The Hunt for the Higgs

Ralf Averbeck, GSI

Seminar „Relativistic Heavy-Ion Physics“
TU Darmstadt February 17, 2011

- Introduction
- Indirect search for the Higgs
- Higgs search at the LEP
- Higgs search at the TEVATRON
- Higgs search at the LHC
Introducing: the Higgs Boson

- mass = fundamental parameter of objects
  - inertia, gravitation, energy
- fundamental forces of the Standard Model do not depend on mass
- symmetry breaking „Higgs mechanism“ invented to provide particles with mass
  - whole universe is filled with „Higgs Field“
  - particles acquire mass by interacting with this field
  - predict the existence of a new fundamental particle: „Higgs Boson“
The famous „Higgs Cartoon“

Higgs field in a vacuum (lots of politicians doing nothing)

Particle (PM) acquires mass from interaction with the Higgs field

Higgs boson (rumour) is a self excitation of the Higgs field
How to find the Higgs: option 1

The PARTICLE ZOO
Subatomic Particle Plush Toys FROM THE STANDARD MODEL OF PHYSICS & beyond!

Can't decide? Order a Particle Pack!

View Cart

Add to Cart

What a snob. He's the one everyone wants to meet, but for now he's playing hard to get. Higgs Boson is also part of the Theoretical 4-Pack and Boson 5-Pack.

Approximately 14 oz/388 grams; 5.5 inches/14 cm across.

For ages 6 and up as it contains small parts.

Made in China. Age 3 and up. Along with the electron, this is currently the only member of the Zoo who is not handmade. We hope you don't mind.

BACK TO
SHOP ALL PARTICLES

HIGGGS BOSON

The HIGGGS BOSON is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland will detect the elusive Higgs Boson when it begins colliding particles at 99.99% the speed of light.

$9.75 PLUS SHIPPING

H

LIGHT

HEAVY

Wool felt, velour with gravel fill for maximum mileage, more work.

HELHOLTZ GESAMTFORKERT RHIP Seminar, 02/17/2011  R. Averbeck, GSI
Search for the Higgs

- NO theory prediction of the Higgs mass, only constraints
- for given mass theory predicts how Higgs decays (in $\sim 10^{-24}$ s)
- Higgs "likes" mass $\rightarrow$ decays preferentially into heaviest objects permitted by energy conservation

- most probable decay modes
  - two b quarks at "low" mass
  - two W bosons at "high" mass
- search strategy
  - find events with two b quarks or two W bosons coming from the decay of an object with specific mass
- that's tough, can theory help as in the case of the top mass?
Indirect: electroweak radiative corrections

- Higgs mass enters logarithmically only in radiative corrections (top enters quadratically)
- Predictive power of electroweak theory fits is limited

\[
G_F = \frac{\pi \alpha}{\sqrt{2} M_W^2 \sin^2(\theta_W)} \frac{1}{1 - \Delta r^W}
\]

\[
\Delta r^H \propto \ln\left(\frac{M_H}{M_W}\right)
\]

\[
\Delta r^t \propto M_t^2
\]
The electroweak world

- precision theory fits with precise measurements of W and top mass
  → „low“ mass Higgs is preferred
Direct Search: Challenges I

- probability of producing a Higgs boson is small

- production cross section in the picobarn range
Direct Search: Challenges II

- background from Standard Model processes is huge

- \( M_H < 130 \text{ GeV} \)
  - associated production and \( bb \) decay: \( W(Z)H \to l\nu(l,l,\nu)bb \)
  - background: top, Wbb, Zbb, ...

- \( M_H > 130 \text{ GeV} \)
  - \( gg \to H \) and decay to \( WW \)
  - background: electroweak WW production, ...

\[ \text{Production Cross Section [pb]} \]

\[ \text{Jets, Heavy Flavor} \]

\[ \text{WW, ZZ, New Physics?} \]
Final State Topologies (low mass Higgs)

Four jets:
H→bb, Z→qq

Missing energy:
H→bb, Z→νν

Two jets + leptons:
H→bb, Z→ll

Tau leptons:
H→bb(ττ), Z→ττ(qq)
LEP
Candidate Events (LEP)

\[ H \rightarrow bb, Z \rightarrow qq \]

\[ H \rightarrow bb, Z \rightarrow \nu\nu \]

\[ H \rightarrow bb, Z \rightarrow \mu\mu \]

\[ H \rightarrow bb, Z \rightarrow ee \]

ALEPH

\[ H \rightarrow bb, Z \rightarrow qq \]

DELPHI

\[ H \rightarrow bb, Z \rightarrow \nu\nu \]

OPAL

\[ H \rightarrow bb, Z \rightarrow qq \]

L3

\[ H \rightarrow bb, Z \rightarrow \nu\nu \]
Crucial: B-tagging

- $b$ quark fragments into massive $B$ hadron
  - long lifetime
  - significant boost

$\rightarrow$ secondary vertex!

- availability of precision vertex spectrometers is crucial for Higgs search
Purest Candidate ever (LEP)

- mass: 114.3 GeV
- good HZ fit
- poor WW and ZZ fits
- probability for background: 2%

- **b-tagging**
  - b-jet probability for Higgs jets: 0.99 & 0.99
  - b-jet probability for Z jets: 0.14 & 0.01
Mass Reconstruction

- reconstruct mass of Higgs candidates for further signal discrimination
- width of (low mass) Higgs small compared to measurement resolution \(\rightarrow\) search for a peak!
- is there a Higgs with \(m_H = 115\) GeV?
- hard to conclude
  \(\rightarrow\) Higgs probability analysis
Higgs Probability Analysis at LEP

- combine all available data
  - expected number of background counts
  - expected signal (as function of $m_H$)
  - consider discriminating variables, e.g. b-tagging, kinematic cuts, etc.

- calculate likelihood for background and for background + signal
  
  $$Q(m_H) = \frac{L_{s+b}}{L_b} = \prod_i \frac{(s_i + b_i)^{n_i} e^{-(s_i + b_i)/n_i}}{b_i^{n_i} e^{-b_i/n_i}}$$

  $$-2 \ln Q(m_H) = 2s_{\text{tot}} - 2 \sum_i n_i \ln \left( 1 + \frac{s_i(m_H)}{b_i} \right)$$

  - high statistics limit: $-2 \ln Q = \Delta \chi^2$
  - $-2 \ln Q > 0$: likely to be background only
  - $-2 \ln Q < 0$: likely to have signal contribution

- test mass $m_H = 115$ GeV
  - background hypotheses: $1\sigma$ (68%) and $2\sigma$ (95%)
  - hint of a Higgs signal at $m_H$ but within $2\sigma$ background likelihood
Higgs at LEP: Summary

- Direct searches at LEP: $m_H > 114$ GeV at 95% C.L.
- Precision theory fits: $m_H < 158$ GeV (95%) or $m_H < 185$ GeV with direct limit

$\Rightarrow$ A low mass Higgs is favored
TEVATRON
Associated Production: WH

- sensitive channel in the 110-130 GeV mass range
- any peaks in dijet mass distribution?
- more sensitive (use all information): multivariate discriminant
$H \rightarrow WW \rightarrow l^+ l^- (m_H > 130 \text{ GeV})$

- **search strategy**
  - 2 high $p_T$ leptons
  - missing $E_T$

- WW pair originates from Higgs with spin 0
  → leptons prefer to point in the same direction
Setting Limits on SM Higgs

- Limits on Higgs cross section set in each individual channel and normalized to SM Higgs cross section at a given mass.

- Line at 1.0 is crossed \( \Rightarrow \) Higgs excluded at that mass.
Combining Channels
Combining CDF and D0

- $158 < m_H < 175$ GeV is excluded at 95 % C.L. at Tevatron!
Combining Indirect & Direct Searches

- Higgs mass is most likely below 150 GeV
TEVATRON “virtual” future

- Expected integrated luminosity by 2014
  - ~19 fb\(^{-1}\) delivered
  - ~16 fb\(^{-1}\) available for analysis
TEVATRON SM Higgs projections

- over $3\sigma$ sensitivity in full allowed mass range
- nevertheless, TEVATRON shuts down in September 2011
Higgs Production in pp collisions

- low $m_H$
- high $m_H$

- expected Higgs production cross section $1 < \sigma < 30$ pb
- expected data samples $\sim 50$ fb$^{-1}$ per year at full luminosity
Signal to Background

- total cross section 9 orders of magnitude above Higgs cross section!
- efficient selection of Higgs candidate events from a large background is crucial
- energy dependence
  - Higgs cross section grows faster than background cross section
  - advantage compared to lower energy machines
Decay Channels

- **low mass**
  - bb dominates
  - large QCD background
  - $H \rightarrow \gamma \gamma$
    - small BR
    - small Higgs width
    - high resolution EM calorimetry

- **intermediate mass**
  - decay to WW and ZZ

- **high mass**
  - „golden channel“
  - $H \rightarrow ZZ$
The “new” Channel: $H \rightarrow \gamma \gamma$

- assumed Higgs mass: 130 GeV
- 100 fb$^{-1}$ integrated luminosity
- energy deposit of photons measured in the PbWO$_4$ electromagnetic calorimeter of CMS
A “golden” Channel: $H \rightarrow ZZ \rightarrow 4\ell$

- high energy muons
- Z mass constraint(s)
- background reduction with vertex cut
- irreducible background: ZZ & $Z\gamma$
Higgs sensitivity of CMS

- 5 fb\(^{-1}\) at 7 TeV reachable by the end of 2012
- exclusion up to \(m_H = 600\) GeV
- discovery (5\(\sigma\)) for low mass Higgs, significant discovery potential also for higher \(m_H\)

<table>
<thead>
<tr>
<th>Channels included</th>
<th>Higgs mass range used in analyses (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H \rightarrow \gamma\gamma)</td>
<td>115-150</td>
</tr>
<tr>
<td>VBF (H \rightarrow \tau\tau)</td>
<td>115-145</td>
</tr>
<tr>
<td>VH, (H \rightarrow bb) (highly boosted)</td>
<td>115-125</td>
</tr>
<tr>
<td>VH, (H \rightarrow WW \rightarrow lvjj)</td>
<td>130-200</td>
</tr>
<tr>
<td>(H \rightarrow WW \rightarrow 2l2v + 0/1 jets)</td>
<td>120-600</td>
</tr>
<tr>
<td>VBF (H \rightarrow WW \rightarrow 2l2v)</td>
<td>130-500</td>
</tr>
<tr>
<td>(H \rightarrow ZZ \rightarrow 4l)</td>
<td>120-600</td>
</tr>
<tr>
<td>(H \rightarrow ZZ \rightarrow 2l2v)</td>
<td>200-600</td>
</tr>
<tr>
<td>(H \rightarrow ZZ \rightarrow 2l2b)</td>
<td>300-600</td>
</tr>
</tbody>
</table>
Higgs sensitivity of ATLAS

- Luminosity required for exclusion (95% C.L.) of Higgs as function of $m_H$
- Significance for Higgs signals as function of $m_H$ assuming different running scenarios
  → performance similar as expected for CMS
Will the Higgs be found at the LHC?

“I think I’ve found the Higgs boson!”

let’s meet again in two years!