Physics at Hadron Colliders

Lecture 3

Search for the Higgs boson

- Higgs boson production and decays
- LHC discovery potential
- What can be covered at the Tevatron?
The Search for the Higgs Boson

- “Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics”

- “A new collider, such as the LHC must have the potential to detect this particle, should it exist.”
What do we know about the Higgs Boson today

- Needed in the Standard Model to generate particle masses
- Mass not predicted by theory, except that $m_H < \sim 1000$ GeV
- $m_H > 114.4$ GeV from direct searches at LEP
- Indirect limits from electroweak precision measurements (LEP, Tevatron and other experiments…)

Results of the precision el.weak measurements: (all experiments, July 2006):

$$M_H = 85 \, (+39) \, (-28) \, \text{GeV/c}^2$$
$$M_H < 166 \, \text{GeV/c}^2 \, \text{(95 \% CL)}$$

$\rightarrow$ Higgs boson could be around the corner!
Properties of the Higgs Boson

• The decay properties of the Higgs boson are fixed, if the mass is known:

\[ H \rightarrow W^+, Z, t, b, c, \tau^+, \ldots, g, \gamma \]

\[ H \rightarrow W^-, Z, t, b, c, \tau^-, \ldots, g, \gamma \]

\[ \Gamma(H \rightarrow f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2 (M_H^2 - m_f^2) M_H \]

\[ \Gamma(H \rightarrow VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 \left(1 - 4x + 12x^2\right) \beta_V \]

where: \( \delta_Z = 1, \delta_W = 2, \quad x = M_V^2/M_H^2, \quad \beta = \text{velocity} \)

\[ \Gamma(H \rightarrow gg) = \frac{G_F}{36\sqrt{2}\pi} \frac{\alpha_s^2(M_H^2)}{M_H^3} \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right) \alpha_s \right] \]

\[ \Gamma(H \rightarrow \gamma\gamma) = \frac{G_F}{128\sqrt{2}\pi^3} \frac{\alpha_s^2}{M_H^3} \left[\frac{4}{3} N_C \alpha_s^2 - 7\right]^2 \]

Higgs boson likes mass:

It couples to particles proportional to their mass

\[ \rightarrow \text{decays preferentially in the heaviest particles kinematically allowed} \]
Upper limit on Higgs boson mass: from unitarity of WW scattering  \( M_H < 1 \) TeV/c\(^2\)
Higgs Boson Production at Hadron Colliders

(i) Gluon fusion

(ii) Vector boson fusion

(iii) Associated production (W/Z, tt)
Higgs Boson Production cross sections

LHC

M. Spira et al.

\[ \sigma(pp \rightarrow H + X) \ [pb] \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ M_h = 175 \text{ GeV} \]
CTEQ4M

qq → W/Z + H    cross sections
~10 x larger at the LHC

gg → H
~70-80 x larger at the LHC

Tevatron

M.Spira et al.

\[ \sigma(pp \rightarrow H + X) \ [pb] \]
\[ \sqrt{s} = 2 \text{ TeV} \]

HqHq
HqHq
HbHb
HbHb
HzHz
HzHz

K. Jakobs, Universität Freiburg

CERN Summer Student Lectures, Aug. 2006
Higgs Boson Decays at Hadron Colliders

**at high mass:**
Lepton final states are essential
(via $H \rightarrow WW, ZZ$)

**at low mass:**
Lepton and Photon final states
(via $H \rightarrow WW^*, ZZ^*$)

**Tau** final states

The dominant $bb$ decay mode is only useable in the associated production mode ($ttH$)
(due to the huge QCD jet background)
How can one claim a discovery?

Suppose a new narrow particle $X \rightarrow \gamma\gamma$ is produced:

Peak width due to detector resolution

**Signal significance:**

$$S = \frac{N_s}{\sqrt{N_B}}$$

- $N_s$ = number of signal events
- $N_B$ = number of background events

\[\sqrt{N_B} \equiv \text{error on number of background events, for large numbers}\]

otherwise: use Poisson statistics

\[S > 5 \text{ : signal is larger than 5 times error on background.}\]

Gaussian probability that background fluctuates up by more than $5\sigma$: $10^{-7} \rightarrow \text{discovery}$
Two critical parameters to maximize $S$

1. **Detector resolution:**
   If $\sigma_m$ increases by e.g. a factor of two, then need to enlarge peak region by a factor of two to keep the same number of signal events

   $\rightarrow N_B$ increases by $\sim 2$

   (assuming background flat)

   $\Rightarrow S = N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$

   $\Rightarrow S \sim 1/\sqrt{\sigma_m}$

   “A detector with better resolution has larger probability to find a signal”

   **Note:** only valid if $\Gamma_H << \sigma_m$. If Higgs is broad detector resolution is not relevant.

   $m_H = 100 \text{ GeV} \rightarrow \Gamma_H \sim 0.001 \text{ GeV}$
   $m_H = 200 \text{ GeV} \rightarrow \Gamma_H \sim 1 \text{ GeV}$
   $m_H = 600 \text{ GeV} \rightarrow \Gamma_H \sim 100 \text{ GeV} \quad \Gamma_H \sim m_H^3$

2. **Integrated luminosity**:

   \[
   N_S \sim L \quad N_B \sim L
   \]

   $\Rightarrow S \sim \sqrt{L}$
H → ZZ(*) → ℓℓℓℓ

**Signal:** \( \sigma \text{BR} = 5.7 \text{ fb} \) (\( m_H = 100 \text{ GeV} \))

**Background:**
- Top production: \( t\bar{t} \to Wb Wb \to \ell\nu c\ell\nu c\ell\nu \) \( \sigma \text{BR} \approx 1300 \text{ fb} \)
- Associated production: \( Z b\bar{b} \) \( Z b\bar{b} \to \ell\ell c\ell\nu c\ell\nu \)

**Background rejection:**
- Leptons from b-quark decays:
  - non isolated
  - do not originate from primary vertex
  - (B-meson lifetime: \( \sim 1.5 \text{ ps} \))

  Dominant background after isolation cuts: ZZ continuum

**Discovery potential:**
- In mass range from \( \sim 130 \) to \( \sim 600 \text{ GeV/c}^2 \)

\[ P_{T}(1,2) > 20 \text{ GeV} \]
\[ P_{T}(3,4) > 7 \text{ GeV} \]
\[ |\eta| < 2.5 \]

**Isolated leptons**
- \( M(\ell\ell) \sim M_Z \)
- \( M(\ell\ell') \sim < M_Z \)
- \( L = 100 \text{ fb}^{-1} \)
A simulated $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ event
$m_H \leq 150 \text{ GeV}$

- $\sigma \times \text{BR} \approx 50 \text{ fb}$ \hspace{2cm} (BR $\approx 10^{-3}$)

- Backgrounds:
  - $\gamma\gamma$ (irreducible): e.g.
    \[ \sigma_{\gamma\gamma} \approx 2 \text{ pb / GeV} \]
    \[ \Gamma_H \approx \text{MeV} \]
    \[ \Rightarrow \text{need } \sigma(m)/m \approx 1\% \]

- $\gamma j + jj$ (reducible):
  \[ \sigma_{\gamma j + jj} \approx 10^6 \sigma_{\gamma\gamma} \]
  with large uncertainties
  \[ \Rightarrow \text{need } R_j > 10^3 \text{ for } \varepsilon_{\gamma} \approx 80\% \text{ to get } \sigma_{\gamma j + jj} \ll \sigma_{\gamma\gamma} \]

\[ \rightarrow \text{most demanding channel for EM calorimeter performance: energy and angle resolution, acceptance, } \gamma/\text{jet} \text{ and } \gamma/\pi^0 \text{ separation} \]

ATLAS and CMS: complementary performance
A simulated $H \rightarrow \gamma \gamma$ event in ATLAS
H → \gamma\gamma (cont.)

Two isolated photons:
P_T(\gamma_1) > 40 \text{ GeV}
P_T(\gamma_2) > 25 \text{ GeV}
|\eta| < 2.5

Signal / background \sim 4\% \quad (\text{Sensitivity in mass range } 100 \text{ – } 140 \text{ GeV/c}^2)
background (dominated by \gamma\gamma \text{ events }*) can be determined from side bands
important: \gamma\gamma\text{-mass resolution in the calorimeters, }\gamma / \text{jet separation}

*) detailed simulations indicate that the \gamma\text{-jet and jet-jet background can be suppressed to the level of 10-20\% of the irreducible }\gamma\gamma\text{-background}
CMS crystal calorimeter
The full allowed mass range

from the LEP limit (~114 GeV)
up to
theoretical upper bound of ~1000 GeV

can be covered using the two “safe” channels

\[ H \to ZZ \to \ell\ell\ell\ell \] and
\[ H \to \gamma\gamma \]

„If the Standard Model Higgs particle exists, it will be discovered at the LHC!“
**Motivation:** Increase discovery potential at low mass
   Improve measurement of Higgs boson parameters
   (couplings to bosons, fermions)

**Distinctive Signature of:**

- two forward tag jets
- little jet activity in the central region
  \[ \Rightarrow \textit{central jet Veto} \]

More difficult channels can also be used: **Vector Boson Fusion**

\[
qq H \rightarrow qq WW \rightarrow qq \ell \nu \ell \nu
\]
Forward jet tagging

Rapidity distribution of tag jets
VBF Higgs events vs. tt-background

Rapidity separation
Transverse mass distributions: clear excess of events above the background from tt-production
Presence of a signal can also be demonstrated in the $\Delta \phi$ distribution (i.e. azimuthal difference between the two leptons)

Evidence for spin-0 of the Higgs boson

Spin-0 $\rightarrow$ WW $\rightarrow \ell \nu \ell \nu$ expect leptons to be close by in space
H → ττ decay modes visible for a SM Higgs boson in vector boson fusion

qq H → qq ττ
→ qq ℓνν ℓνν
→ qq ℓνν ℓνν

• large boost (high-P_T Higgs)
  → collinear approximation:
  assume neutrinos go in the direction of the visible decay products
  → Higgs mass can be reconstructed

• main background: Z jj, Z → ττ
ATLAS Higgs discovery potential for 30 fb$^{-1}$

- Full mass range can already be covered after a few years at low luminosity

- Several channels available over a large range of masses

- Comparable situation for the CMS experiment
Can LHC also discover Higgs bosons in a supersymmetric world?

**SUSY:**

5 Higgs particles

\[ H, h, A \]

\[ H^+, H^- \]

determined by two SUSY model parameters:

\[ m_A, \tan \beta \]

One of the Higgs bosons is light:

\[ m_h < 135 \text{ GeV} \]

The others will most likely be heavy!
LHC discovery potential for MSSM Higgs bosons

\[ m_{\text{SUSY}} = 1 \text{ TeV}, \ m_{\text{top}} = 175 \text{ GeV/c}^2 \]

Two or more Higgs can be observed over most of the parameter space \( \rightarrow \) disentangle SM / MSSM

- Plane fully covered (no holes) at low \( L \) (30 fb\(^{-1}\))
- **Main channels**: \( h \rightarrow \gamma \gamma, \ tth \ h \rightarrow bb, \ A/H \rightarrow \mu \mu, \tau \tau, \ H^\pm \rightarrow \tau \nu \)

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K. Jakobs, Universität Freiburg  CERN Summer Student Lectures, Aug. 2006
Parameter space is fully covered:

\[ \rightarrow \]

„Also in a SUSY world, Higgs bosons will be discovered at the LHC“
Determination of Higgs Boson Parameters

1. Mass

2. Couplings to bosons and fermions
Measurement of the Higgs boson mass

 Dominated by $ZZ \rightarrow 4\ell$ and $\gamma\gamma$ resonances!
 well identified, measured with a good resolution

 Dominant systematic uncertainty: $\gamma/\ell$ E scale.
 Assumed 0.1 %
 Goal 0.02 %
 Scale from $Z \rightarrow \ell\ell$ (close to light Higgs)

Higgs boson mass can be measured with a precision of 0.1% over a large mass range (130 - ~450 GeV / c$^2$)
Measurement of Higgs Boson Couplings

Global likelihood-fit (at each possible Higgs boson mass)
Input: measured rates, separated for the various production modes

Output: Higgs boson couplings, normalized to the WW-coupling

Relative couplings can be measured with a precision of 10-20% (for 300 fb⁻¹)
Can the Higgs boson already be discovered at Fermilab
Impressions from Fermilab
Search channels at the Tevatron

• important production/decay modes: associated WH and ZH
  + gluon fusion with H → WW → ℓν ℓν

• hopeless:
  gluon fusion in H → γγ, 4 ℓ
  σ BR (H → ZZ → 4 ℓ) = 0.07 fb (M_H=150 GeV)

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<th>110 - 130 GeV:</th>
<th>LHC</th>
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<td>WH → ℓν bb</td>
<td>(✓) weak</td>
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<tr>
<td>ZH → ℓ+ℓ- bb</td>
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<td></td>
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<tr>
<td>ZH → νν bb</td>
<td>Ø (trigger)</td>
<td></td>
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<tr>
<td>ZH → bb bb</td>
<td>Ø (trigger)</td>
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<tr>
<td>ttH → ℓν b jjb bb</td>
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<tr>
<td>WH → WWW(*) → ℓν ℓν jj</td>
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Triggering:
slightly easier at the Tevatron:
- better P_T^miss-resolution
- track trigger at level-1
(seems to work)

Background:
electroweak production:
~10 x larger at the LHC
QCD production (e.g, tt):
~ 100 x larger at the LHC
WH Signals at the LHC and the Tevatron

\[ M_H = 120 \text{ GeV}, \quad 30 \text{ fb}^{-1} \]

most important: control of the background shapes, very difficult!
Tevatron discovery potential for a light Higgs Boson

combination of both experiments and all channels
(discovery in a single channel not possible)

For 8 fb⁻¹ :
(i) 95% CL exclusion of a SM Higgs boson is possible up to 135 GeV/ c² and for 150 - 180 GeV/ c²
(ii) 3-σ evidence for M_H < 130 GeV/ c²
(iii) Sensitivity at low mass starts with an int. luminosity of 2 fb⁻¹ (mid - end 2006)
Results from the present Run II data

typically, data corresponding to 300 – 350 pb⁻¹ analyzed
Low Mass: $WH \rightarrow e\nu \ bb$

**Data sample**: 382 pb$^{-1}$

**Event selection**: 1 e, ($|\eta| < 1.1$, $E_T > 20$ GeV), $E_T^{\text{miss}} > 20$ GeV, 2 jets ($E_T > 20$ GeV) additional b-tags

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<th>Source</th>
<th>Observed</th>
<th>Expected</th>
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<td>Backgrounds</td>
<td>135.5</td>
<td>5.73</td>
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**Additional b-tags**
Higgs boson searches at the Tevatron

- Many analyses (in many different channels) presented
- No excess above SM background  \( \Rightarrow \) Limits extracted

Combination of current analyses (DØ): for \(~325\) pb\(^{-1}\)

\( \rightarrow \) upper limit about 15 times larger than Standard Model prediction at 115 GeV/c\(^2\)
Summary on Higgs Boson Searches

• Electroweak precision data from LEP/SLC/Tevatron suggest a light Higgs boson

• Should a SM Higgs boson or MSSM Higgs bosons exist, they cannot escape detection at the LHC

• Tevatron might have a 3-σ discovery windows at low mass, however, much depends on the detector and accelerator performance.
Der Higgs Mechanismus, eine Analogie:

Higgs-Hintergrundfeld erfüllt den Raum

Ein Teilchen im Higgs-Feld...

... Widerstand gegen Bewegung ... Trägheit ↔ Masse