In Search of...
The Higgs boson
or
"Is this what we ordered?"

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What does it mean to find the Higgs?

- Higgs is the agent responsible for EWSB
  $\rightarrow$ must have gauge couplings to weak bosons
  $\rightarrow$ produced in association with W, Z

- Higgs generates fermion masses
  $\rightarrow$ coupling strength proportional to mass
  $\rightarrow$ light Higgs decays predominantly to $b\bar{b}$

So is seeing a “bump” in $(W, Z)b\bar{b}$ events around $m_{b\bar{b}}$ of 115 GeV or so evidence for the light Higgs we expect?

Tevatron finds a bump!

Let's suppose that Run II of the Tevatron, after 5 years or so, sees a resonance around 115 GeV in $Wb\bar{b}, Zb\bar{b}, t\bar{t}b\bar{b}$ events, the "expected" Higgs boson channels.

This could be any of the following:

- A SM Higgs
- The light CP-even Higgs of the MSSM
- The heavy CP-even Higgs of the MSSM
- A non-SUSY light CP-even Higgs of a 2HDM
- A non-SUSY heavy CP-even Higgs of a 2HDM
- A neutral technicolor or topcolor pion
- A radion (or Higgs-radion mixing)
- A flavon, or something even weirder, etc...

Point: lots of things can LOOK like a Higgs, i.e. a narrow $b\bar{b}$ resonance, when produced with low statistics at the Tevatron.

What do you (the experimentalists) do to sort this out?
(Theorists will be busy trying to claim bragging rights for SM v. MSSM. v. technicolor v. topcolor, etc...)

What we need to do

First, observe all the physical states
(1HDM, 2HDM, SUSY, topcolor, etc.)

Second, determine all the quantum numbers of the states:

- charge, color (easy)
- masses (mostly easy)
- spins (moderately easy)
- SM couplings [gauge, Yukawa] (harder)
- total widths (maybe yet harder)
- CP transformation properties (not so difficult)
- self-couplings (seriously difficult)

Are all the bumps there?

Observing all the physical states might be tricky.

In the case of the MSSM, H & A can be heavy and degenerate. Observing them at all might be difficult, depending on $tan\beta$. If visible, separating them is an enormous challenge, and may not be possible at a hadron collider or e^+e^- machine. A muon collider could do it, but this is presently only fantasy.

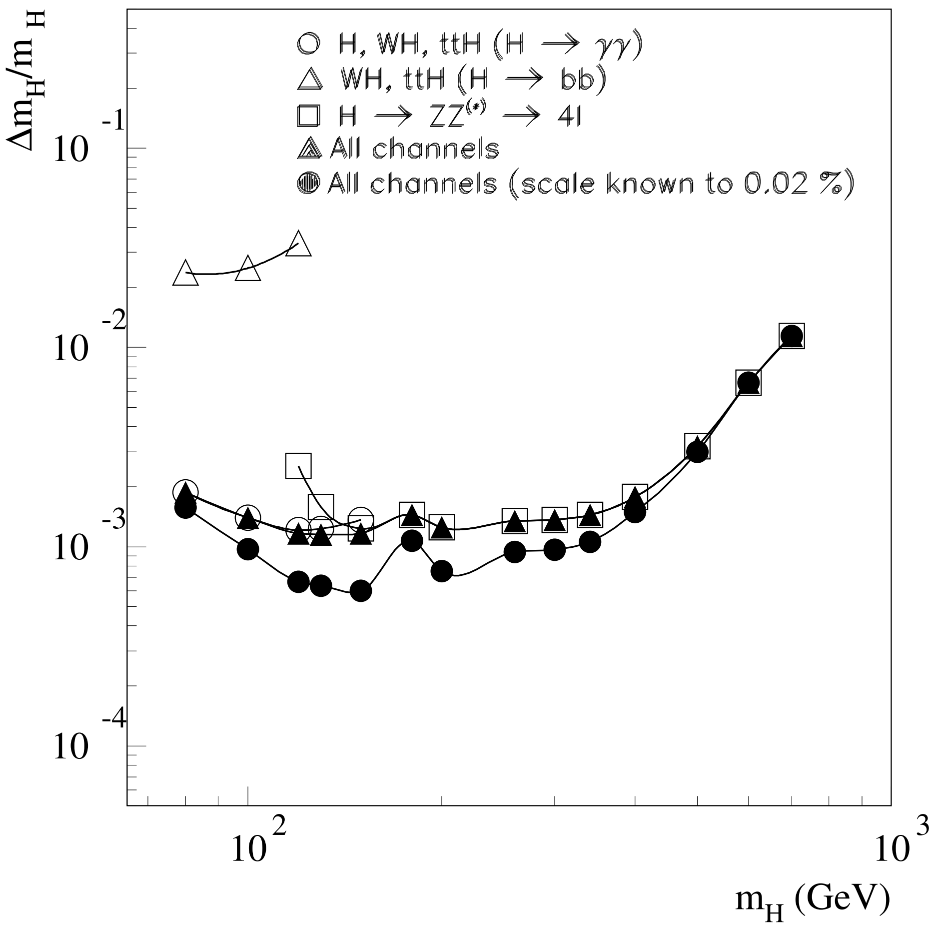
This means that sorting out CP in the Higgs sector might be impossible.

A heavy H^+/H^- can also be difficult to pick out of the backgrounds.

In topcolor models, the toppions might be visible, but the Higgs modes can be extremely heavy, out of reach at the LHC. Seeing only 3 physical states would be perplexing, and doesn't really reveal the new physics.

If some physical states are invisible or barely visible, then measuring their properties will be essentially impossible. Our knowledge of the EWSB sector is then incomplete!
Again we ask, is this what we ordered?

LHC is expected to achieve 0.1% or better Higgs mass resolution.



Expected Higgs boson mass resolution for ATLAS.

Depending on what new physics might be found, this could be more than sufficient.

E.g., in the MSSM, it would require 4-loop calculations for theory to match the precision of data.

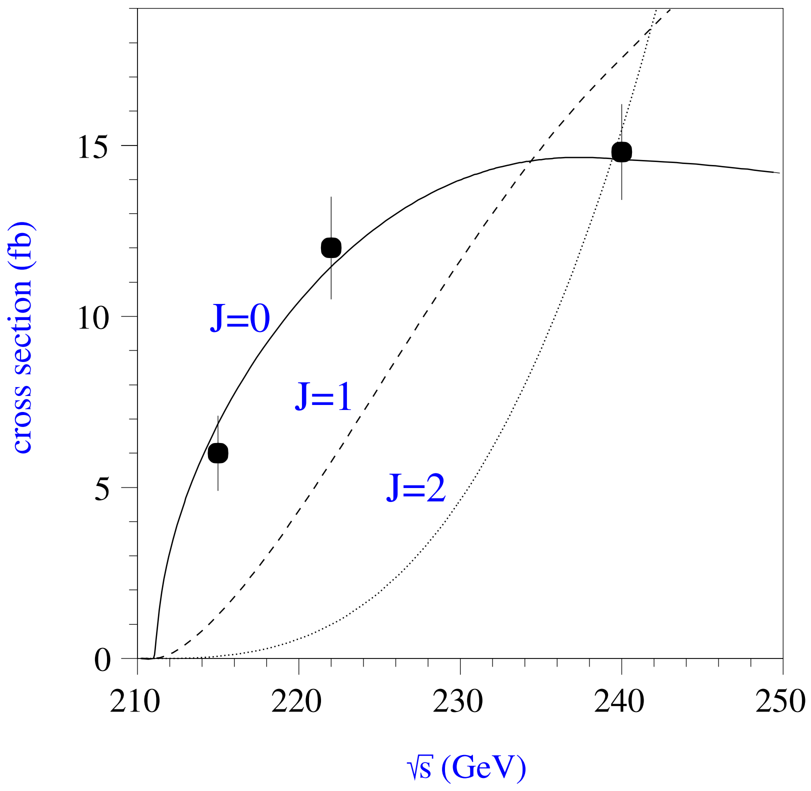
Spin of the resonance

It better be a scalar!

We will know a few things from the LHC:

- If $H \to \gamma\gamma$ is seen, H is not a vector, but $\gamma\gamma$ is not observable for $M_H \gtrsim 150$ GeV.
- $H \to ZZ \to l^+l^-l^+l^-$ can demonstrate scalar nature, but is not accessible for some Higgs masses.

TESLA or NLC can make this measurement a piece of cake: examine the ZH cross section behavior at threshold.



Determination of Higgs couplings

For a light Higgs, any coupling can be exchanged for a partial width:

$$\Gamma_i \propto g_i^2$$

e.g.: $\Gamma_W \propto g^2$, $\Gamma_\tau \propto Y_\tau^2$

Higgs production/decay cross sections may then be written in terms of partial widths:

$$\sigma \propto \frac{\Gamma_i \cdot \Gamma_f}{\Gamma_{tot}} = \Gamma_i \cdot BR$$

$\to$ Need multiple measurements to determine even a single coupling!

A few points...

1. We must examine channels where both the Higgs production rate and the decay branching ratio are sufficiently large to see enough events.
2. A heavy Higgs boson has a large width, which can be measured experimentally in the mass peak. Direct gauge coupling measurments are possible, but fermion couplings are not as BR($f\bar{f}$) are too small.
3. A light Higgs boson has a width smaller than experimental resolution, so we are one measurement short to determine couplings directly, but some fermionic decays are accessible. We must be more clever!
4. We expect a light Higgs boson from EW precision data fits – although, if there is TeV-scale new physics other than SUSY, this expectation is misleading.
5. Ideally we would like to measure all Higgs couplings, but this is dreaming: light fermions couple very weakly, so experimentally they are unobservable. (maybe...) (Does the up quark even have a mass??)

Estimated LHC accuracy of the couplings

1. $\frac{\text{WBF } H\to\tau\tau}{\text{WBF } H\to WW}$ yields $7-10\%$ for Y_t

2. $\frac{\text{WBF } H\to\gamma\gamma}{\text{WBF } H\to WW}$ or $\frac{gg\to H\to\tau\tau}{gg\to H\to WW}$ yields $7-10\%$ for $g_{H\gamma\gamma}$

3. $\frac{gg\to H\to\gamma\gamma}{\text{WBF } H\to\gamma\gamma}$ or $\frac{gg\to H\to WW}{\text{WBF } H\to WW}$ yields $10-15\%$ for g_{Hgg}

4. overall 5% for g_{HWW} (and g_{HZZ} by SU(2))

But for this to happen we first need a LOT of work:

$\to$ full NNLO or even NNNLO $gg\to H$

$\to$ better understanding of min. bias and underlying event

$\to$ better understanding of radiation in WBF events

$\to$ QCD contributions to Hjj production

$\to$ NLO or “sideband” understanding of $t\bar{t}+jets$

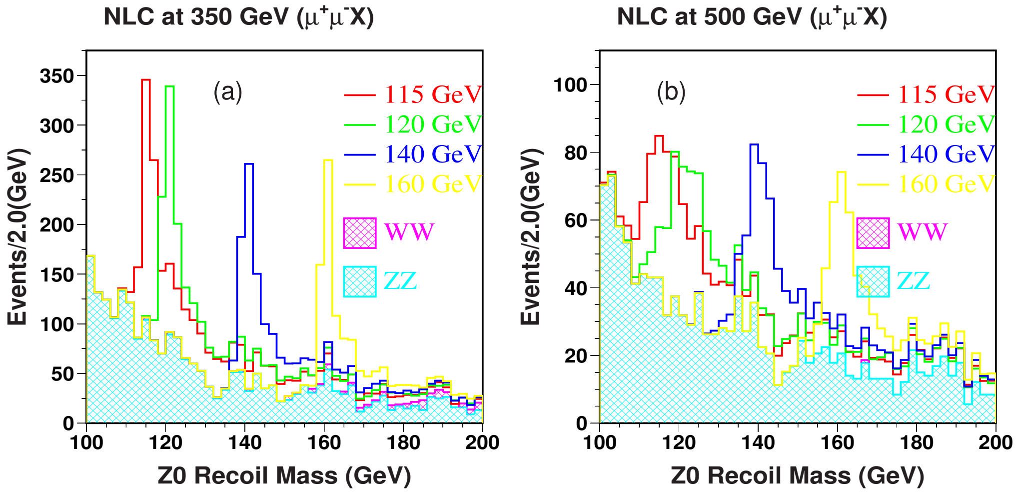
HIGGS COUPLINGS AT A LINEAR COLLIDER

Here we can measure the total ZH production cross section, which depends only on g_{ZZH} (Γ_Z) and is independent of the total width (Γ_{tot}).

The key to this is the recoil mass distribution.

Look at $Z \to \mu^+\mu^-$ events, and construct the following:

$$M_{rec} = \sqrt{s - 2\sqrt{s} \cdot E_{\mu^+\mu^-} + M^2_{\mu^+\mu^-}}$$



The Higgs peak above SM backgrounds is the total ZH cross section.

Accuracy at TESLA or NLC is $\lesssim 5\%$.

Looking in the same $ZH, Z \to \mu^+\mu^-$ channel but specific Higgs decays, we then know that Higgs BR "exactly".

To determine individual couplings, we still need the total Higgs width. There are at least 3 possible methods:

1. $\Gamma_{tot} = \sigma_{H\nu\bar{\nu}}$ / BR(WW) / BR($b\bar{b}$)
   for $\nu\bar{\nu}b\bar{b}$ events (light Higgs).

2. $\Gamma_{tot} = \sigma_{H\nu\bar{\nu}}$ / BR$(WW)^2$
   for $\nu\bar{\nu}W^+W^-$ events (heavier Higgs).

3. $\Gamma_{tot} = \sigma_{ZH}$ / BR$(WW)^2$
   for ZW^+W^- events (heavier Higgs).

The uncertainty on the total width is also $\lesssim 5\%$.

An e^+e^- machine can clearly perform much better model distinguishing than the LHC for a Higgs of mass $M_H \lesssim 200$ GeV.

For a heavier Higgs, everything is much tougher anyway, because the fermion couplings are not accessible (except top, indirectly).

$H \to \mu^+\mu^-$: A Snowmass study

Even a linear collider can't observe $H \to \mu^+\mu^-$.

If nature realizes a 2HDM and $tan\beta$ is large, then $H \to c\bar{c}$ is unobservable, and we have no idea if the "Higgs" has only third-generation couplings or not!

This is an uncomfortable hole to be in.

A Snowmass study of $pp \to WW \to H$ (weak boson fusion) showed that a VLHC operating at $\sqrt{s} = 200$ TeV would be able to measure the muon Yukawa coupling to about 10%.

This would establish the second generation couplings, but would also leave the first generation couplings unchecked.

We apparently can't have it all...

The Higgs potential

SM Higgs potential: $V(H) = -\lambda v^2 H^\dagger H + \lambda (H^\dagger H)^2$ and so $M_H = v\sqrt{2\lambda}$, but lambda is a "free" parameter in the SM.

In a 2HDM, things are more complicated:

$$\begin{aligned} V = \quad & m_1^2|H_1|^2 + m_2^2|H_2|^2 + (m_3^2 H_1 H_2 + h.c.) \\ & + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 \\ & + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2)^2 + \lambda_4 (H_1 H_2)(H_1^\dagger H_2^\dagger) \\ & + \left[\frac{\lambda_5}{2}(H_1 H_2)^2 + \left[\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_1^\dagger H_2^\dagger)\right](H_1 H_2) + h.c.\right] \end{aligned}$$

But in SUSY, these become gauge couplings:

$$\lambda_1 = \lambda_2 = \frac{(g^2+g'^2)}{4}, \; \lambda_3 = \frac{(g^2-g'^2)}{4}, \; \lambda_4 = \frac{-g^2}{4}, \; \lambda_{5,6,7} = 0$$

Relations of the λ_i reveal the fundamental nature of the deeper physics that contains the Higgs sector.

In some sense, mapping the Higgs potential is the most interesting part of the game!

What have we learned?

Observing a resonance in an expected channel at the Tevatron or LHC (say, $Wb\bar{b}$ or $t\bar{t}b\bar{b}$) is FAR from identifying the Higgs boson, *especially* if the experiment in question produces low statistics.

Proving or disproving the Higgs nature of the new object may take only a few years at the LHC: unexpected or missing states, and couplings.

However, determining the specific model of new physics could easily take a decade and input from a linear collider or other machine beyond the LHC. Some measurements may ultimately be impossible.