Particle Physics II
Lecture 10: The Higgs boson

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The Higgs mechanism

- we have introduced ideas of gauge symmetries and electroweak unification:
  - problem: it works only for massless gauge bosons
  - introducing masses in any naïve way violates the underlying gauge symmetry
- the Higgs mechanism provides a way of giving the gauge bosons (and fermions) mass
- here, we motivate the main idea behind the Higgs mechnism
- start with an analogy

The Higgs mechanism: Analogy

- consider electromagnetic radiation propagating through a plasma
- plasma acts as a polarizable medium $\implies$ obtain "dispersion relation":

$$n^2 = 1 - \frac{n_e e^2}{\varepsilon_0 m_e \omega^2} = 1 - \frac{\omega_p^2}{\omega^2},$$

where

  - n – refractive index,
  - ω – angular frequency
  - ω_p – plasma frequency

- because of interactions with the plasma, wave-groups only propagate if they have frequency/energy greater than some minimum value:

$$E > E_0 = \hbar \omega_p$$

- above this energy waves propagate with a group velocity:

$$v_g = c^2 / v_p = nc$$

- dropping the subscript and using the previous expression for n:

$$v^2 = c^2 n^2 = c^2 \left(1 - \frac{\hbar^2 \omega_p^2}{\hbar \omega^2} \right) = c^2 \left(1 - \frac{E_0^2}{E^2} \right)$$

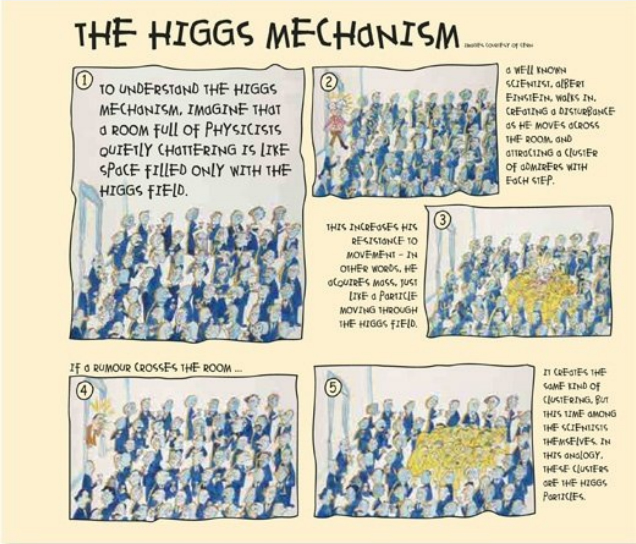
- rearranging gives

$$\frac{E_0^2}{E^2} = 1 - \frac{v^2}{c^2} \implies E = E_0 \left(1 - \frac{v^2}{c^2} \right)^{-\frac{1}{2}} = \gamma m c^2 \text{ with } m = E_0 / c^2$$

Result: massless photons propagating through a plasma behave as massive particles propagating in a vacuum!

The Higgs mechanism

- propose a scalar field with a non-zero vacuum expectation value (VEV)
- massless gauge bosons propagating through the vacuum with a non-zero Higgs VEV correspond to massive particles:

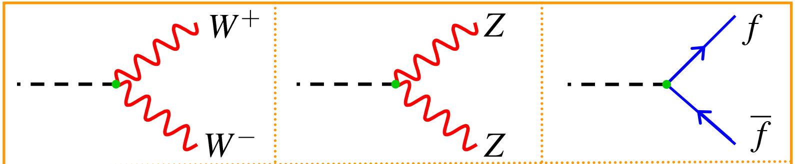


The Higgs mechanism

- the Higgs boson is electrically neutral but carries weak hypercharge of 1/2
- the photon does not couple to the Higgs field (charge = 0!) and remains massless
- the W bosons and the Z couple to weak hypercharge and become massive
- the Higgs mechanism results in absolute predictions for masses of gauge bosons
- in the SM, fermion masses are also ascribed to interaction with the Higgs field, however there is no prediction of the masses - they are just put in by hand

The Higgs mechanism

- Feynman vertex factors:



$ig_W m_W g^{\mu\nu}$	$ig_Z m_Z g^{\mu\nu}$	$-i\frac{g_W}{2m_W}m_f$

- within the SM of electroweak unification with the Higgs mechanism:

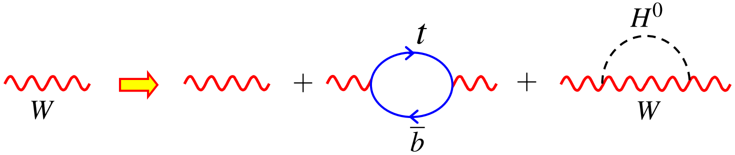
$\Longrightarrow$ relations between standard model parameters

$$m_W = \left(\frac{\pi\alpha_{em}}{\sqrt{2}G_F}\right)^{\frac{1}{2}} \frac{1}{\sin\theta_W},\; m_Z = \frac{m_W}{\cos\theta_W}$$

- hence if we know any three of: α_{em}, G_F, m_W, m_Z, $\sin\theta_W$ – predict the other two

Precision tests of the standard model

- from LEP have precise measurements: can test predictions of the SM:
  - e.g. predict $m_W = m_Z \cos\theta_W$
  - measure $m_Z = 91.1875 \pm 0.0021$ GeV, $\sin^2\theta_W = 0.23154 \pm 0.00016$
  - therefore expect: $m_W = 79.946 \pm 0.008$ GeV
  - but measure $m_W = 80.376 \pm 0.033$ GeV
- close but not quite right: we only considered lowest order diagrams
- mass of W boson also includes terms from virtual loops

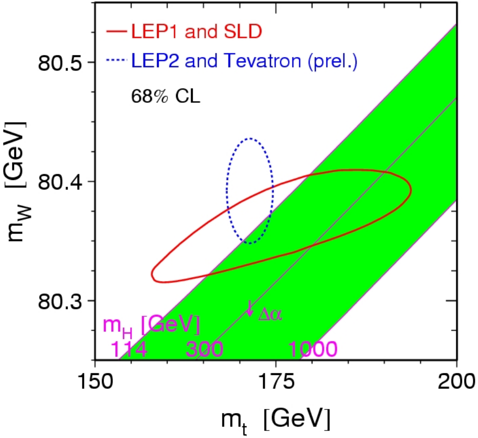


$$m_W = m_W^0 + a m_t^2 + b \ln\left(\frac{m_H}{m_W}\right)$$

- above "discrepancy" due to these virtual loops: making very high precision measurements become sensitive to the masses of particles inside the virtual loops

Precision tests of the standard model

- the W mass depends on the Higgs mass (only logarithmically)
- measurements at LEP times were sufficiently precise to have some sensitivity to the Higgs boson mass

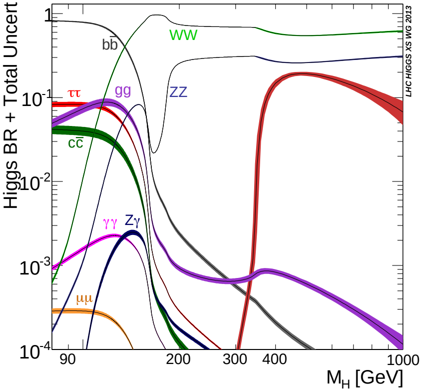


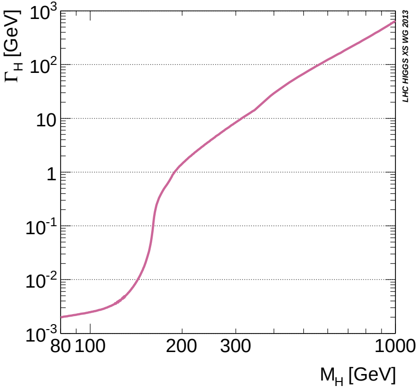
- direct and indirect values of the top quark and W mass can be compared to the prediction for different Higgs boson mass:
  - direct: W and top quark masses from direct reconstruction
  - indirect: from SM interpretation of Z mass, θ_W
- data favored a light Higgs boson:

$$m_H < 200 \text{ GeV}$$

Before LHC times: hunting the Higgs boson at LEP

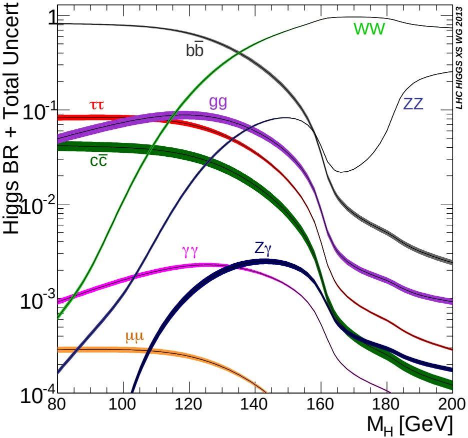
- for Higgs boson searches need to know how it decays:



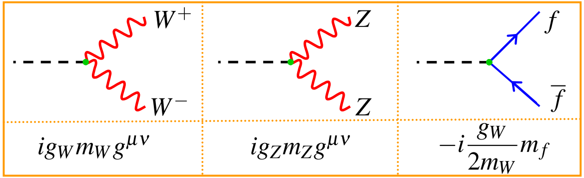


- note that at the mass of 1 TeV, H boson width is compatible with the H boson mass
- from here and from WW scattering cross section behavior consideration is clear that Higgs boson should be lighter than 1 TeV

Before LHC times: hunting the Higgs boson at LEP



- H couplings proportional to particle mass



- H decays predominantly to heaviest particles which are energetically allowed

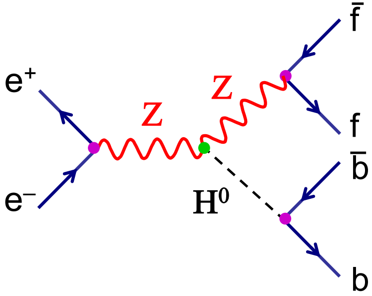
- $m_H < 2m_W$: mainly $H \to b\bar{b} + \sim 10\%H\to \tau^+\tau^-$
- $2m_W < m_H < 2m_t$: almost entirely $H \to W^+W^- + H \to ZZ$
- $m_H > 2m_t$: either $H \to W^+W^-, H \to ZZ, H \to t\bar{t}$

Before LHC times: hunting the Higgs boson at LEP

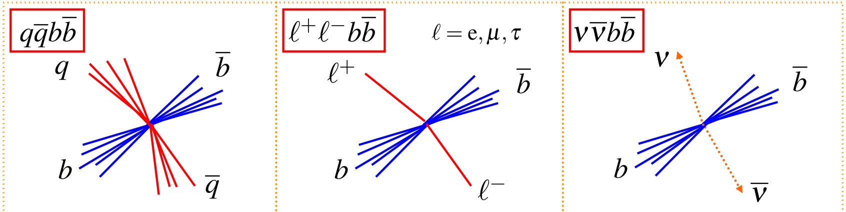
- LEP operated at $\sqrt{s}$ up to 207 GeV
- for this energy the main production mechanism would be the "Higgsstrahlung" process
- need enough energy to make a Z and H, therefore could produce the H if

$$m_H < 207\text{ GeV} - m_Z,$$

i.e. if $m_H < 116$ GeV

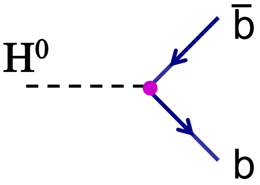


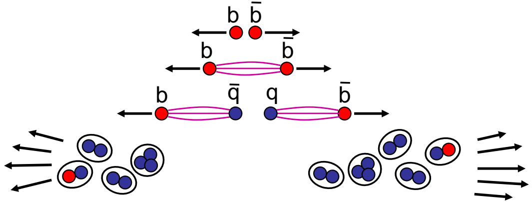
- for such H masses the dominant decay mode would be $H \to b\bar{b}$:



Tagging the H boson decays at LEP

- one signature for a H decay is the production of two b quarks:

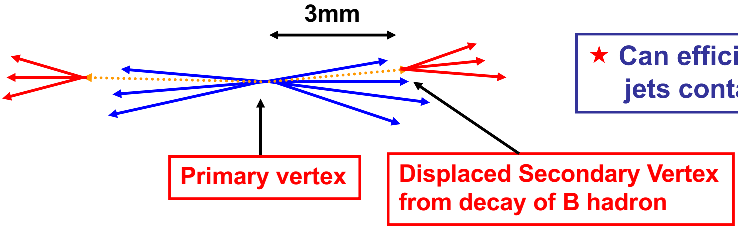




- each jet will contain one b-hadron which will decay weakly

Tagging the H boson decays at LEP

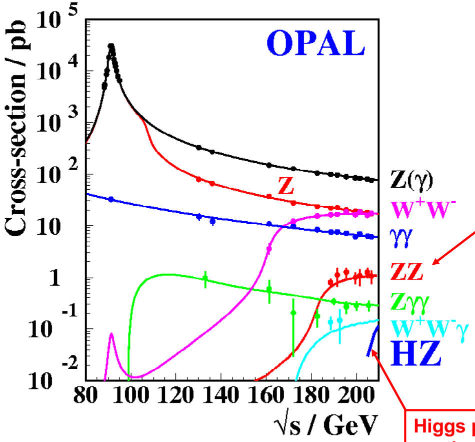
- since V_{cb} is small ($V_{cb} \approx 0.04$) hadrons containing b-quarks are relatively long-lived
- typical lifetimes of $\tau \sim 10^{-12}$ s (1 ps)
- at LEP b-hadrons travel approximately 3 mm before decaying



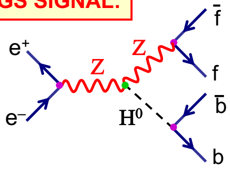
★ Can efficiently identify jets containing b quarks

Tagging the H boson decays at LEP

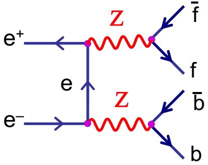
- clear experimental signature but small cross section, e.g. for $m_H \approx 115$ GeV would only produce a few tens of $e^+e^- \to HZ$ events at LEP
- in addition, there are large backgrounds



HIGGS SIGNAL:



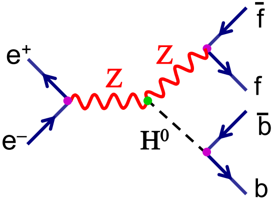
MAIN BACKGROUND:



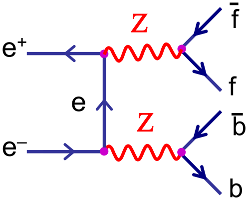
Higgs production cross section (m_H=115 GeV)

Tagging the H boson decays at LEP

- the only way to distinguish ZH and ZZ is the form of the invariant mass of the jets from the boson decays



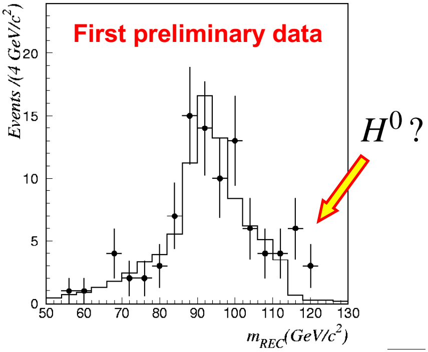
$$m_{b\bar{b}} = m_H$$



$$m_{b\bar{b}} = m_Z$$

- in 2000 (the last year of LEP running) the ALEPH experiment reported an excess of events consistent with being a Higgs boson with m=115 GeV

Tagging the H boson decays at LEP

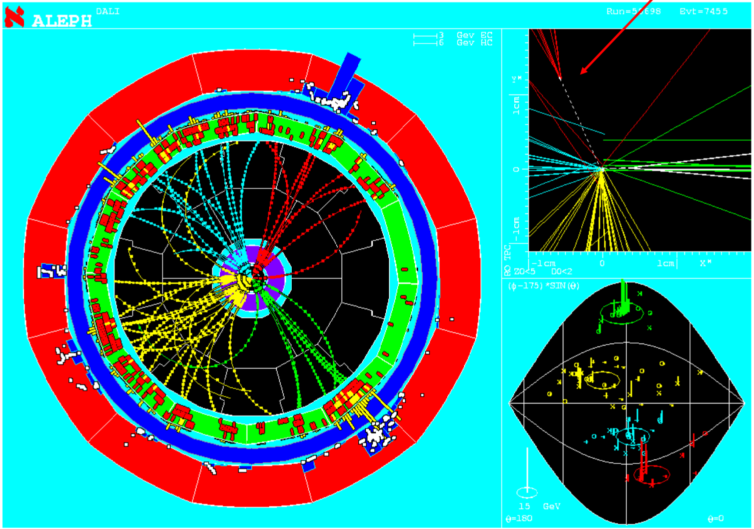


- ALEPH found 3 events which were high relative probability of being signal
- L3 found 1 event with high relative probability of being signal
- OPAL and DELPHI found none

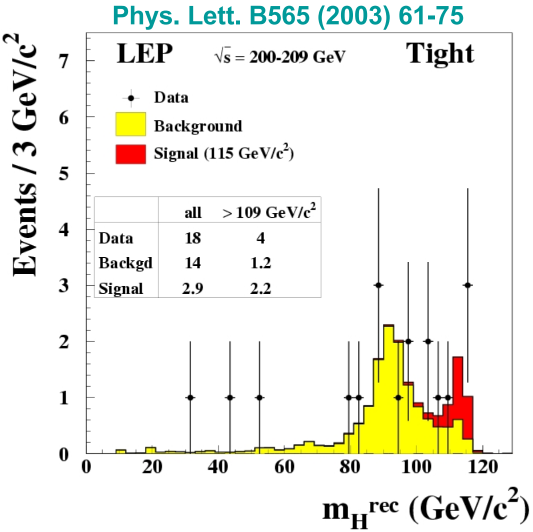
Tagging the H boson decays at LEP

Example event:

Displaced vertex from b-decay



Combined LEP results

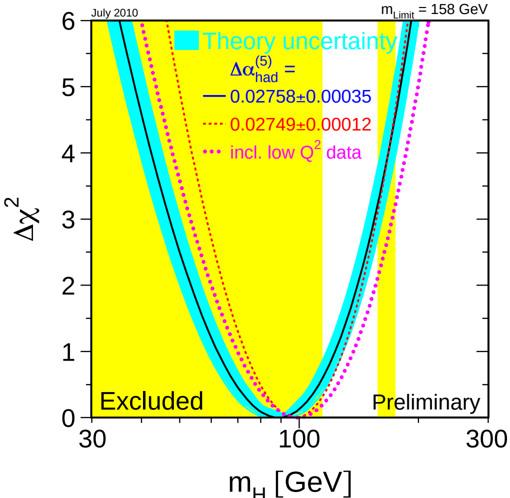


- final combined LEP results were rather inconclusive
- interpreted as a hint rather than strong evidence
- all that was found:

$$m_H > 114 \text{ GeV}$$

Higgs boson mass before 2011

- from direct searches at LEP and indirect constraints:



Direct exclusion:

- $m_H > 114.4$ GeV (LEP)
- $m_H < 158$ GeV or > 175 GeV (Tevatron)

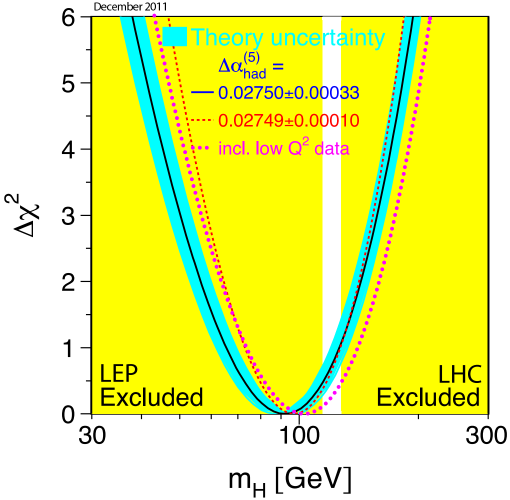
"Preferred" value from indirect measurements: $m_H = 89^{+35}_{-26}$ GeV

Significant tension between direct and indirect results.

Waiting for the LHC data...

After LHC 2011 data

LHC data start to come in ...



Conclusion of 2011 LHC run:

- either a “light” Higgs boson exists in a range ~ 115 to 127 GeV
- or no light Higgs boson exists

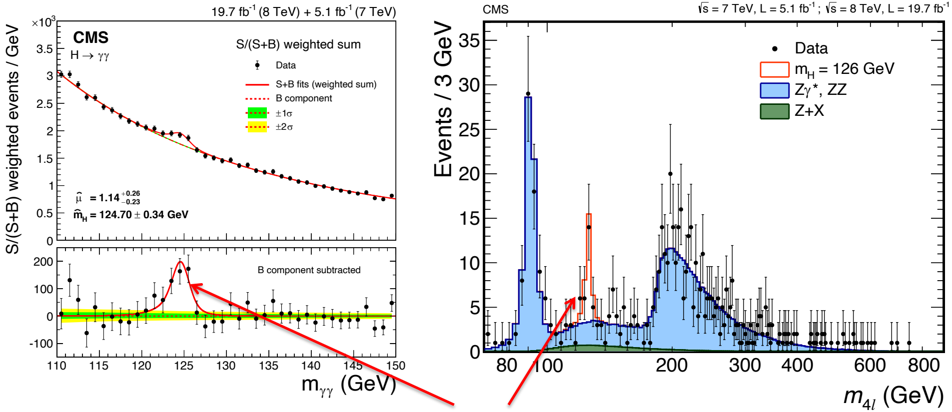
... and in 2012 ...

"I think we have it!"

-Rolf Heuer,
CERN director general

... a Higgs-like boson?

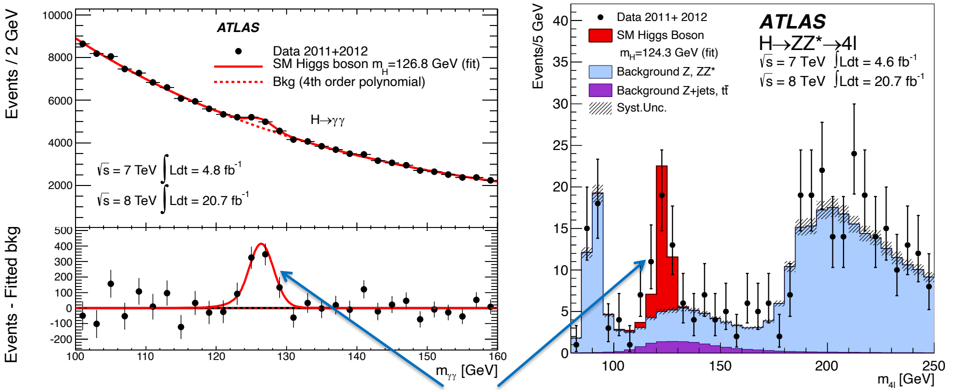
CMS results



excess of events over expected background,
in two different “channels”

... in 2 experiments

ATLAS results



excess of events over expected background,
in two different "channels"

Why we're still not happy with it?

Many open questions:

- Is the Higgs mechanism responsible for particles' mass? Does the Higgs boson exists and what is its own mass?
- Can gravity be included into an extension of SM ?
- Can the 4 forces be unified to one fundamental force ?
- What is the dark matter ?
- What about neutrino masses ?
- Why is $M_{W,Z} << M_{Planck}$? Hierarchy problem ?
- Are there 3+1 =4 dimensions or more ?