Entdeckung eines Higgs-artigen Teilchens am LHC

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Entdeckung eines Higgs-artigen Teilchens am LHC
Higgs-Teilchen offenbar entdeckt
From the editorial:

The top Breakthrough of the Year – the discovery of the Higgs boson – was an unusually easy choice, representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers.
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

Decay observed into particles with same spin and electric charge sum = 0 → a new neutral boson has been discovered
The Standard Model of Particle Physics

(i) Constituents of matter: quarks and leptons (spin-$\frac{1}{2}$ fermions)

(ii) Four fundamental forces: described by quantum field theories (except gravitation)
\[ m_W \approx 80.4 \text{ GeV} \]
\[ m_Z \approx 91.2 \text{ GeV} \]
\[ \rightarrow \text{massless spin-1 gauge bosons} \]

(iii) The Higgs field:
\[ \rightarrow \text{scalar field, spin-0 Higgs boson} \]
The Brout-Englert-Higgs Mechanism

The Brout-Englert-Higgs Mechanism

Complex scalar (spin 0) field $\phi$ with potential:

$$V(\phi) = \mu^2 (\phi^* \phi) + \lambda (\phi^* \phi)^2$$

For $\lambda > 0$, $\mu^2 < 0$:
“Spontaneous Symmetry Breaking”

→ Omnipresent Higgs field: vacuum expectation value $v \approx 246$ GeV

→ Higgs Boson (mass not predicted, except $m_H < \sim 1000$ GeV)

→ Particles acquire mass through couplings to the Higgs field
The Brout-Englert-Higgs Mechanism

For $\lambda > 0$, $\mu^2 < 0$: "Spontaneous Symmetry Breaking"

Complex scalar (spin 0) field $\phi$ with potential:

$$V(\phi) = \mu^2 (\phi^* \phi) + \lambda (\phi^* \phi)^2$$

- Couplings proportional to mass
- Higgs boson decays preferentially into the heaviest accessible particles
The Higgs field solves two fundamental problems:

(i) Masses of the vector bosons W and Z and fermions

(ii) Divergences in the theory (scattering of W bosons)
(“Ultraviolet regulator”)

\[-iM(W^+W^- \to W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \to \infty \quad \text{(no Higgs boson)}\]

\[-iM(W^+W^- \to W^+W^-) \sim m_H^2 \quad \text{for} \quad s \to \infty \quad \text{(with Higgs boson)}\]
The ATLAS experiment

Diameter             25 m
Barrel toroid length                         26 m
End-cap end-wall chamber span    46 m
Overall weight                         7000 Tons

ATLAS Germany:
BMBF-Forschungsschwerpunkt ATLAS

- HU Berlin, Bonn, DESY, Dortmund, Dresden
  Freiburg, Giessen, Göttingen, Heidelberg,
  Mainz, LMU München, MPI München, Siegen,
  Würzburg, Wuppertal

- ~420 scientists (~200 students)
The CMS experiment

**Superconducting Coil, 4 Tesla**

**CALORIMETERS**
- **ECAL**: 76k scintillating PbWO4 crystals
- **HCAL**: Plastic scintillator/brass sandwich

**IRON YOKE**

**TRACKER**
- Pixels
- Silicon Microstrips
- 210 m² of silicon sensors
- 9.6M channels

**MUON BARREL**
- Drift Tube Chambers (DT)
- Resistive Plate Chambers (RPC)

**Total weight**: 12500 t
- **Overall diameter**: 15 m
- **Overall length**: 21.6 m

**CMS Germany:**
- BMBF-Forschungsschwerpunkt CMS
  - Aachen (Ib, IIa, IIIb), DESY, Hamburg, Karlsruhe
  - ~ 200 scientists (~90 students)
Data taking in 2011/2012

- Excellent LHC performance
  Peak luminosities > $7 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ (world record, 2012)

- Excellent performance of the experiments:
  - Data recording efficiency ~93.5%
  - Working detector channels >99%
  - Speed of data analysis

**Until end 2012:**

- > $10^{15}$ pp collisions
- ~$10^{10}$ pp collisions recorded
- $25 \cdot 10^6 Z \rightarrow \mu\mu$ decays produced
The Standard Model at the LHC

July 2012

ATLAS Preliminary

LHC pp $\sqrt{s} = 7$ TeV
- Theory
- Data 2010 (L = 35 pb$^{-1}$)
- Data 2011 (L = 1.0 - 4.7 fb$^{-1}$)

LHC pp $\sqrt{s} = 8$ TeV
- Theory
- Data 2012 (L = 5.8 fb$^{-1}$)

$H \rightarrow ZZ$ (0.5 pb)
$H$ (20 pb)
Higgs Boson Production

*) LHC Higgs cross-section working group
Large theory effort
Higgs Boson Decays

Important channels at hadron colliders:

- $H \rightarrow WW \rightarrow \ell^+ \ell^- \ell^+ \ell^-$
- $H \rightarrow gg$
- $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$
- $H \rightarrow \gamma \gamma$
- $H \rightarrow t\bar{t}$
- $H \rightarrow b\bar{b}$
- $H \rightarrow c\bar{c}$
- $H \rightarrow t\bar{t}$
- $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$
Discovery of a Higgs-like particle

Expected number of decays in data:

\[ m_H = 125 \text{ GeV} \]

\[ \sim 950 \ H \rightarrow \gamma \gamma \]
\[ \sim 60 \ H \rightarrow ZZ \rightarrow 4 \ell \]
\[ \sim 9000 \ H \rightarrow WW \rightarrow \ell \nu \ell \nu \]
Search for the $H \rightarrow \gamma\gamma$ decay

- 2 photons (isolated) with large transverse momenta
- Mass of the Higgs boson can be reconstructed $m_{\gamma\gamma}$

Both experiments have a good mass resolution
ATLAS: $\sim 1.7$ GeV/$c^2$ for $m_H \sim 120$ GeV/$c^2$

- Challenges:
  - signal-to-background ratio
    (small, but smooth irreducible $\gamma\gamma$ background)
  - reducible backgrounds from $\gamma j$ and $jj$
    (several orders of magnitude larger than irreducible one)
Result of the ATLAS search for $H \rightarrow \gamma\gamma$

**July 2012**

- $p_0$ value for consistency of data with background-only: $\sim 10^{-13}$ (7.4$\sigma$)

More details: “Eingeladener Vortrag” by Kerstin Tackmann (Thursday) (Hertha-Sponer Preisträgerin)
Result of the ATLAS search for $H \rightarrow \gamma\gamma$

**Mass:**

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

**Signal strength:**

$$\mu := \frac{\sigma}{\sigma_{SM}} = 1.65 \pm 0.24 \text{(stat)}^{+0.17}_{-0.13} \text{(syst)}^{+0.18}_{-0.13} \text{(theo)}$$
Separation of different production processes for $H \rightarrow \gamma\gamma$

- Best fit
- $68\%$ CL
- $95\%$ CL
- $\times$ SM

ATLAS Preliminary
2011-2012
$m_H = 126.8$ GeV

Full dataset

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

$\mathcal{L}dt = 20.7$ fb$^{-1}$, $\sqrt{s} = 8$ TeV
Result of the CMS search for $H \rightarrow \gamma\gamma$

July 2012

CMS $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$ $\sqrt{s} = 8$ TeV, $L = 5.3$ fb$^{-1}$

$S/(S+B)$ Weighted Events / 1.5 GeV

Events / 1.5 GeV

$\sigma/\sigma_{SM}$

$H \rightarrow \gamma\gamma + H \rightarrow ZZ$

Combined

$H \rightarrow \gamma\gamma$ (untagged)

$H \rightarrow \gamma\gamma$ (VBF tag)

$H \rightarrow ZZ$
Search for the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- \ell^+\ell^-$ decay

- The "golden mode"
  4 leptons (isolated) with large transverse momenta

- Mass of the Higgs boson can be reconstructed $m_{4\ell}$

  Both experiments have a good mass resolution
  ATLAS: $\sim 2.5$ GeV/c$^2$ (4e) for $m_H \sim 130$ GeV/c$^2$
  $\sim 2.0$ GeV/c$^2$ (4$\mu$) for $m_H \sim 130$ GeV/c$^2$

- Low signal rate, but also low background
  - Mainly from ZZ continuum
  - In addition from tt and Zbb events:
    $tt \rightarrow Wb Wb \rightarrow \ell \nu c\bar{\nu} \ell \nu c\bar{\nu}$
    $Z bb \rightarrow ll c\bar{\nu} c\bar{\nu}$
Candidate event for $a \, H \rightarrow ZZ \rightarrow e^+e^- \mu^+ \mu^-$ decay
4ℓ invariant mass spectra

- \( p_0 \)-values in both experiments

\[ \sim 10^{-11} \quad (>6\sigma) \]

Signal strengths:

**ATLAS:** \( \mu = 1.7 \pm 0.5 \)

**CMS:** \( \mu = 0.91^{+0.30}_{-0.24} \)
Time evolution of the $H \to ZZ \to 4\ell$ signal

$\sqrt{s} = 7$ TeV $\int L dt = 0.18$ fb$^{-1}$

May 4 09:15:50 2011

$H \to ZZ^{(*)} \to 4\ell$ channel

- Signal ($m_H = 125$ GeV)
- Background $ZZ^{(*)}$
- Background $Z+$jets, $t\bar{t}$
- Data
Time evolution of the $H \to ZZ \to 4\ell$ signal
Time evolution of the $H \rightarrow ZZ \rightarrow 4\ell$ signal

$\sqrt{s} = 7$ TeV \ $Ldt = 4.83$ fb$^{-1}$

$\sqrt{s} = 8$ TeV \ $Ldt = 20.65$ fb$^{-1}$ \ $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel
Separation of different production processes for $H \rightarrow ZZ \rightarrow 4\ell$

- $\mu_V (qqH, ZH, WH) = 1.0^{+2.4}_{-2.3}$
- $\mu_F (gg \rightarrow H, t\bar{t}H) = 0.9^{+0.5}_{-0.4}$
Results on the search for $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ decays

**ATLAS Preliminary**

$\sqrt{s} = 8 \text{ TeV}, \int L dt = 13.0 \text{ fb}^{-1}$

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$ (0 jets)

0-jet leading e

**Signal strength:**

**ATLAS:** $\mu = 1.4 \pm 0.3$

**CMS:** $\mu = 0.76 \pm 0.21$

Clear excess in both experiments
Determination of mass, compatibility of channels

\[ m_H = 125.2 \pm 0.3 \text{ (stat) } \pm 0.6 \text{ (syst) GeV} \]

\[ m_H = 125.8 \pm 0.4 \text{ (stat) } \pm 0.4 \text{ (syst) GeV} \]

Updated mass values (full dataset, preliminary):

\[ m_H (\gamma\gamma) = 126.8 \pm 0.2 \text{ (stat) } \pm 0.7 \text{ (syst) GeV} \]

\[ m_H (4\ell) = 124.3^{+0.6}_{-0.5} \text{ (stat) } ^{+0.5}_{-0.4} \text{ (syst) GeV} \]
Couplings to quarks and leptons?

Search for $H \rightarrow \tau\tau$ and $H \rightarrow bb$ decays
Why is the search in these decay modes so challenging?

- The $\tau$ lepton is the heaviest lepton
  
  $m_\tau = 1.78 \text{ GeV } / c^2$, lifetime $2.9 \times 10^{-13} \text{ s}$

  Decays into hadrons $\tau \rightarrow \text{hadrons } \nu_\tau$ (65%)
  
  $\tau \rightarrow e\nu_e\nu_\tau$, $\mu\nu_\mu\nu_\tau$ (35%)

- Challenge: distinguish hadronic $\tau$ decays from hadronic jet activity

- Neutrinos in the final state, poor mass resolution
Analysis is split into three sub-channels:
- \( H \rightarrow \tau \tau \rightarrow \ell \nu \nu \ell \nu \nu \)
- \( H \rightarrow \tau \tau \rightarrow \ell \nu \nu \) had \( \nu \)
- \( H \rightarrow \tau \tau \rightarrow \) had \( \nu \) had \( \nu \)

Data set: 13 – 17 fb\(^{-1}\)

Signal strength (all sub-channels):

ATLAS: \( \mu = 0.7 \pm 0.7 \)

CMS: \( \mu = 0.7 \pm 0.5 \)

More details: “Eingeladener Vortrag” by Stanley Lai (Thursday)
Results on H → bb searches

- Small excess is showing up around 125 GeV
- However, the significance is still low!
Results on $H \rightarrow b\bar{b}$ from ATLAS

**ATLAS Preliminary**
\[
\int L dt=13.0 \text{ fb}^{-1}, \quad \sqrt{s} = 8 \text{ TeV}
\int L dt=4.7 \text{ fb}^{-1}, \quad \sqrt{s} = 7 \text{ TeV}
\]

0,1,2 lepton

**Signal strength:**

**ATLAS:** $\mu = -0.4 \pm 1.0$

**CMS:** $\mu = 1.3^{+0.7}_{-0.6}$
Is the new particle the Higgs Boson?

- Production rates?
- Couplings to bosons and fermions
- Spin, $J^P$ quantum number

More details: “Eingeladener Vortrag” by Johannes Elmsheuser (Thursday)
“Hauptvortrag” by Thomas Müller (Friday)
Signal strength in individual decay modes
-including new data up to Sept. 2012-

- Data are consistent with the hypothesis of a Standard Model Higgs boson!

- Experimental uncertainties are still too large to get excited about “high” $\gamma\gamma$ and “low” fermionic ($\tau\tau$ and $bb$) signal strengths!
Test of coupling strengths

Couplings to W and Z bosons

W, Z versus fermion couplings

\[ \lambda_{WZ} = \text{ratio of W/Z coupling strength} \]
(normalized to ratio in the SM)

\[ \kappa_V = \text{common scale factor for all fermion couplings (t, b, \tau, \ldots)} \]

\[ \kappa_Z = \text{scale factor for Z coupling strength} \]

update expected very soon
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

*Wolfgang Pauli und Niels Bohr bei der wissenschaftlichen Untersuchung der Kreiselbewegung (1952, anlässlich der Eröffnung des Instituts für Theoretische Physik in Lund / Schweden)*
Spin studies using $H \rightarrow \gamma\gamma$ events

Decay angle in the Higgs boson rest frame (Collins-Soper frame)

Likelihood hypothesis test of spin-0 versus spin 2:

Data favour spin 0,

exclude $J^P = 2^+_m$ w.r.t. $J^P = 0^+$ with

ATLAS: $1.4\sigma$ (p value = 0.12)
Spin studies using $H \rightarrow ZZ^{(*)} \rightarrow 4 \ell$ events

- Sensitive variables:
  - Masses of the two $Z$ bosons
  - Production angle $\theta^*$
  - Four decay angles $\Phi_1$, $\Phi$, $\theta_1$ and $\theta_2$

Likelihood hypothesis test of $J^P = 0^+$ vs. $J^P = 0^-$
- ATLAS: $2.8\sigma$ ($2.7$ exp)
- CMS: $3.3\sigma$ ($2.6$ exp)

Likelihood hypothesis test of $J^P = 0^+$ vs. $J^P = 2^+_m$
- ATLAS: $1.2\sigma$ ($1.5$ exp)
- CMS: $2.7\sigma$ ($1.8$ exp)

Data favour $J^P = 0^+$ w.r.t. other $J^P$ configurations (including $0^-$, $1^-$, $1^+$, $2^+$)
Conclusions

• With the operation of the LHC at high energies, particle physics has entered a new era

• Performance of the LHC and the experiments is superb

• A milestone discovery made in July 2012

Strong evidence that the new particle is the long-sought Higgs boson

- Clear signals in bosonic decays
- Evidence for fermionic decays is building up, but still weak....
- Tensions in some signal/coupling strength (?)
- First evidence for spin 0

• Exciting times ahead of us:
  - Study of the Higgs-like boson itself
  - Search for Physics Beyond the Standard Model