Standard Model Higgs searches at the LHC

3rd MPI Young Scientists Workshop
Ringberg Castle • October 27, 2004
The Higgs Mechanism...

The Higgs field: gives a mass to an originally massless particle.

...and the Higgs Boson
The Higgs Mechanism

The invariant Lagrangian $\mathcal{L}$ of the SU(2)$_L \times$U(1) electroweak theory contains massless gauge bosons ($W$, $B$) and fermions ($\psi$).

$$\mathcal{L} = -\frac{1}{4} (\partial_\nu W^i_\mu - \partial_\mu W^i_\nu + g \epsilon^{ijk} W^j_\mu W^k_\nu) (\partial^\nu W^{i\mu} - \partial^{i\mu} W^{\nu\nu} + g \epsilon^{ijk} W^{i\mu} W^{k\nu}) - \frac{1}{4} (\partial_\nu B_\mu - \partial_\mu B_\nu) (\partial^\nu B^{\mu} - \partial^{\mu} B^{\nu}) + i \bar{\psi}_R \gamma^\mu \left( \partial_\mu + i \frac{g'}{2} Y_R B_\mu \right) \psi_R + i \bar{\psi}_L \gamma^\mu \left( \partial_\mu + i \frac{g}{2} \tau_i W^i_\mu + i \frac{g'}{2} Y_L B_\mu \right) \psi_L.$$

P.W.Higgs 1964; F.Englert and R.Brout 1964;

Introduction of a scalar field $\Phi$ provides for the particle masses.

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} \quad ; \quad V(\Phi) = -\lambda v^2 |\Phi^\dagger \Phi| + \lambda (|\Phi^\dagger \Phi|)^2$$

$$\mathcal{L}_\Phi = (D^\mu \Phi)^\dagger (D_\mu \Phi) - g_f \left( \bar{\psi}_L \Phi \psi_R + \bar{\psi}_R \Phi^\dagger \psi_L \right) - V(\Phi)$$
The invariant Lagrangian $\mathcal{L}$ of the SU(2)$_L$ x U(1) electroweak theory contains masseless gauge bosons ($W$, $B$) and fermions ($\psi$).

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$$-\frac{1}{4} (\partial_\nu B_\mu - \partial_\mu B_\nu) \left( \partial^\nu B^\mu - \partial^\mu B^\nu \right)$$

$$+ i \bar{\psi}_R \gamma^\mu \left( \partial_\mu + ig' 2 Y_R B_\mu \right) \psi_R + i \bar{\psi}_L \gamma^\mu \left( \partial_\mu + ig 2 \tau_i W^i_\mu + ig' 2 Y_L B_\mu \right) \psi_L.$$
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**↓ interaction with gauge bosons**

$$m_{W^\pm} = \frac{g \nu}{2}, \quad m_Z = \frac{\nu \sqrt{(g^2 + g'^2)}}{2}$$
The invariant Lagrangian $\mathcal{L}$ of the $SU(2)_L \times U(1)$ electroweak theory contains massless gauge bosons $(W, B)$ and fermions ($\psi$).

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\mathcal{L} = -\frac{1}{4} \left( \partial_\nu W^i_\mu - \partial_\mu W^i_\nu + g \epsilon^{ijk} W^j_\mu W^k_\nu \right) \left( \partial^\nu W^{i\mu} - \partial^\mu W^{i\nu} + g \epsilon^{ijk} W^{j\mu} W^{k\nu} \right) - \frac{1}{4} \left( \partial_\nu B_\mu - \partial_\mu B_\nu \right) \left( \partial^\nu B^{\mu} - \partial^\mu B^{\nu} \right) + i \bar{\psi}_R \gamma^\mu \left( \partial_\mu + i \frac{g'}{2} Y_R B_\mu \right) \psi_R + i \bar{\psi}_L \gamma^\mu \left( \partial_\mu + i \frac{g}{2} \tau_i W^i_\mu + i \frac{g'}{2} Y_L B_\mu \right) \psi_L.
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\[
\downarrow \quad \text{interaction with fermions}
\]

\[
m_f = \frac{g_f \nu}{\sqrt{2}}
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The invariant Lagrangian $\mathcal{L}$ of the SU(2)$_L \times$U(1) electroweak theory contains massless gauge bosons $(W, B)$ and fermions $(\psi)$.

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$$

self-interaction

Existence of a spin − 0 particle, the Higgs boson with a mass $m_H = \sqrt{2\lambda \nu}$. 
The Higgs Boson Mass

Not specified explicitly, but...
Bounds derived from the evolution of the self-coupling $\lambda$ with energy:

$$\lambda(\Lambda) < \infty$$

Upper bound:
SM valid up to the scale $\Lambda$

$$\lambda(\Lambda) > 0$$

Lower bound:
vacuum stability
(finite minimum for $V(\Phi)$)

The Higgs boson discovery can provide the constraints on the validity of the Standard Model.
Current experimental status

by Claus Grupen

by Claus Grupen
## Experimental Data

<table>
<thead>
<tr>
<th>Collider</th>
<th>Running Period</th>
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Indirect tests, setting bounds on the Higgs mass from precision measurement of electroweak observables taking into account the radiative corrections.

\[ \propto \log \frac{m_H^2}{m_Z^2} \]
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**direct search, Higgs produced by Higgs-Strahlung; large coupling to Z, all other processes negligible**

\[
\begin{align*}
  e^+ & \rightarrow Z^* \\
  e^- & \rightarrow Z \\
  Z^* & \rightarrow Z \\
  Z & \rightarrow H
\end{align*}
\]
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Direct searches; Higgs produced by gluon fusion and Higgs-Strahlung
Precision measurements of electroweak observables:

- Z boson lineshape
- forward-backward asymmetries
- W boson mass

With the recent world average value $m_{top} = (178.0 \pm 4.3)$ GeV (April 2004):

$$m_H = 117^{+67}_{-45} \text{ GeV}$$

$m_H < 251$ GeV, 95% confidence level

Direct searches in the production channel $e^+e^- \rightarrow Z^* \rightarrow HZ$ give the lower bound

$$m_H > 114.4 \text{ GeV}$$
Observed Higgs event?

golden 4−jet event
14.06.2000.

\[ e^+ e^- \rightarrow HZ \rightarrow \bar{b}bq\bar{q} \]

\[ m = (114 + 3) \text{ GeV} \]

All other channels in all experiments are compatible with background!
collected integrated luminosity of $\sim0.4$ fb$^{-1}$, 
$\sim0.2$ fb$^{-1}$ analysed so far

- goal: 4-9 fb$^{-1}$ by the end of 2009
- still an early stage of data taking,
  emphasis on understanding the detector performance
- the Higgs search has begun

Main signatures for the Standard Model Higgs boson:

- For $m_H < 130$ GeV: $q\bar{q} \rightarrow (W/Z)H \rightarrow (W/Z)b\bar{b}$
- For $m_H > 130$ GeV: $gg \rightarrow H \rightarrow WW^* \rightarrow 2l2\nu$
Recent Tevatron Results (July 2004)

**WH → Wb̅b**
- leptonic W-decay
- 2 jets required, ≤1 b-tagged

\[ \sigma(Wbb) < 20.3 \text{ pb} \]
\[ \sigma(WH)xB(H \rightarrow b\bar{b}) < 12.4 \text{ pb} \]

**H → WW* → 2l2ν**
- 2 high-\(p_T\) leptons
- large missing energy
- spin correlation (charged leptons are collinear)

\[ \sigma xB(H \rightarrow WW) < 5.7 \text{ pb} \]
Higgs discovery in a single channel is not possible.

Combined CDF/D0 discovery reach up to 2009:

- 115–130 GeV covered for exclusion
- Worst case scenario, $L=4.4$ fb$^{-1}$
- 3σ evidence up to 125 GeV

Higgs Mass $m_H$ (GeV/c$^2$) vs. Int. Luminosity per Exp. (fb$^{-1}$)

- Higgs Sensitivity Study ('03)
- SUSY/Higgs Workshop ('98-'99)
- Statistical power only (no systematics)
- 5σ Discovery
- 3σ Evidence
- 95% CL Exclusion
Higgs discovery in a single channel is not possible.

Combined CDF/D0 discovery reach up to 2009:

- 3σ evidence up to 130 GeV
- 5σ discovery up to 120 GeV
- best case scenario, L=8.5 fb$^{-1}$
Large Hadron Collider at CERN

first 3 years at low luminosity: $L = 30 \text{ fb}^{-1}$

high luminosity afterwards: $L = 100 \text{ fb}^{-1} / \text{year}$
Higgs Signatures at the LHC

by Claus Grupen

by Claus Grupen
The Higgs signal hidden behind the large background contributions.

Challenging detector performance needed:
- powerful trigger
- high granularity
- radiation hardness
- high particle detection efficiency and resolution
Higgs Production Mechanisms

- Gluon–gluon fusion
- Vector boson fusion, VBF
- Higgs–Strahlung
- Associated production

10,000 - 1,000,000 Higgs Bosons produced per year at high luminosity
Branching ratios are completely determined by the Higgs mass.

**Low mass** $m_H < 2m_Z$:
- The most difficult region, combining several channels:
  - $H \rightarrow b\bar{b}$, $H \rightarrow \gamma\gamma$,
  - $H \rightarrow \tau^+\tau^-$ (via VBF),
  - $H \rightarrow ZZ^* \rightarrow 4l$,
  - $H \rightarrow WW^* \rightarrow 2l2\nu$ (via VBF)

**Large mass** $m_H > 180$ GeV:
- the gold-plated channel
  - $H \rightarrow ZZ \rightarrow 4l$
- supplementary channel at very high masses (>800 GeV)
  - $H \rightarrow WW \rightarrow l\nu jj$
Hadronic final states dominate for all values of $m_H$, but are difficult to distinguish from large QCD background.

We rather look for final states with leptons, photons, missing energy.
LHC Detectors

Ladbrokes (the biggest betting company in the world):

As of August 2004 accepts the bets on finding the Higgs boson at LHC before 2010, the odds are set to 6 to 1.
Design optimized for the Higgs discovery in a wide mass range:

- large solid angle, efficient and precise particle detection,
  good calorimetry and missing energy measurement
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Discovery Potential

“You call this evidence for the Higgs?”
“Yes! Zero lifetime and infinite width!”
Low-mass Higgs: \( t\bar{t}H, H \rightarrow b\bar{b} \)

- Identification via top-quark tagging
  1. \( t \rightarrow Wb \rightarrow l\nu b \): lepton used for triggering
  2. \( t \rightarrow Wb \rightarrow jjb \)

- Selecting final states with 4 b-tagged jets, precise vertexing needed

- Need for a very good understanding of background (ttbb, ttjj, Ztt)

Signal significance \( (S/\sqrt{B}) \) at 30 fb\(^{-1}\): 3.4\(\sigma \) for \( m_H = 115 \text{ GeV} \)
Low-mass Higgs: $H \rightarrow \gamma\gamma$

$B(H \rightarrow \gamma\gamma) = 10^{-3}$ $B(H \rightarrow b\bar{b})$ only, but $H \rightarrow \gamma\gamma$ is a clean channel.

Main background processes:

- **reducible:** $qg \rightarrow q\gamma \rightarrow q\gamma\gamma$
  need excellent $\gamma$/jet separation,
  (in particular $\gamma/\pi^0$),
  high granularity detectors

- **irreducible:** $gg \rightarrow \gamma\gamma$, $q\bar{q} \rightarrow \gamma\gamma$
  subtraction of a smooth continuous background,
  excellent calorimetry needed
  for a narrow $m_{\gamma\gamma}$-resonance

Additional improvement:

- associated Higgs production: $WH$, $ZH$ and $t\bar{t}H$,
  process triggered by a lepton from $W$, $Z$ or $t$
Low-mass Higgs: $H \rightarrow \gamma\gamma$

Signal significance ($S/\sqrt{B}$) at 100 fb$^{-1}$: $3-4\sigma$ for $m_H < 150$ GeV

CMS has a 10% better calorimeter resolution than ATLAS.
Low-mass Higgs: \( qqH, \ H \rightarrow \tau^+ \tau^- \)

- hadronic jets in forward-backward region, forward jet-tagging, central jet veto
- leptonic or hadronic decay in \( \tau \)-direction, missing \( p_T \) measurement, lepton identification
- background: \( Zjj, \ t\bar{t} + \text{jets}, \ WWjj \)

Signal significance \((S/\sqrt{B})\) at 40 \( \text{fb}^{-1} \): \( >5\sigma \) for \( m_H < 140 \text{ GeV} \)
Low-mass Higgs: \((qq)H, H \rightarrow WW^{(*)} \rightarrow ll\nu\nu\)

This is the main decay channel in the region around \(m_H=170\) GeV. A good missing energy measurement is needed.

Main backgrounds:

- \(WW, WbW\bar{b}\) - suppressed by WW spin correlations in the signal
- Drell-Yan \(ee, \mu\mu\) - lepton cuts (\(p_T^{\text{miss}} > 30\) GeV, \(m < 75\) GeV)
- \(t\bar{t}, \tau\tau\) - b-jet and \(\tau\) veto in the central region

Signal significance \((S/\sqrt{B})\) of \(5\sigma\) reachable at \(10\) fb\(^{-1}\) for \(m_H \approx 170\) GeV.
Low-mass Higgs: $H \rightarrow ZZ^* \rightarrow 4l$

- relatively clean signature
  - one pair with $m_{2l}$-peak at the Z-resonance
- reducible background: $Zb\bar{b}, t\bar{t}$
  - lepton isolation, small impact parameter
- irreducible background: $ZZ \rightarrow 4l$
Low-mass Higgs: $H \rightarrow ZZ^* \rightarrow 4l$

Particularly clean signature from muons:

- no cuts applied on the muon tracks
- $m_{2\mu} = (m_Z \pm 2\Gamma_Z)$
- selecting isolated leptons
- cut on the impact parameter

Signal significance for $H \rightarrow 4\ell$ at 30 fb$^{-1}$: 3-5$\sigma$ for $m_H < 200$ GeV.
Low-mass Higgs: \( H \rightarrow ZZ^* \rightarrow 4l \)

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- cut on the impact parameter

![H → 4μ ATLAS](image)

Signal significance for \( H \rightarrow 4l \) at 30 fb\(^{-1}\): \( 3-5\sigma \) for \( m_H < 200 \text{ GeV} \).
Low-mass Higgs: $H \rightarrow ZZ^* \rightarrow 4l$

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Signal significance for $H \rightarrow 4l$ at 30 fb$^{-1}$: 3-5σ for $m_H < 200$ GeV.
combination of all channels is needed for the $5\sigma$ discovery in the first three years of running LHC
\( H \rightarrow ZZ \rightarrow 4l \) gives a clean signature for the region \( m_H > 200 \text{ GeV} \)

- **complete coverage** of the theoretically allowed mass range \( m_H \);
  - \( 5\sigma \) discovery possible already in the first year

\[ \begin{align*}
\text{Signal significance} \\
\text{L = 10 fb}^{-1} \\
\text{L = 30 fb}^{-1} \\
\text{L = 100 fb}^{-1}
\end{align*} \]

**ATLAS + CMS** (no K-factors)
Precision Measurements of Higgs Properties

The graph shows the total width of the Higgs resonance $\Gamma(H)$ in GeV as a function of the Higgs mass $M_H$ in GeV. The graph indicates that experimentally resolvable total widths of the Higgs resonance are expected below a certain mass threshold.
Width measurement:
6% for $m_H > 300$ GeV

Mass measurement:
<1% for all $m_H$
Relative widths and branching ratios

### Relative Widths

**ATLAS**

\[ \int L \, dt = 30 \, fb^{-1} \]

- \( \Gamma_{Z}/\Gamma_{W} \)
- \( \Gamma_{\gamma}/\Gamma_{W} \)
- \( \Gamma_{\tau}/\Gamma_{W} \)
- without syst. uncertainty

### Relative Branching Ratios

**ATLAS**

\[ \int L \, dt = 30 \, fb^{-1} \]

- \( \sigma(VBF) \cdot BR(H \rightarrow WW) \)
- \( \sigma(ggH) \cdot BR(H \rightarrow WW) \)
- \( \sigma(VBF) \cdot BR(H \rightarrow ZZ) \)
- \( \sigma(ggH) \cdot BR(H \rightarrow ZZ) \)
- \( \sigma(ttH) \cdot BR(H \rightarrow WW) \)
- \( \sigma(WH) \cdot BR(H \rightarrow WW) \)
Relative widths and branching ratios

**Relative widths**

\[ \frac{\Gamma(Z)}{\Gamma_W}, \frac{\Gamma(\gamma)}{\Gamma_W}, \frac{\Gamma(t)}{\Gamma_W}, \frac{\Gamma(b)}{\Gamma_W} \]

**Relative branching ratios**

\[ \frac{\sigma(VBF) \cdot BR(H \rightarrow WW)}{\sigma(ggH) \cdot BR(H \rightarrow WW)} \]

\[ \frac{\sigma(VBF) \cdot BR(H \rightarrow ZZ)}{\sigma(ggH) \cdot BR(H \rightarrow ZZ)} \]

\[ \sigma(ttH) \cdot BR(H \rightarrow WW) \]

\[ \sigma(WH) \cdot BR(H \rightarrow WW) \]
Couplings to fermions and gauge bosons

**Absolute**

\[ \frac{\Delta g^2(H,X)}{g^2(H,X)} \]

\[ \frac{\Delta g^2(H,Z)}{g^2(H,Z)} \]

\[ \frac{\Delta g^2(H,W)}{g^2(H,W)} \]

\[ \frac{\Delta g^2(H,t)}{g^2(H,t)} \]

\[ \frac{\Delta g^2(H,b)}{g^2(H,b)} \]

\[ \frac{\Delta g^2(H,t)}{g^2(H,t)} \]

\[ \Gamma_H \]

**Relative**

\[ \frac{g^2(H,Z)}{g^2(H,W)} \]

\[ \frac{g^2(H,t)}{g^2(H,W)} \]

\[ \frac{g^2(H,b)}{g^2(H,W)} \]

\[ \frac{g^2(H,t)}{g^2(H,W)} \]

without syst. uncertainty

ATLAS

\[ \int L \, dt = 30 \text{ fb}^{-1} \]
Couplings to fermions and gauge bosons

[Graphs showing absolute and relative coupling variations with Higgs mass]

**Absolute Couplings**

- $g^2_{(H,Z)}$
- $g^2_{(H,W)}$
- $g^2_{(H,t)}$
- $g^2_{(H,b)}$
- $g^2_{(H,X)}$
- $\Gamma_H$

**Relative Couplings**

- $g^2_{(H,Z)} / g^2_{(H,W)}$
- $g^2_{(H,t)} / g^2_{(H,W)}$
- $g^2_{(H,b)} / g^2_{(H,W)}$

ATLAS

$\int L \, dt = 300 \text{ fb}^{-1}$

HIGGS MECHANISM / CURRENT RESULTS / LHC: Signatures, Detectors, Discovery Potential, Precision Measurements
The first pp-collisions at the LHC are expected end of 2007.

The LHC detectors (ATLAS, CMS) are designed for the Higgs search covering the full mass spectrum.

The 5\(\sigma\)-discovery limit can be reached in the whole mass range already after one year.
(However, a time will be needed to understand the detectors.)

Physics studies are currently concentrated on the more difficult region of lower Higgs masses, which is favoured by the theoretical and experimental observations.

If the Standard Model Higgs boson exists, it will be seen at the LHC.
Searching Beyond the Standard Model...