Higgs searches at the LHC: where do we stand?

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- Introduction
- Higgs searches at LEP and the Tevatron
- Latest results from the LHC: status and interpretation
- Conclusions
Introduction: exploring the Terascale

$1 \text{ TeV} \approx 1000 \times m_{\text{proton}} \Leftrightarrow 2 \times 10^{-19} \text{ m}$

### Temperature / Energy

<table>
<thead>
<tr>
<th>meV</th>
<th>eV</th>
<th>keV</th>
<th>MeV</th>
<th>GeV</th>
<th>TeV</th>
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<tbody>
<tr>
<td>Atomic physics</td>
<td>Nuclear physics</td>
<td>Particle physics</td>
<td></td>
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</table>

- Cathode ray tube
- Cyclotron
- LEP, SLC
- Tevatron
- ILC, LHC
- W, Z Higgs
- top SUSY
- Extra Dimensions
- Inflation
- Baryogenesis
- Neutrino Decoupling
- WIMP Decoupling

### Time (s)

- $10^{17}$
- $10^{12}$
- $10^{6}$
- now
- $10^{-6}$
- $10^{-12}$

[Plot adapted from J. Feng '05]

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How to find the Higgs (or more than one)?

- Heavy particle
  ⇒ need high-energy collider, $E = mc^2$

- Unstable:
  ⇒ need to look for decay products

- Comprehensive set of precision measurements and accurate theory predictions will be needed to establish the Higgs mechanism and to determine the Higgs properties

⇒ One of the main goals for physics at the LHC and a future Linear Collider
What’s so special about the Higgs and electroweak symmetry breaking?

- The fundamental interactions of elementary particles are described very successfully by quantum field theories that follow an underlying symmetry principle: “gauge invariance”

- This fundamental symmetry principle requires that all the elementary particles and force carriers should be massless

- However: $W, Z, \text{top, bottom, } \ldots$, electron are massive, have widely differing masses

How can elementary particles acquire mass without spoiling the fundamental symmetries of nature?
The Higgs mechanism

Spontaneous symmetry breaking: the interaction obeys the symmetry principle, but not the state of lowest energy

New field postulated that fills all of the space: the Higgs field

The state of the lowest energy of the Higgs field (vacuum state) does not obey the underlying symmetry principle (gauge invariance)

⇒ Spontaneous breaking of the gauge symmetry
**The Higgs field and the Higgs boson**

Higgs mechanism: fundamental particles obtain their **masses** from interacting with the Higgs field

Higgs boson(s): field quantum of the Higgs field
(like the photon is the quantum of the electromagnetic field)

Higgs coupling to other particles is proportional to their **masses**

The postulated Higgs boson is a **scalar** particle (spin 0)

Up to now **no** fundamental scalar particle has been observed in nature
The Higgs mechanism sounds like a rather bold assumption to cure a theoretical/aesthetical problem

But: we know that there has to be new physics that is responsible for electroweak symmetry breaking

Our current description breaks down at the TeV scale

⇒ The physics of electroweak symmetry breaking must manifest itself at the TeV scale

Possible alternatives to the Higgs mechanism:

- A new fundamental strong interaction (“strong electroweak symmetry breaking”)
- New dimensions of space (electroweak symmetry breaking via boundary conditions for SM gauge bosons and fermions on “branes” in a higher-dimensional space)
Higgs: last missing ingredient of the "Standard Model"

But: the Standard Model cannot be the ultimate theory

- The Standard Model does not include gravity
  ⇒ breaks down at the latest at $M_{\text{Planck}} \approx 10^{19}$ GeV

- “Hierarchy problem”: $M_{\text{Planck}}/M_{\text{weak}} \approx 10^{17}$

  How can two so different scales coexist in nature?

  Via quantum effects: physics at $M_{\text{weak}}$ is affected by physics at $M_{\text{Planck}}$

  ⇒ Instability of $M_{\text{weak}}$

  ⇒ Would expect that all physics is driven up to the Planck scale

- Nature has found a way to prevent this
  The Standard Model provides no explanation

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Hierarchy problem: how can the Planck scale be so much larger than the weak scale?

⇒ Expect new physics at the TeV scale to stabilise the hierarchy

Supersymmetry:
Large quantum corrections cancel out because of symmetry
fermions ⇔ bosons

Extra dimensions of space:
Fundamental Planck scale is $\sim$ TeV (large extra dimensions),
hierarchy of scales is related to a “warp factor”
(“Randall–Sundrum” scenarios)
**Higgs phenomenology: SM and beyond**

**Standard Model:** a single parameter determines the whole Higgs phenomenology: $M_H$

**Branching ratios of the SM Higgs:**

⇒ dominant BRs:

- $M_H \lesssim 140 \text{ GeV}$: $H \rightarrow b\bar{b}$
- $M_H \gtrsim 140 \text{ GeV}$: $H \rightarrow W^+W^-, ZZ$
In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

⇒ extensions of the Higgs sector having (at least) two doublets are quite “natural”

⇒ Would result in several Higgs states
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Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”
**Higgs physics beyond the SM**

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Example: SUSY in the “decoupling limit”

But there is also the possibility that none of the Higgs bosons is SM-like
"Simplest" extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters
Higgs physics in Supersymmetry

“Simplest” extension of the minimal Higgs sector:

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- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters

$\Rightarrow$ Two parameters instead of one: $\tan \beta \equiv \frac{v_u}{v_d}$, $M_A$ (or $M_{H^\pm}$)

$\Rightarrow$ Upper bound on lightest Higgs mass, $M_h$ (FeynHiggs):

[S. Heinemeyer, W. Hollik, G. W. ’99], [G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. ’02]

$M_h \lesssim 135$ GeV

Very rich phenomenology
BSM ⊕ Higgs phenomenology

- Large enhancement / suppression of standard search channels possible
  Example: large enhancement of $H\bar{b}b$ coupling
  $\Rightarrow$ large suppression of BR($h \rightarrow \gamma\gamma$), BR($h \rightarrow WW^*$), ...

- New channels, different phenomenology:
  - Experimental evidence for dark matter
    $\Rightarrow$ if dark matter particle is lighter than $M_H/2$
    $\Rightarrow$ large branching fraction into invisible particles
    $\Rightarrow$ large suppression of all other BRs
  - Higgs production in decays of BSM particles
    $h_i \rightarrow h_jh_j$ decays
  - Higgs–radion mixing, ...
  - Higgses with nearly degenerate masses: large interference effects, resonance-type behaviour possible
**Indirect constraints**

**EW precision data:**

\( M_Z, M_W, \sin^2 \theta_{\text{eff}}^{\text{lept}}, \ldots \)

**Theory:**

SM, MSSM, \ldots

\[ \Downarrow \]

Test of theory at quantum level: loop corrections

\[ \Downarrow \]

Sensitivity to effects from unknown parameters: \( M_H, M_{\tilde{t}}, \ldots \)

**Window to “new physics”**
Constraints on the SM Higgs from electroweak precision data

Indirect constraint on $M_{H_{SM}}$, no direct search limits included in the fit

$\Delta \chi^2$ vs. $m_H$ [GeV]

$\Delta \alpha_{\text{had}} = \Delta \alpha_{\text{(5)}}$
- $0.02750 \pm 0.00033$
- $0.02749 \pm 0.00010$
  incl. low $Q^2$ data

July 2011

$m_{\text{Limit}} = 161$ GeV

⇒ Preference for a light Higgs, $M_{H_{SM}} < 161$ GeV, 95% C.L.
Indirect prediction for the Higgs mass in constrained SUSY model: pre-LHC vs. LHC2011

$\chi^2$ fit for $M_h$, without imposing direct search limit CMSSM:

$\Rightarrow$ Accurate indirect prediction
Compatibility with LEP limit improves with the inclusion of LHC SUSY search limits
Higgs searches at LEP and the Tevatron

Search for the Standard Model Higgs at LEP

Dominant production process: $e^+e^- \rightarrow ZH$

Dominant decay process: $H \rightarrow b\bar{b}$

Highest energy: $E_{CM} \approx 206$ GeV

Exclusion limit, 95% C.L.: $M_H > 114.4$ GeV (expected: 115.3 GeV)
LEP limit on production cross section, normalised to SM case

95% C.L. upper bound:
- expected limit for background-only hypothesis, ±1σ, ±2σ
- observed limit

⇒ A Higgs with reduced couplings to gauge bosons is still possible below the limit on a SM-like Higgs
Example: MSSM with complex parameters:

*a very light SUSY Higgs?*

MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

Light Higgs, $h_1$: strongly suppressed $h_1VV$ couplings

Second-lightest Higgs, $h_2$, possibly within LEP reach (with reduced $VVh_2$ coupling), $h_3$ beyond LEP reach

Large $\text{BR}(h_2 \to h_1h_1) \Rightarrow$ difficult final state

\[ m_t = 174.3 \text{ GeV} \]

⇒ Light SUSY Higgs not ruled out!

[LEP Higgs WG '06]
SM Higgs search: Tevatron results

\[ (p\bar{p}, \, E_{CM} \approx 2 \, \text{TeV}) \]

Upper limit on the cross section (CDF + D0 combined), normalised to the SM expectation

[CDF and D0 Collaborations '11]

Tevatron Run II Preliminary, \( L \leq 8.6 \, \text{fb}^{-1} \)

\[
\begin{array}{c|c|c|c|c|c|c}
\text{m}_H (\text{GeV}/c^2) & 100 & 110 & 120 & 130 & 140 & 150 & 160 & 170 & 180 & 190 & 200 \\
\hline
95\% \text{ CL Limit}/\text{SM} & & & & & & & & & & & \\
\end{array}
\]

\[
\begin{array}{c|c|c|c|c|c|c}
\text{LEP Exclusion} & \text{Expected} & \text{Observed} & 1\sigma \text{ Expected} & 2\sigma \text{ Expected} & & \\
\hline
\text{Tevatron Exclusion} & & & & & & \\
\end{array}
\]

\[ \Rightarrow \text{In the regions where the observed limit drops below } 1 \] a SM-like Higgs is excluded at the 95\% C.L.

Slight excess (\( \sim 1\sigma \)) in low mass region.
Latest results from the LHC: status and interpretation

LHC, 2010 & 2011: \( pp, E_{CM} = 7 \) TeV

Production of a SM-like Higgs at the LHC:

Dominant production processes:

- Gluon fusion: \( gg \to H \), weak boson fusion (WBF): \( q\bar{q} \to q'\bar{q}'H \)
Main search channels for a SM-like Higgs

- $H \rightarrow \gamma\gamma$: loop-induced process, rare decay, most sensitive channel for a light Higgs
- $H \rightarrow b\bar{b}$: very challenging, huge QCD backgrounds
- $H \rightarrow \gamma\gamma$: good mass resolution $\Rightarrow$ look for small peak in $\gamma\gamma$ invariant mass distribution over continuum background (estimated from data; sidebands) [ATLAS Collaboration '12]

$\Rightarrow$ Excess at $M_H \approx 126$ GeV
**Main search channels for a SM-like Higgs**

- \( H \rightarrow ZZ(*) \rightarrow 4l \): “golden channel” for Higgs searches at LHC; clean signal, but low statistics in low-mass region

- \( H \rightarrow WW(*) \rightarrow ll\nu\nu \): higher rate, but poor mass resolution
  \( \Rightarrow \) signal would give rise to a broad excess over a wide range of Higgs masses  

[CMS Collaboration ’12]
ATLAS SM Higgs search: combined upper limit normalised to the SM expectation (left) and observed result vs. expectation for a SM Higgs signal (right)

[ATLAS Collaboration ’12]
Combined result from CMS

CMS SM Higgs search: combined upper limit normalised to the SM expectation

\[
CMS, \ \sqrt{s} = 7 \text{ TeV} \\
L = 4.6-4.8 \text{ fb}^{-1}
\]

\[\text{95\% CL limit on } \sigma/\sigma_{SM}\]

\[\Rightarrow \text{SM-like Higgs is excluded for } 127 \text{ GeV } \lesssim M_{H_{SM}} \lesssim 600 \text{ GeV}\]

⇒ SM-like Higgs is excluded for $127 \text{ GeV } \lesssim M_{H_{SM}} \lesssim 600 \text{ GeV}$
ATLAS result in low-mass region

ATLAS SM Higgs search: combined upper limit (left) and best-fit signal strength (right), normalised to the SM expectation

\[ \text{Observed} \pm 1 \sigma \pm 2 \sigma \]

\[ \int \text{Ldt} = 1.0-4.9 \text{ fb}^{-1} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ \Rightarrow \ 3.6\sigma \ \text{excess at} \ M_{H} \approx 126 \ \text{GeV} \]

signal strength compatible with SM expectation

Interpretation of excess is subject to “look elsewhere effect”
**CMS result in low-mass region**

Combined upper limit (left) and best-fit signal strength (right), normalised to the SM expectation

[CMS Collaboration '12]

$\Rightarrow 3.1\sigma$ excess at $M_H \approx 124$ GeV (smaller excess at $\approx 119$ GeV)

signal strength compatible with SM expectation

Interpretation of excess is subject to “look elsewhere effect”

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Exclusion limits from LEP, Tevatron, ATLAS, CMS:

Allowed mass range for SM Higgs reduced to

\[ 114 \text{ GeV} \lesssim M_{H^{SM}} \lesssim 127 \text{ GeV} \]

(+ high mass region above 600 GeV)
Exclusion limits from LEP, Tevatron, ATLAS, CMS:

Allowed mass range for SM Higgs reduced to

$114 \text{ GeV} \lesssim M_{H_{\text{SM}}} \lesssim 127 \text{ GeV}$

(+ high mass region above $600 \text{ GeV}$)

In agreement with favoured region from electroweak precision data, compatible with SM and MSSM
Summary on current situation of SM Higgs searches

Exclusion limits from LEP, Tevatron, ATLAS, CMS:
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In agreement with favoured region from electroweak precision data, compatible with SM and MSSM

Excess observed by ATLAS and CMS in SM-like Higgs searches near \[ M_{H_{\text{SM}}} \approx 125 \text{ GeV} \], supported by several channels (in particular \( \gamma\gamma, ZZ^* \))
Slight excess observed also at the Tevatron
Implications of the results from the SM Higgs searches for SUSY
The SUSY relations imply an upper bound on the mass of the light $\mathcal{CP}$-even Higgs, $M_h$

⇒ In the MSSM: $M_h \lesssim 135$ GeV
**Implications of the results from the SM Higgs searches for SUSY**

The SUSY relations imply an upper bound on the mass of the light $\mathcal{CP}$-even Higgs, $M_h$

$$\Rightarrow \text{In the MSSM: } M_h \lesssim 135 \text{ GeV}$$

- The detection of a SM-like Higgs with $M_H \gtrsim 135 \text{ GeV}$ would have unambiguously ruled out the MSSM

  Region above the upper bound of the MSSM is meanwhile ruled out for a SM-like Higgs

- Unexcluded low-mass region corresponds to the mass range predicted for the light $\mathcal{CP}$-even Higgs of the MSSM
Search for the heavy SUSY Higgs bosons $H, A$:
limits in the $M_A - \tan \beta$ plane

$\LARGE{[ATLAS \text{ Collaboration '11}]}
\LARGE{[CMS \text{ Collaboration '11}]}

$\begin{align*}
\text{CMS Preliminary 2011 4.6 fb}^{-1} \\
\text{ATLAS Preliminary}
\end{align*}$

$\Rightarrow$ Large coverage in $M_A - \tan \beta$ plane
LHC + LEP start to narrow down the region of very low $M_A$

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MSSM interpretation of latest Higgs search results from ATLAS and CMS

Statistical significance of reported excess near $125 \text{ GeV}$ is not yet conclusive

In the following: investigate MSSM interpretation of assumed Higgs signal at $125 \pm 1 \text{ GeV}$

Intrinsic theoretical uncertainties from unknown higher-order corrections, $\Delta M_{h}^{\text{intr}} \sim 2 \text{ GeV}$, and parametric uncertainties (variations of $m_t$ by $\pm 1\sigma$) taken into account.
Interpretation of an assumed Higgs signal at $\sim 125$ GeV

in terms of the light MSSM CP-even Higgs $h$

Assumed signal would imply a lower bound on $M_h$

$\Rightarrow$ Set parameters entering via higher-order corrections such that $M_h$ is maximised ($m_h^{\text{max}}$ benchmark scenario)

$\Rightarrow$ Lower bounds on $M_A$, $\tan \beta$

Search limits from LEP and from LHC $H, A \rightarrow \tau^+ \tau^-$ search taken into account:

*HiggsBounds*

[P. Bechtle, O. Brein, S. Heinemeyer, G. W., T. Stefaniak, K. Williams ’08, ’11]
Lower bounds on $M_A$ and $\tan \beta$ from assumed Higgs signal at $\sim 125$ GeV

Green region: compatible with assumed Higgs signal with / without $m_t$ variation

$\Rightarrow \tan \beta \gtrsim 3$, $M_A \gtrsim 130$ GeV, $M_{H\pm} \gtrsim 152$ GeV

[S. Heinemeyer, O. Stål, G. W. ’11]
Interpretation of an assumed Higgs signal at $\sim 125$ GeV in terms of the heavy MSSM CP-even Higgs $H$

Scan over $M_A, \tan \beta, M_{\text{SUSY}}, X_t$

$\Rightarrow$ possible for low $M_A$, moderate $\tan \beta$

[S. Heinemeyer, O. Stål, G. W. ’11]

Higgs searches at the LHC: where do we stand?, Georg Weiglein, WA Sitzung, DESY, 02/2012 – p.34
Interpretation of an assumed Higgs signal at $\sim 125$ GeV in terms of the heavy MSSM CP-even Higgs $H$

The light Higgs $h$ in this scenario has a mass that is always below the LEP limit of $M_{H_{\text{SM}}} > 114.4$ GeV (with reduced couplings to gauge bosons, in agreement with LEP bounds)

Could have, for instance, $M_H \sim 125$ GeV, $M_h \sim 98$ GeV (slight excess observed at LEP at $M_h \sim 98$ GeV)

⇒ It is important to extend the LHC Higgs searches to the region below 114 GeV!
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The best way of experimentally proving that an observed state is not the SM Higgs is to find in addition (at least one) non-SM like Higgs!
Conclusions

Higgs searches have made tremendous progress with the latest results from the LHC and the Tevatron
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→ Either a state compatible with a SM Higgs will be discovered this year or the SM will be ruled out
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- Figuring out the nature of an observed Higgs-like state (SM or something else, elementary or composite, . . . ?) will both be exciting and challenging