Exciting (the) Vacuum: Possible Manifestations of the Higgs particle at the LHC

David E Kaplan
5 Aug 2009
The standard model of particle physics

Leptons
- $e$, $\mu$, $\tau$
- $\nu_e$, $\nu_\mu$, $\nu_\tau$

Quarks
- $u$, $c$, $t$
- $d$, $s$, $b$

Particles:
- Photon ($\gamma$)
- W bosons ($W^+, W^-$)
- Z boson ($Z^0$)
- Gluons ($g$)

Higgs Boson
The LHC

CMS

LHCb

Atlas

ALICE
QM and SR

\[ E = mc^2 \]

Kinetic energy can be converted to mass.

Particles are excitations of (quantized) fields -- the fields are fundamental.

We are searching for the fields that fill spacetime by seeing what particle states can be excited.

\[ \hbar = c = 1 \]
Summary

- What is the Higgs Boson
- How do we find it (and why haven’t we)?
- What will it look like?
What is the Higgs?

- Differentiate Between the ‘Higgs Mechanism’ and the ‘Higgs Boson’

The *mechanism* is a consistent way to give spin-one particles a mass -- the Z and W bosons mass in the standard model (with quark/lepton masses as a bonus)
**Internal Symmetry Breaking**

The potential is independent of theta.

\[ V(\phi) = (|\phi|^2 - v^2)^2 \]

\[ \phi \rightarrow e^{i\alpha}\phi(x) \]

\[ |\phi_{min}| = v \]

\[ \phi(x) = (v + \rho(x))e^{i\theta(x)} \]

\[ V = (2v\rho + \rho^2)^2 \]
The potentials live at every point in space and waves of fluctuations between vacua move through space.
Gauge-Goldstone mixing

The pi-particle gets ‘eaten’ - is not an eigenstate of the Hamiltonian (not even approximate).

Lorentz invariance guarantees that this completes the spin-one multiplet.
Radial Excitations

\[ V(\phi) = (|\phi|^2 - v^2)^2 \]

\[ \phi \rightarrow e^{i\alpha} \phi(x) \]

\[ |\phi_{\text{min}}| = v \]

\[ \phi(x) = (v + \rho(x))e^{i\theta(x)} \]

\[ V = (2v\rho + \rho^2)^2 \]

That’s the Higgs field
Mass for everyone

What it ‘adds’ to those fields must be Lorentz invariant.

A rest mass.
Julian Schwinger, in 1961, had shown that particles with spin 1 could be massive in a consistent theory (i.e., not break gauge invariance), despite the common wisdom that it was not so (shown in 1949 by Julian Schwinger).

The next year, Philip W. Anderson, inspired by Schwinger’s work, showed an explicit example in condensed matter in which a gauge excitation (effectively a spin-1 particle) gained a degree of freedom and was massive.

(They read each other’s papers back then...
... and the particle

Englert and Brout wrote down a relativistic field theory where a scalar field condenses and spin one particles are massive (1964).

Peter Higgs, wrote a similar paper and submitted to the same journal two months later.

At the same time, G. S. Guralnick, C. R. Hagen, and T. W. B. Kibble produced the same mechanism independently (1964).
Glashow had a model with the right spin 1 particles, but no explanation for their mass (1961), based on an earlier project given to him by his advisor, Julian Schwinger.

Weinberg, and independently Salam, incorporated the mechanism in Glashow’s model and could also give fermions their masses (1967).

The three shared the 1979 Nobel Prize.
How do we find it?

The Higgs couples strongly to heavy fields and weakly to light fields (interactions are proportional to mass).

Problem - light particles are what we collide (they don’t decay).
Original Searches

(1976) Linde/Weinberg: $m_h > 4$ GeV

(1989) LEP I: $m_h > 25$ GeV
(1997) LEP I: $m_h > 55$ GeV
(2002) LEP II: $m_h > 114$ GeV
Production at ‘Hadron’ Colliders (Tevatron and the LHC)
CMS, 30 fb$^{-1}$

14 TeV!
D. Kovar, HEPAP meeting (May, 2009)
If the standard model is wrong...

...will we still see the Higgs?
Regulating the Theory

Whatever makes this finite becomes important at energies of order $\Lambda$

From the top loop,

$$\delta m_h \sim (1/5) \Lambda,$$
and so the cutoff is $\Lambda \sim 1$ TeV
Regulating the Theory

Whatever makes this finite becomes important at energies of order $\Lambda$

Momentum-dependent couplings (compositeness)

$\delta m_h \sim (1/5)\Lambda$, and so the cutoff is $\Lambda \sim 1$ TeV
Regulating the Theory

Whatever makes this finite becomes important at energies of order $\Lambda$

New particles in the loop

$\delta m_h \sim (1/5)\Lambda$, and so the cutoff is $\Lambda \sim 1$ TeV
Regulating the Theory

Supersymmetry: copies of the standard model particles with over 100 new parameters (but weakly coupled).

Composite Higgs (Randall-Sundrum ultraviolet structure)/Extra Dimensions

Technicolor (no Higgs)

I focus on supersymmetry as my example.
Variations on a Higgs

- Multiple Higgses (new light neutral particles)
- Higgs, but different production mechanism?
- Higgs, but different decay products?
- (No Higgs?)
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- (No Higgs?)
New Higgs decays

Decay rates are proportional to a positive power of the mass.

2 x mass

\[ \mu \quad s \quad \gamma \quad c \quad T \quad b \quad g \quad W \quad Z \quad t \]

\[ 3.5 \quad 10 \quad 160 \quad 182 \quad 350 \]

\[ h \quad b \quad \bar{b} \]
New Higgs decays

$\Gamma \sim \frac{m_X^4}{m_h v^2}$ for a scalar
Non-Standard Higgs?

95% CL limit on $\sigma^2$

LEP

$\sqrt{s} = 91-210$ GeV

(a) Observed

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Expected for background

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$m_H(\text{GeV}/c^2)$

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Higgs Boson Search Results

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Exclusion contour for a non-standard Higgs boson search at LEP.
Non-Standard Higgs?

LEP
\( \sqrt{s} = 91-210 \text{ GeV} \)

95\% CL limit on \( \sigma^2 \)

(a)

Suppress SM decays to 20\%
Suppression of standard searches

If the rate of Higgs boson decays to multiple jets is, for example, 5 times that into standard model modes, standard searches are dramatically weakened.
Supersymmetric examples

‘NMSSM’
Nilles, Srednicki, Wyler (1983), Frere, Jones, Raby (1983), ...

Dermisek, Gunion (2005)
Decays into fermions

\[ h \xrightarrow{\chi} \chi \]

In supersymmetry - lightest superpartner is stable

Haber, Kane (1984)

Or not...

Carpenter, DEK, Rhee (2006)
Other scalar decays in supersymmetry

LEP Bounds

\[ h \rightarrow aa \rightarrow \bar{b}b\bar{b}b \quad m_h > 110 \text{ GeV} \]
\[ h \rightarrow aa \rightarrow \bar{\tau}\tau\bar{\tau}\tau \quad m_h > 86 \text{ GeV} \]
\[ h \rightarrow aa \rightarrow gg\bar{g}g \quad m_h > 82 - 95 \text{ GeV} ? \]
\[ h \rightarrow ss \rightarrow aaa\bar{a} \rightarrow \bar{b}b\bar{b}b\bar{b}b \quad m_h > 82 \text{ GeV}?\]

Typical decays

A

B

C

D
Need to look at the new decay modes

The invisible Higgs
Two forward jets

Eboli, Zeppenfeld (2007)

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>150</th>
<th>200</th>
<th>300</th>
<th>400</th>
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<tbody>
<tr>
<td>10 fb$^{-1}$</td>
<td>12.6%</td>
<td>13.0%</td>
<td>13.3%</td>
<td>14.1%</td>
<td>16.3%</td>
<td>22.3%</td>
<td>30.8%</td>
</tr>
<tr>
<td>100 fb$^{-1}$</td>
<td>4.8%</td>
<td>4.9%</td>
<td>5.1%</td>
<td>5.3%</td>
<td>6.2%</td>
<td>8.5%</td>
<td>11.7%</td>
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</table>

Eboli, Zeppenfeld (2007)
Two forward jets

\[ \overline{E_T} \]

\begin{tabular}{lcccccccc}
\hline

$M_H$ & 110 & 120 & 130 & 150 & 200 & 300 & 400 \\
(GeV) & & & & & & & \\
10 fb$^{-1}$ & 12.6\% & 13.0\% & 13.3\% & 14.1\% & 16.3\% & 22.3\% & 30.8\% \\
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\hline
\end{tabular}

Eboli, Zeppenfeld (2007)
Hadronic decays

Much harder.

Signal:
\[ \sigma \sim 25 \text{pb} \]
\[ 5 \times 10^4 \text{ events} \]

Background:
\[ \sigma \sim 0.5 \mu \text{b} \]
\[ \sim 500,000 \text{pb} \]
\[ 10^9 \text{ events} \]

\[ h \]

\[ a \]
\[ \overline{b} \]
\[ b \]
\[ \overline{b} \]

\[ P_T \text{ cuts help!} \]
Nice kinematic regions

Background

\begin{align*}
M_h &= 115 \text{ GeV}, \quad M_a = 15\text{GeV} \\
M_h &= 145 \text{ GeV}, \quad M_a = 15\text{GeV} \\
M_h &= 115 \text{ GeV}, \quad M_a = 35\text{GeV} \\
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\end{align*}
Nice kinematic regions

<table>
<thead>
<tr>
<th>$m_h$</th>
<th>$m_a$</th>
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<th>$\epsilon_{req}$</th>
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<tr>
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<td>165</td>
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<td>1.00</td>
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</table>
For all gluons

Background at least 1,000 times larger - no tricks yet...
Why believe in light scalars?
Interlude: Nambu-Goldstone Bosons

Let’s see the classical phenomenon using the wave description. An infinite straight rope breaks translation invariance in directions perpendicular to the rope. The transverse waves are the Goldstone modes.

\[
\mathcal{L} = \frac{1}{2} \sigma \left( \frac{\partial \phi}{\partial t} \right)^2 - \frac{1}{2} \tau \left( \frac{\partial \phi}{\partial x} \right)^2 \quad \rightarrow \quad \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = \frac{\partial^2 \phi}{\partial x^2}
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Fourier transform:

\[ \phi(x, t) = \int \frac{dk \, d\omega}{4\pi^2} \tilde{\phi}(k, \omega) e^{i(kx-\omega t)} \quad \rightarrow \quad \omega^2 = k^2 c^2 \]

Can have waves with arbitrarily low frequency.
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\]

Can have waves with arbitrarily low frequency.

quantize:

Particles with arbitrarily low energy \(\rightarrow\) massless particles

\[
E^2 = p^2
\]
Internal Symmetry Breaking

\[ V(\phi) = (|\phi|^2 - v^2)^2 \]

This again...
Internal Symmetry Breaking

The potentials live at every point in space and waves of fluctuations between vacua move through space.
Propagating Goldstones
Propagating Goldstones
Propagating Goldstones
Propagating Goldstones

These particles have no potentials and no interactions (at long wavelengths)
Pseudo-Goldstone Bosons

Equation of motion:

\[ \mathcal{L} = \frac{1}{2} \sigma \left( \frac{\partial y}{\partial t} \right)^2 - \frac{1}{2} \tau \left( \frac{\partial y}{\partial x} \right)^2 - \frac{1}{2} \eta^2 y^2 \]

\[ \frac{1}{c^2} \frac{\partial^2 y}{\partial t^2} = \frac{\partial^2 y}{\partial x^2} - \mu^2 c^2 y^2 \]
Pseudo-Goldstone Bosons

A mass gap appears:

\[ \omega^2 = k^2 + \mu^2 \]
Decaying fermion

6 jets in principle has a smaller background, but these jets are of very low energy
Macroscopic lifetimes

What allows us to distinguish jets with bottom quarks is their decay length:

3-body decay

\[ \Gamma \sim \frac{m_b^5}{v^4} \times \epsilon^2 \]

\[ \ell_b = c \tau_b \simeq 0.5 \text{ mm} \]
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Neutralinos may have a long decay length.

$$L \sim 3 \mu m \left( \frac{10^{-2}}{\lambda''} \right)^2 \left( \frac{m_{\tilde{q}}}{100 \text{ GeV}} \right)^4 \left( \frac{30 \text{ GeV}}{m_\chi} \right)^5$$
Part b

Atlas

CMS

LHCb

ALICE
Pile-up veto:
Remove bunch crossings with too many beam-beam interactions
(not applied to $\mu$-trigger)

- Hardware trigger (customs boards) with 4 $\mu$s latency
- Reduces 10 MHz inelastic collision rate to 1 MHz:
  - $P_{T\mu_1} + P_{T\mu_2} > 1.3$ GeV
  - $E_{T\gamma} > 2.8$ GeV  $E_{T\gamma} > 2.6$ GeV  $E_{T\pi^0} > 4.0$ GeV
  - $E_{T\pi,K,p} > 3.6$ GeV
Boosted frames

Event typically boosted w.r.t. the lab frame. Allows for the spreading out of b-decays due to time dilation.

Hard partons inside protons typically carry small fractions of the total momentum.
Higgs/Neutralino search at LHCb

At least 5 charged tracks in acceptance each

Single Events
Double Events

squark mass = 1 TeV
coupling = 0.01

1 year of running

Aside: all susy

DEK, K. Rehermann (2007)
LHCb simulated data after acceptance requirements and cuts:

Could reconstruct the Higgs and measure its mass with ~10% accuracy.

Other discriminants

So macroscopic decays (‘displaced vertices’) and special kinematics allow for distinguishing above background.

We need more generic observables if possible...
Color flow
Showering differences

The “Chudakov Effect” (QED)

\[ \theta_{ee}, \theta \ll 1 \rightarrow k_T \sim zp\theta \]

\[ \Delta E \sim k_T^2/zp \sim zp\theta^2 \sim 1/\Delta t \]

\[ \Delta b \sim \theta_{ee}\Delta t > \lambda/\theta \sim (zp\theta)^{-1} \]

\[ \theta_{ee}(zp\theta^2)^{-1} > (zp\theta)^{-1} \rightarrow \theta_{ee} > \theta \]
Preliminary tests

Here is a simulation of Higgs production and QCD production of two b-jets boosted w.r.t. the lab frame.
Preliminary tests

Here is a simulation of Higgs production and QCD production of two b-jets boosted w.r.t. the lab frame.
It has been 30 years since something unexpected happened at a collider.
Conclusion

The Standard Model is our best guess
Conclusion

Theory strongly suggests physics beyond the standard model.

The Higgs is very susceptible to huge modifications in phenomenology

A broader range of search strategies is required to cover the possibilities for the Higgs
Excess...
Effects on Z-boson Data

LEP I made 17 million Z-bosons…
Precision Tests

Precision measurements agree well

biggest discrepancy

\[ \chi^2 / \text{d.o.f.} = 16.8 / 14 \]

continuing updates
Higgs mass fit

90 $^{+36}_{-27}$ GeV

$< 163$ GeV (95\% C.L.)

LEP II Bound: $> 114.4$ GeV

Tevatron: $< 160$ or $> 170$ GeV

$\Delta \chi^2$

$\Delta \alpha_{\text{had}}^{(5)} = 0.02758 \pm 0.00035$

$0.02749 \pm 0.00012$
iincl. low $Q^2$ data

Theory uncertainty

March 2009

m_{\text{Limit}} = 163$ GeV
The Higgs Completes the Standard Model

At high energies, the probability of scattering is greater than one.

\[ \lim_{E \to \infty} A \propto E^2 \]

Theory breaks down at \( E \sim 1 \text{ TeV} \)
The Higgs Completes the Standard Model

At high energies, the probability of scattering is greater than one.

Theory breaks down at $E \sim 1 \text{ TeV}$
The Higgs Completes the Standard Model

\[ \lim_{E \to \infty} A \propto \text{const.} \]

With the Higgs particle, the theory remains predictive.