sapienza”
Viernes IVICFA de Física Experimental
Valencia, 30 de Noviembre 2012
• Why we need the Higgs boson?
• The Large Hadron Collider
• The ATLAS detector
• Higgs boson searches at the LHC with ATLAS
  – Will focus on the low mass region
• Higgs-like boson measurements & prospects
• Conclusions
The Standard Model

• The Standard Model of particles and fields describes the properties of the fundamental constituents of (visible) matter in the Universe.

• It describes successfully a large variety of physics results obtained at accelerator experiments.

• One fundamental piece is missing – but perhaps discovered very recently at the Large Hadron Collider: the Higgs boson.
The existence of the Higgs boson was postulated for the first time in 1964:


 based on earlier theoretical work that introduced spontaneous symmetry breaking into condensed matter and particle physics:


These ideas were incorporated into the Standard Model in 1967 by S. Weinberg and A. Salam


and demonstrated in 1971 by G. ‘t Hooft, to allow a calculable and predictive unified theory and weak and electromagnetic interactions

Some history\(^1\)… (cont.)

- From 1973 onwards, an impressive successful list of discoveries and experimental tests:
  - 1973: discovery of the neutral currents
  - 1974: discovery of the charm quark
  - 1983: discovery of the $W^\pm$ and $Z^0$ gauge bosons
  - 1995: discovery of the top quark
  - 2012: discovery of the SM Higgs boson ??

Spontaneously broken symmetries in hep: the pioneers

Kibble, Guralnik, Hagen, Englert, e Brout; on the right-hand: Higgs
The Brout-Englert-Higgs mechanism

• Local Gauge invariance is an important property of the Standard Model theory
• Mass term of W/Z bosons and fermions is not gauge invariant
• But W and Z have a mass (as well as fermions)
• \(\Rightarrow\) these particles acquire mass by some other mechanism or interaction, without breaking local gauge and Lorentz invariance
• The SM hypothesizes a scalar field which is responsible for this effect: the Higgs field
Higgs boson couplings

- The SM Higgs boson couples to massive vector bosons and fermions. The couplings depend on the particle and Higgs boson mass;
  - $H W^+ W^-$, $H ZZ$
  - $H ttbar$, $H bbbar$, $H ccbar$
  - ...
  - $H \tau^+ \tau^-$, $H \mu^+ \mu^-$, $H e^+ e^-$

- At the Next-to-Leading-Order (loop level) the Higgs boson can couple also with massless bosons, such as $\gamma$ and $g$ (gluon-gluon)
  - This has an important impact on Higgs production (and decay as well)

Example: $HWW$
The 95% one-sided confidence level upper limit on $m_H$ (taking the theory-uncertainty band into account) is 158 GeV. The 95% C.L. lower limit on $m_H$ of 114.4 GeV obtained from direct searches at LEP-I I and the region between 158 GeV and 175 GeV excluded by the Tevatron experiments are not used in the determination of this limit (July 2010).
Direct Higgs boson searches

- Direct searches were made with two major projects:
  - LEP-II: $e^+e^- \sqrt{s}$ up to 210 GeV
    - ALEPH, DEPLHII, L3, OPAL
  - Tevatron (ppbar $\sqrt{s} = 1.98$ TeV)
    - CDF, D0
- Results:
  - Exclusion on the Higgs boson limits were set:
    - LEP: $m_H < 114.4$ GeV excluded at 95% CL
    - Tevatron: $158 < m_H < 175$ GeV excluded at 95% CL
The Large Hadron Collider (LHC)
The Experiments at the LHC
The Large Hadron Collider

proton-proton collider $\sqrt{s}=14$ TeV (design); in 2012: $\sqrt{s}=8$ TeV
### The Large Hadron Collider

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012(*)</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [TeV]</td>
<td>3.5</td>
<td>3.5</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>$\beta^*$ [m] (IP1,IP2,IP5,IP8)</td>
<td>3.5, 3.5, 3.5, 3.5</td>
<td>1.5, 10, 1.5, 3.0</td>
<td>.6, 3,.6, 3</td>
<td>0.55, 10, 0.55, 10</td>
</tr>
<tr>
<td>Emittance [μm] (start of fill)</td>
<td>2.0 – 3.5</td>
<td>1.5 – 2.2</td>
<td></td>
<td>3.75</td>
</tr>
<tr>
<td>Transverse beam size at IP1&amp;5 [μm]</td>
<td>60</td>
<td>28</td>
<td></td>
<td>16.7</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$1.2\times10^{11}$ p</td>
<td>$1.5\times10^{11}$ p</td>
<td>$1.7\times10^{11}$ p</td>
<td>$1.15\times10^{11}$ p</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>368</td>
<td>1380</td>
<td>1380</td>
<td>2808</td>
</tr>
<tr>
<td>Number of collisions (IP1 &amp; IP5)</td>
<td>348</td>
<td>1318</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Stored energy [MJ]</td>
<td>28</td>
<td>110</td>
<td></td>
<td>360</td>
</tr>
<tr>
<td>Peak luminosity [cm$^{-2}$s$^{-1}$]</td>
<td>$2\times10^{32}$</td>
<td>$3.65\times10^{33}$</td>
<td>$7.7\times10^{33}$</td>
<td>$1\times10^{34}$</td>
</tr>
<tr>
<td>Max delivered lum. (1 fill) [pb$^{-1}$]</td>
<td>6.23</td>
<td>122</td>
<td>237.32</td>
<td>-</td>
</tr>
<tr>
<td>Longest Stable Beams fill [hrs]</td>
<td>12:09</td>
<td>25:59</td>
<td>20:5</td>
<td>-</td>
</tr>
</tbody>
</table>

(*) not official
The ATLAS detector
The ATLAS detector

Valencia had a major involvement on the ATLAS Forward Silicon Tracker construction and its corresponding readout electronics. Now very active on Inner Detector Alignment, SCT maintenance and data analysis.

Valencia has been responsible for the design, assembly, test and commissioning of the Read Out Drivers (RODs) for the Hadronic Tile Calorimeter. The group has also built a large fraction of this detector. Now very active on calibration and on data analysis.

ATLAS Tile Calorimeter during construction

ATLAS SCT (SemiConductor Tracker) during installation
Valencia also very active on computing: Tier2 computing center contributing to the distributed data analysis and MC sample generation.
The CMS Experiment
The ATLAS physics programme

- The understanding of the origin of the electroweak symmetry breaking is one of the most important items of the scientific programme of the experiment: search for the Higgs boson(s) predicted by SM and beyond
- Many other topics are at the top of this programme
- Searches for New Physics, as predicted by Supersymmetry and many other models beyond SM (Exotics)
- Standard Model processes study, in particular
  Top quark physics: important contribution from Valencia with Maria Jose Costa as Top Group co-convener
- B-Physics
- Heavy Ion
Standard Model Higgs boson search
SM Higgs production at the LHC

- Gluon fusion is the dominant mechanism for Higgs production at present hadron colliders
  - At LHC this is x10 higher than at Tevatron!
- Associated production is also important: qqH, VH, ttH
Higgs cross-sections

- **H→γγ**: rare channel, but the best for low mass
- **H→ZZ(*)**:  
  - → 4l: golden channel  
  - → llvv: good for high mass  
  - → llbb: also high mass
- **H→WW(*)**:  
  - →lllv: very important in the intermediate mass range  
  - → llqq: highest rate, important at high mass
- **H→ττ**: good signal/background, important at low mass, rare
- **Associated prod. H→ bb-bar**  
  - ttH, WH, ZH  
  - It is useful for the discovery  
  - It is very important for Higgs property studies if SM Higgs is discovered

<table>
<thead>
<tr>
<th>m_H, GeV</th>
<th>WW→lllv</th>
<th>ZZ→4l</th>
<th>γγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>159</td>
<td>1.9</td>
<td>54</td>
</tr>
<tr>
<td>150</td>
<td>485</td>
<td>5.9</td>
<td>22</td>
</tr>
<tr>
<td>300</td>
<td>124</td>
<td>5.7</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Higgs cross-sections

- $H \rightarrow \gamma \gamma$: rare channel, but the best for low mass
- $H \rightarrow ZZ(*)$:
  - $\rightarrow 4l$: golden channel
  - $\rightarrow ll\nu\nu$: good for high mass
  - $\rightarrow llbb$: also high mass
- $H \rightarrow WW(*)$:
  - $\rightarrow l\nu l\nu$: very important in the intermediate mass range
  - $\rightarrow lvqq$: highest rate, important at high mass
- $H \rightarrow \tau\tau$: good signal/background, important at low mass, rare
- Associated prod. $H \rightarrow bb$-bar
  - $ttH$, $WH$, $ZH$
  - It is useful for the discovery
  - It is very important for Higgs property studies if SM Higgs is discovered

Events expected to be produced with $\sqrt{s} = 8$ TeV, $L = 1$ fb$^{-1}$

<table>
<thead>
<tr>
<th>$m_H$, GeV</th>
<th>$WW \rightarrow l\nu l\nu$</th>
<th>$ZZ \rightarrow 4l$</th>
<th>$\gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>159</td>
<td>1.9</td>
<td>54</td>
</tr>
<tr>
<td>150</td>
<td>485</td>
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<td>22</td>
</tr>
<tr>
<td>300</td>
<td>124</td>
<td>5.7</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Data sample analysed: $L \sim 4.8$ (2011) + $5.8-13$ fb$^{-1}$ (2012)
$H \rightarrow \gamma \gamma$
H→γγ: event selection

- **Very simple signature**
- Photon identification based both on lateral and longitudinal segmentation of the electromagnetic calorimeter (see illustrations)
- Two high-quality isolated high-\(p_T\) photons
  - \(p_{T1} > 40\) GeV; \(p_{T2} > 25\) GeV
  - \(|\eta_{12}| < 1.37\) and \(< |\eta_{12}| < 2.37\)
- To increase sensitivity, events are classified in 10 categories based on \(\gamma\) rapidity, converted/unconverted, \(p_{T_t}\) (\(p_T^{\gamma\gamma}\) perpendicular to \(\gamma\gamma\) thrust axis in the transverse plane); 2 jets

After all selections, expect (10.7 fb\(^{-1}\), \(m_H \sim 126\) GeV)

- \(~ 170\) signal events (total signal efficiency \(~ 40\%)\)
- \(~ 6340\) background events in mass window

\(\Rightarrow S/B \sim 3\%\) inclusive (\(~ 20\%\) 2jet category)
Mass reconstruction

\[ m^2 = 2P_1P_2(1-\cos \vartheta) \]

\[ \frac{\delta m}{m} = \left( \frac{1}{\sqrt{2}} \right) \frac{\delta P}{P} \oplus \left( \frac{1}{2} \right) \frac{\delta \vartheta}{\tan \vartheta / 2} \]

It is important to measure the photon momentum in space with high resolution:

- **accurate measurement of the photon energy**
- **accurate measurement of the photon direction of flight**

Electron scale and resolution transported to photons using MC (systematics few % from material effects)

Present understanding of calorimeter E response (from Z, J/\(\psi\) \(\rightarrow\) ee, W \(\rightarrow\) ev data and MC):

- **Energy scale at \(m_Z\) known to \(\sim 0.5\)%**
- **Linearity better than 1%** (over few GeV-few 100 GeV)
- **“Uniformity”** (constant term of resolution): 1% (barrel) -1.7 % (end-cap)
Mass reconstruction

\[ m^2 = 2P_1 P_2 (1 - \cos \theta) \]

\[ \delta m/m = \left( \frac{1}{\sqrt{2}} \right) \frac{\delta P}{P} \oplus \left( \frac{1}{2} \right) \frac{\delta \theta}{(\tan \frac{\theta}{2})} \]

It is important to measure the photon momentum in space with high resolution:

- \( \Rightarrow \) accurate measurement of the photon energy
- \( \Rightarrow \) accurate measurement of the photon direction of flight

**ATLAS:**
- high energy resolution
- Measure the photon direction using the longitudinal segmentation of the LAr calorimeter, and fit the \( \gamma \gamma \) production vertex using the pp beam line

\[ 1/N \cdot dN/dm_{\gamma} / 0.5 \text{ GeV} \]

**Mass resolution:**
\[ \sigma (m_H = 120 \text{ GeV}) \approx 1.7 \text{ GeV} \]
The big challenge in 2012

Experiment's design value (expected to be reached at $L=10^{34}$ !)

$Z \rightarrow \mu \mu$ event from 2012 data with 25 reconstructed vertices
# of events selected: 59039

**H→γγ: results**

\[ m_H = 126.5 \text{ GeV} \]

### Background composition

<table>
<thead>
<tr>
<th>Category</th>
<th>( \sqrt{s} = 7 \text{ TeV} )</th>
<th>( \sqrt{s} = 8 \text{ TeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconv. central, low ( p_T )</td>
<td>( N_D )</td>
<td>( N_S )</td>
</tr>
<tr>
<td>Conv. central, low ( p_T )</td>
<td>2054</td>
<td>10.5</td>
</tr>
<tr>
<td>Conv. central, high ( p_T )</td>
<td>97</td>
<td>1.5</td>
</tr>
<tr>
<td>Conv. rest, low ( p_T )</td>
<td>7129</td>
<td>21.6</td>
</tr>
<tr>
<td>Conv. rest, high ( p_T )</td>
<td>444</td>
<td>2.8</td>
</tr>
<tr>
<td>Conv. central, high ( p_T )</td>
<td>1493</td>
<td>6.7</td>
</tr>
<tr>
<td>Conv. rest, low ( p_T )</td>
<td>77</td>
<td>1.0</td>
</tr>
<tr>
<td>Conv. rest, high ( p_T )</td>
<td>8313</td>
<td>21.1</td>
</tr>
<tr>
<td>Conv. transition</td>
<td>501</td>
<td>2.7</td>
</tr>
<tr>
<td>2-jet</td>
<td>3591</td>
<td>9.5</td>
</tr>
<tr>
<td>All categories (inclusive)</td>
<td>23788</td>
<td>79.6</td>
</tr>
</tbody>
</table>

\( \sqrt{s} \) = 7-8 TeV, \( \sqrt{s} \) = 8 TeV, \( \sqrt{s} \) = 7 TeV, \( \sqrt{s} \) = 8 TeV

### Photon reconstruction and identification efficiency

- \( \gamma j + jj \ll \gamma \gamma \) irreducible (purity \( \sim 76\% \))

### Overall Higgs boson selection efficiency

\( \sim 40\% \)
### H$\rightarrow\gamma\gamma$: systematic uncertainties

<table>
<thead>
<tr>
<th>Category</th>
<th>Uncertainty [N_{evl}]</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>7.3</td>
<td>10.6</td>
<td></td>
</tr>
<tr>
<td>Unconverted central, low $p_T$</td>
<td>2.1</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Unconverted central, high $p_T$</td>
<td>0.2</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Unconverted rest, low $p_T$</td>
<td>2.2</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Unconverted rest, high $p_T$</td>
<td>0.5</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Converted central, low $p_T$</td>
<td>1.6</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Converted central, high $p_T$</td>
<td>0.3</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Converted rest, low $p_T$</td>
<td>4.6</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>Converted rest, high $p_T$</td>
<td>0.5</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Converted transition</td>
<td>Exp. of 2nd order pol.</td>
<td>3.2</td>
<td>4.6</td>
</tr>
<tr>
<td>2-jets</td>
<td>0.4</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

### Background modeling uncertainties

**Fit background distribution predicted by RESBOS with the chosen background parametrization adopted to describe the data; Max deviation of background model from expected background distribution taken as systematic uncertainty**
**H → γγ: results**

Excluded (95% CL):
112-122.5 GeV, 132-144 GeV

Expected: 110-139.5 GeV

*p₀* is the probability for the background to produce a fluctuation at least as large as the one observed in data (and in our case assumes that the relative signal strength between event classes follows SM predictions)

Excess of events around m_H ~ 126 GeV

Local significance: 4.5 σ  
Global significance: 2.4 σ
H$\rightarrow$ZZ($\ast$)$\rightarrow$ 4 leptons
H → ZZ(*) → 4 leptons

- Small cross section × BR: σ × BR ~ 2-5 fb
- However:
  - **mass can be fully reconstructed** → events would cluster in a (narrow) peak
  - **large signal-to-background ratio**: S/B ~ 1
- Event Selection:
  - 4 leptons: \( p_T^{1,2,3,4} > 20,20,7,7 \) GeV;
  - \( m_{12} = m_Z ± 15 \) GeV; \( m_{34} > 15-60 \) GeV (depending on \( m_H \)) [ATLAS]
- Main backgrounds:
  - ZZ(*) (irreducible)
  - \( m_H < 2m_Z \): Zbb, Z+jets, tt with two leptons from \( b/q \)-jets → lepton
- Suppressed with isolation and impact parameter cuts on two softest leptons
- Signal acceptance x efficiency: ~ 15 % for \( m_H \sim 125 \) GeV

**Crucial experimental aspects:**

- High lepton reconstruction and identification efficiency down to lowest \( p_T \)
- Good lepton energy/momentum resolution
- Good control of reducible backgrounds (Zbb, Z+jets, tt) in low-mass region:
  - cannot rely on MC alone (theoretical uncertainties, b/q-jet → lepton modeling, ..)
  - need to compare MC to data in background-enriched control regions (but: low statistics ..)
- Conservative/stringent \( p_T \) and m(ll) cuts used at this stage of the analysis
ATLAS: Electron and muon performance

Identification efficiency from J/ψ → ll, W → lν, Z → ll data samples

Crucial to understand low-p_{T} electrons (affected by material) with data

Variation of electron efficiency with pile-up (cuts not re-tuned yet) well modeled by simulation: from Z → ee data and MC samples

2012 Z → μμ mass peak

H → 4μ mass resolution: 2.13 GeV
Event fraction in ±2\sigma: ~ 84%

Mass resolution ~ 2 GeV

ATLAS Preliminary

Data 2012 \( \int L dt = 770 \text{ pb}^{-1} \)

Simulation
H → ZZ* → 4μ (\( \sqrt{s} = 8 \text{ TeV} \))
\( m = (129.50 \pm 0.04) \text{ GeV} \)
\( \sigma = (2.13 \pm 0.04) \text{ GeV} \)
fraction outside ±2\sigma: 16%

With mass fit constraint: resolution is 1.78 GeV

ATLAS Preliminary

Data 2012

Electron identification efficiency [%]

Number of reconstructed primary vertices

Electron identification efficiency [\%]

ATLAS Preliminary
Data 2012 \( \int L dt = 770 \text{ pb}^{-1} \)

Event fraction in ±2\sigma: ~ 84%

With mass fit constraint: resolution is 1.78 GeV
H → ZZ(*) → 4 leptons: ATLAS

Mass window: 125 ± 5 GeV

<table>
<thead>
<tr>
<th>Dataset</th>
<th>2011</th>
<th>2012</th>
<th>2011+2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected background</td>
<td>2.1 ± 0.3</td>
<td>2.9 ± 0.4</td>
<td>5.1 ± 0.8</td>
</tr>
<tr>
<td>Expected signal</td>
<td>2.0 ± 0.3</td>
<td>3.3 ± 0.5</td>
<td>5.3 ± 0.8</td>
</tr>
<tr>
<td>data</td>
<td>4</td>
<td>9</td>
<td>13</td>
</tr>
</tbody>
</table>
H→ZZ(*)→4 leptons: ATLAS results

- **Observed exclusion**: 131-162 GeV and 170 - 460 GeV
- **Expected exclusion**: 124-164 GeV and 176 - 500 GeV
- For $m_H \sim$120-130 GeV, much weaker limit than expected in the background-only hypothesis

- 7 TeV (2011): 2.3σ at 125 GeV, expected 1.5σ
- 8 TeV (2012): 2.7σ at 125.5 GeV, expected 2.1σ
- **Combined**: 3.4σ at $m_H$=125 GeV, expected 2.6σ
The most sensitive process for $130 < m_H < 200$ GeV

But also one of the most challenging channels: complete reconstruction of the invariant mass of this final system is not possible because the production of neutrinos

Largest background is the irreducible WW SM production

- But also Drell-Yan and top process when looking to final states associated to one jet

Preselection: select events with two high-$p_T$ opposite sign different flavour ($e, \mu$) leptons ($25, 15$ GeV) and large transverse missing energy ($E_T^{\text{miss}}$), produced in association of 0, 1 and 2 jets ($p_T^{\text{jet}}>25$ GeV for $|\eta|<2.5$; $p_T^{\text{jet}}>30$ GeV for $2.5<|\eta|<4.5$)

After $E_T^{\text{miss}}$ cut, divide the events in three classes: 0-, 1- and 2-jet category.

Selection:

- Apply topological cuts ($m_{ll}, p_T^{ll}, \Delta \phi^{ll}$)
- Reconstruct and study the transverse mass $m_T$
The leading backgrounds from SM processes producing two isolated high-
$p_T$ leptons are WW and top (ttbar and single top). These are estimated using
partially data-driven techniques.

Top control sample: 0-jet channel: the top quark background prediction is first
normalised using events satisfying the pre-selection criteria without jet
multiplicity or b-tagging requirements. Then the fraction of events passing 0-jet
selection in data is evaluated using MC with corrections determined with data.

WW control sample: defined with the same selections as for the signal region
except that the $\Delta\phi$ requirement is removed and the upper bound on $m_{ll}$ is
replaced with a lower bound $m_{ll} > 80$ GeV
Transverse mass distribution $m_T$ in the H+0-jet channel, for events satisfying all selection criteria.

The $W+$jets background is estimated directly from data and $WW$ and top backgrounds are scaled to use the normalisation derived from control regions described in the text. The hashed area indicates the total uncertainty on the background prediction.

An excess of 2.8 sigma is observed, an excess of 2.3 sigma is expected.

$H \rightarrow WW(*) \rightarrow e\nu\mu\nu$
Combination

- Combine statistically the individual channels in a global likelihood, taking into account correlations between the various experimental and theoretical uncertainties (jet energy scale, lepton efficiencies, …, Higgs cross-sections, PDFs, …)

111 < m_H < 582 GeV and 131 < m_H < 559 GeV excluded at 95% CL

113 < m_H < 114 GeV , 117 < m_H < 121 GeV and 132 < m_H < 527 GeV excluded at 99% CL

<table>
<thead>
<tr>
<th>H→γγ</th>
<th>H→ZZ*→4l</th>
<th>H→WW*→eνμν</th>
<th>Combine d</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>3.6</td>
<td>2.8</td>
<td>6.0</td>
</tr>
<tr>
<td>2.5</td>
<td>2.7</td>
<td>2.3</td>
<td>4.9</td>
</tr>
</tbody>
</table>
Signal strength

Best fit value for the signal strength as a function of the assumed Higgs boson mass for the combined analysis.

Fitted signal strength, assuming $m_H = 126$ GeV

<table>
<thead>
<tr>
<th>$H \rightarrow \gamma\gamma$</th>
<th>$H \rightarrow ZZ^* \rightarrow 4l$</th>
<th>$H \rightarrow WW^* \rightarrow e\nu\mu\nu$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.8 \pm 0.5$</td>
<td>$1.2 \pm 0.6$</td>
<td>$1.3 \pm 0.5$</td>
<td>$1.4 \pm 0.3$</td>
</tr>
</tbody>
</table>
The observed invariant mass distribution for the decay channel $\gamma\gamma$ (top channel) and $ZZ*\rightarrow4l$ (top right). The corresponding local p-value values are also shown as a function of the Higgs boson mass.

The observed local p-value for decay modes with high mass-resolution channels, $\gamma\gamma$ and $ZZ$, as a function of the SM Higgs boson mass. The dashed line shows the expected local p-values for a SM Higgs boson with a mass $m_H$. 

Results from CMS
• The fundamental question now:

Is the new physics object discovered by ATLAS and CMS the Standard Model Higgs boson?
To answer this question we should analyse the physics properties of this new particle, i.e.:

- Measure the mass
- Measure the couplings to fermions and vector bosons
- Determine Spin/CP quantum numbers
- Measure the self-coupling
- Also, set an upper limit to the natural width

➤ compare these findings with the predictions from Standard Model for the Higgs boson

- As far as the mass is concerned, as the theory does not predict its values, we should compare with the allowed values from experimental constraints
Higgs couplings - 1

- Couplings are extracted analysing the results of processes that combine different production mechanisms and decay channels:

\[ \sigma(H) \times \text{BR}(H \to xx) = \frac{\sigma(H)^{\text{SM}}}{\Gamma_p^{\text{SM}}} \times \frac{\Gamma_p \Gamma_x}{\Gamma}, \]

where \( \Gamma_p \) is the Higgs partial width involving the production couplings and where the Higgs branching ratio for the decay is written as \( \text{BR} = \frac{\Gamma_x}{\Gamma} \)

- \( \Gamma_x \) proportional to the square of the coupling, \( c_x^2 \)

- Leading Order motivated scale \( k_i \) factors are defined such us \( c_i = k_i \times c_i^{\text{SM}} \)

- The scale factors \( k_i \) can be defined for individual Higgs couplings, of for groups (e.g. fermions, vector bosons, u-like or d-type quarks, etc.) or just as one unique overall scale factor \( k \).

- For the Higgs width we use a scale factor \( k_H \)

- An example: \( \text{ggF } H \rightarrow \gamma\gamma \):

\[ (\sigma \cdot \text{BR})(\text{gg} \to H \to \gamma\gamma) = \sigma_{\text{SM}}(\text{gg} \to H) \cdot \text{BR}_{\text{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_{\gamma}^2}{k_H^2} \]
Higgs couplings - 2

• Statistical procedure:
  – For each production mode $i$, a signal strength factor $\mu_i = \sigma_i / \sigma_{i,SM}$ is introduced. Similarly for each decay final state, $\mu_f = B_f / B_{f,SM}$. For each analysis category $k$, the number of signal events $n^k_{\text{signal}}$ is given by

\[
  n^k_{\text{signal}} = \left( \sum_i \mu_i \sigma_{i,SM} \times A^k_i \times \varepsilon^k_{if} \right) \times \mu_f \times B_{f,SM} \times L^k
\]

  – $A$ is the acceptance
  – $\varepsilon$ is the efficiency
  – $L$ is the luminosity
Higgs couplings - 3

• Given the observed data, the resulting likelihood function is a function of a vector of signal strength factors $\mu$ which in turn are functions of the scale factors $k$, $\mu = \mu(k)$. Hypothesized values of $\mu$ are tested with the test statistics $\Lambda(\mu)$

$$\Lambda(\mu) = \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})}$$

• Based on the profile likelihood ratio method
Higgs couplings - 4

- **One overall k-factor:**
  \[ \kappa = 1.19 \pm 0.11 \text{ (stat)} \pm 0.03 \text{ (syst)} \pm 0.06 \text{ (theory)} \]

- **k_V - k_F fit**

Assume only SM particles contribute to the Higgs boson width.

\[ \lambda_{FV} = \frac{k_F}{k_Z} \]
\[ k_{VV} = k_V \cdot k_V / k_H \]
Higgs couplings - 5

- New Physics probing the $gg\rightarrow H$ and $H\rightarrow \gamma\gamma$ loops

Fits for benchmark models probing for contribution from non-SM particles, analyzing the $gg\rightarrow H$ and $H\rightarrow \gamma\gamma$ loops, assuming no sizeable contribution to the Higgs total width.

Best fit values for $k_g(k_\gamma)$ profiling over $k_\gamma(k_g)$:

$$k_g = 1.1^{+0.2-0.3}$$
$$k_\gamma = 1.2^{+0.3-0.2}$$
Latest results

• In occasion of the Hadron Collider Physics conference (HCP, Kyoto), ATLAS has presented new results, based on an overall 13 fb\(^{-1}\) of 2012 data, on:
  • \(H \rightarrow WW(*) \rightarrow e\nu\mu\nu\) (inclusive)
  • \(H \rightarrow \tau\tau \rightarrow \text{lep-lep, lep-had, had-had}\)
  • \(VH, H \rightarrow bbbar (V=W,Z)\)
  • Update on the signal strength \(\mu\)
The local significance for $m_H = 125$ GeV is $1.1\sigma$ observed (1.7$\sigma$ expected).

For 2011/2012 rate plot, observed $\mu$ limit at 125 GeV is 1.8 and expected limit is 1.9.
**Signal strength**

- ATLAS has updated the combined signal strength $\mu$, based on all available inputs, including in particular the most recent results on WW and fermionic final states.

- Previous result in July paper, using 2011 analyses of $\tau\tau$ and $bb$, July analyses for $\gamma\gamma$, 4 lepton, and WW, gave $\mu = 1.4 \pm 0.3$.
- New (preliminary) result is $\mu = 1.3 \pm 0.3$. 

![Graph showing signal strength results]
Higgs boson outlook

- We are just at the beginning of a new era in high-energy physics!
- The study of this new object, candidate to the Higgs boson predicted by the Standard Model, will require more data and a very accurate physics analysis, with low and well under control systematic uncertainties
- The future LHC data will be used to continue the analysis of the Higgs properties
- This physics programme represents also the physics case of new accelerator programmes in discussion in the community:
  - HL-LHC, LHC Luminosity Upgrade
  - e+e- circular/linear colliders
  - HE-LHC, Energy LHC Upgrade
  - New Very High Energy Hadron Collider
  - .....
Conclusions

• ATLAS has performed the search for the Higgs boson looking to several final states in 4.8 (\(\sqrt{s}=7\) TeV) + 5.9 fb\(^{-1}\) (respectively at \(\sqrt{s}=7\) and \(\sqrt{s}=8\) TeV) of proton-proton collision data

• An excess of events has been found at the mass of about 126 GeV in the \(H\rightarrow\gamma\gamma\) and \(H\rightarrow ZZ^*\rightarrow 4l\) final states; an excess is found also in the low mass resolution channel \(H\rightarrow WW^*\rightarrow e\nu\mu\nu\): combining statistically these three channels we found a 6\(\sigma\) significance for this excess: a new particle has been discovered
Conclusions

• This is not an arrival point: on the contrary, we opened a new era. We are called to write a new exciting chapter of the High-Energy, and this is what we are going to do during next months and years of research at the LHC.
Gracias a todos
Backup
Two of the historical papers

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction\(^1\) by a gauge vector meson we mean a Yang-Mills field\(^2\) associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.\(^3\) In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.\(^4,5\) A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.\(^4,5\) We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.

We shall first treat the case where the original fields are a set of bosons \(\phi_j\) which transform as a basis for a representation of a compact Lie group. This example should be considered as a rather general phenomenological model. As such, we shall not study the particular mechanism by which the symmetry is broken but simply assume that such a mechanism exists performed in lowest order perturbation theory indicates that

\[\begin{align*}
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&3. \text{ A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.} \\
&4. \text{ We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.} \\
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&\text{...}
\end{align*}\]
The Higgs field

- The mechanism of symmetry breaking in particle physics is associated with the concept of “vacuum”
- In quantum physics, even in absence of physical particles, there are effects due to virtual particles.
- The vacuum is the state with the lowest possible energy, after taking into account also quantum effects (see also slides in backup)
The Higgs field

Consider a Universe permeated by a scalar complex field, whose potential is depicted in the figure. The physical state associated to the vacuum has a non-zero expectation value $<\phi>_0$ (vev).

In particle physics, the presence of a field with a vev $\neq 0$ leads to the spontaneous symmetry breaking, and hence to the appearance of W, Z masses (as well as masses for fermions);

- $v$ is evaluated from experimental measurements: $vev \approx 246$ GeV

The quantum of the Higgs field is the Higgs boson.
Higgs Couplings

Feynman Rules

They are independent of the details of the Higgs potential except the vev

Higgs coupling proportional to $m_f, M_W^2, M_Z^2$
Higgs boson B.R.

The end of a Higgs boson

\[ \Gamma (H \rightarrow ff) = \frac{M_H}{8\pi} \left( \frac{M_f}{v} \right)^2 N_c \left( 1 - \frac{4M_f^2}{M_H^2} \right) \]

\[ \Gamma (H \rightarrow WW) = \frac{M_H}{16\pi} \left( \frac{M_H}{v} \right)^2 \left( 1 - \frac{4M_W^2}{M_H^2} \right)^{1/2} \]

\[ \times \left[ 1 - 4 \left( \frac{M_W^2}{M_H^2} \right) + 12 \left( \frac{M_W^2}{M_H^2} \right)^2 \right] \]

\[ \Gamma (H \rightarrow ZZ) = \frac{M_H}{32\pi} \left( \frac{M_H}{v} \right)^2 \left( 1 - \frac{4M_Z^2}{M_H^2} \right)^{1/2} \]

\[ \times \left[ 1 - 4 \left( \frac{M_Z^2}{M_H^2} \right) + 12 \left( \frac{M_Z^2}{M_H^2} \right)^2 \right] \]

from C. Anastasiou, CTEQ–MCnet summer school 2008
• Energy resolution contribution $\delta p \approx 1.3$ GeV
  – Energy scale calibration from $Z \rightarrow e^+e^-$
• Interaction point spread: $\sigma(z) \approx 5.6$ cm $\rightarrow \delta m(\theta) \approx 1.4$ GeV
• Resolution with pointing: $\sigma(z) \approx 1.5$ cm;
  – Use of recoil tracks less effective with large number of pile-up collisions
• Use conversion tracks as well