Search for the Higgs–Boson with the DØ– and ATLAS– Detectors

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Outline

- Introduction
- Higgs mechanism and phenomenology
- The DØ Higgs–Analysis
  - Selection
  - Results
- The ATLAS Higgs–Analysis
  - Selection
  - Expected Higgs sensitivity
- Summary and outlook
The Standard Model

- Matter is composed of leptons and quarks
  ▲ Leptons and quarks are divided into three families

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e )</td>
<td>( u )</td>
</tr>
<tr>
<td>( e )</td>
<td>( d )</td>
</tr>
<tr>
<td>( \nu_\mu )</td>
<td>( c )</td>
</tr>
<tr>
<td>( \mu )</td>
<td>( s )</td>
</tr>
<tr>
<td>( \nu_\tau )</td>
<td>( t )</td>
</tr>
<tr>
<td>( \tau )</td>
<td>( b )</td>
</tr>
</tbody>
</table>

0 \hspace{1cm} +2/3 \hspace{1cm} -1/3

- Four different forces act on the particles
  ▲ Strong, electromagnetic and weak interaction
  ▲ Gravity is not included in the Standard Model

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Force carriers</th>
<th>Participating particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong</td>
<td>Gluons</td>
<td>Quarks</td>
</tr>
<tr>
<td>electromagnetic</td>
<td>Photon</td>
<td>charged particles</td>
</tr>
<tr>
<td>weak</td>
<td>( W, Z ) Bosons</td>
<td>all particles</td>
</tr>
</tbody>
</table>
The Higgs Mechanism

- Within the scope of gauge theories the gauge boson are massless
- Contradiction to the experimental observations
  \[ m_{W^\pm} = 80.4 \text{ GeV}/c^2, \quad m_{Z^0} = 91.2 \text{ GeV}/c^2, \quad \text{only } m_{\gamma} = 0 \text{ GeV}/c^2 \]
- Introduce new complex scalar field in the theory \( \Rightarrow \) Higgs field
- Spontaneous symmetry breaking gives mass to the gauge bosons
- Higgs mechanism predicts one new particle \( \Rightarrow \) The Higgs boson
- Particles acquire mass due to the coupling to the Higgs field
  ▲ The stronger the coupling the heavier the particle

If the Higgs mechanism is nature’s way to give masses to the particles the Higgs boson must be found!
What Do We Know About the Higgs?

As of End of 2008

- **Direct searches at LEP (CERN) and Tevatron (Fermilab)**
  - **LEP (Aleph, Delphi, Opal, L3)**
    - No Higgs boson found
  - **Tevatron (DØ, CDF)**
    - No sensitivity to SM Higgs boson (yet)

- **Indirect searches at LEP, SLC, and Tevatron**
  - Higgs boson in loops impacts many observables
  - Use precision measurements to get constraints on the Higgs mass
What Do We Know About the Higgs?

As of End of 2008

- Direct searches
  - \( M_H > 114.4 \text{ GeV}/c^2 \)
- Indirect searches
  - \( M_H = 84^{+34}_{-26} \text{ GeV}/c^2 \)
  - \( M_H < 154 \text{ GeV}/c^2 \)
- Limits are at 95% CL
Higgs Production and Decay

- Four different production processes
  - Gluon fusion, vector boson fusion, Higgs bremsstrahlung and associated quark production
  - Production cross section
    - 0.1–1 pb @ 2 TeV (Tevatron)
    - 10–100 pb @ 14 TeV (LHC)

- Higgs decay
  - \( M_H < 135 \text{ GeV}/c^2 \): \( b\bar{b} \) decay
  - \( M_H > 135 \text{ GeV}/c^2 \): WW decay
Signal and Background

- Signal final state characterized by decay products of W bosons
  ▲ Main decay channels involve jets
    ► Huge background ⇒ Not feasible
  ▲ Leptonic decay modes provide clean final state
    ► Drawback: Small branching fraction
  ▲ Final state characterized by two oppositely charged leptons and missing energy due to escaping neutrinos

- Main background processes
  ▲ Processes with two leptons
    ► Drell–Yan production: $Z/\gamma^* \rightarrow ee, \mu\mu, \tau\tau$
    ► Diboson–production: $WW, WZ, ZZ$
    ► Top–production: $t\bar{t}$
  ▲ Processes with misidentified leptons
    ► $W(\rightarrow e, \mu)+$jets
    ► $W(\rightarrow e, \mu)+$photon
    ► Multi–jet production
Backgrounds and Selection

- Main background is QCD multijet production
  ▲ Very large cross section

![Graph showing Proton-(Anti-)Proton Wirkungsquerschnitte]

- Proton-(Anti-)Proton Wirkungsquerschnitte
  - Tevatron
  - LHC
  - \( \sigma_{tot} \) vs. \( \sqrt{s} \) (TeV)
  - \( \sigma_{b} \) (barn)
  - \( \sigma_{W} \) (barn)
  - \( \sigma_{Z} \) (barn)
  - \( \sigma_{\text{jet}(E_{T,jet}>\sqrt{s}/20)} \) (barn)
  - \( \sigma_{\text{jet}(E_{T,jet}>100 \text{ GeV})} \) (barn)
  - \( \sigma_{\text{Higgs}(M_{H}=150 \text{ GeV})} \) (barn)

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Backgrounds and Selection

- Main background is QCD multijet production
  ▲ Very large cross section
- Require two isolated leptons
  ▲ Main contributions from $Z/\gamma$ production

![Graph showing background contributions and selection criteria](image)

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Backgrounds and Selection

- Main background is QCD multijet production
  ▲ Very large cross section
- Require two isolated leptons
  ▲ Main contributions from $Z/\gamma$ production
- $E_T$ requirements
  ▲ WW, $t\bar{t}$ and $W+\text{jet}/\gamma$ dominant

![Graph showing W, Z, and jet cross sections](image)
Search for the Higgs Boson with the DØ–Detector
Tevatron and Data Taking

- \( p\bar{p} \) collisions @ \( E_{\text{cms}} = 1.96 \text{ TeV} \)
- Collision rate 2.5 MHz
- Integrated luminosity 6.2 \( \text{fb}^{-1} \)
  - Events produced: \( 500 \cdot 10^{12} \)
  - Recording: 100 Hz
- Detector comprises several subdetectors
The DØ Detector

- Detector comprises several subdetectors
- Vertex– and tracking detector
  - Silicon and scintillating fibres
  - Tracks up to $|\eta| < 2.5$
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  - Uranium/Liquid Argon calorimeter
  - Electrons up to $|\eta| < 3.2$
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  - Muon spectrometer
    - Mini/Proportional drift tubes
    - Reconstruction of muons up to $|\eta| < 2$

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Event Reconstruction

- **Electrons**
  - ▲ Energy deposition in electromagnetic calorimeter
  - ▲ Corresponding track in inner detector
- **Muons**
  - ▲ Hits in three layers of the muon system
  - ▲ Corresponding track in inner detector
- **Jets**
  - ▲ Energy deposition in electromagnetic and hadronic calorimeter
- **Neutrinos**
  - ▲ Indirect detection via missing transverse energy $E_T$
  - ▲ $E_T \equiv$ Vectorial sum of all energy depositions in calorimeter and all muons in transverse plane
• Use event kinematics to suppress backgrounds
  ▲ Two oppositely charged leptons
  ▲ Require $E_T$ to account for neutrinos
    ► Reject events where $E_T$ is caused by mismeasured leptons or jets

▲ Use spin correlations
  ► Small opening angle in transverse plane

$e^-$ $W^-$ $H$ $W^+$ $e^+$

$s = +1/2$ $s = +1$ $s = 0$ $s = -1/2$ $s = -1/2$ $s = 0$
Neural Net

- Expected and observed events
  - Background
    - Preselection: $465204 \pm 725$ events
    - Final selection: $4994 \pm 30$ events
  - Signal ($M_H = 165$ GeV)
    - Preselection: $32.0 \pm 0.1$
    - Final selection: $23.2 \pm 0.1$
- Signal/background improved from $7 \cdot 10^{-5}$ to $5 \cdot 10^{-3}$
  - Still not good enough
- Use Neural Network to get better separation from signal and background
  - Sensitivity at high NN output values where S/B is 0.5–1
A Closer Look

• Compare background subtracted data with signal expectation

![Graph showing data and background comparison](image)

- No evidence for a Higgs signal ⇒ Set limits on production cross section

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The Tevatron Limit

- Combination of all channels from DØ and CDF

Tevatron Run II Preliminary, L=0.9-4.2 fb⁻¹

- Exclude Higgs boson with mass of 160–170 GeV
The Present and Future

- **Direct searches**
  - $M_H > 114.4 \text{ GeV (LEP)}$ and $M_H \notin [160 \text{ GeV}, 170 \text{ GeV}]$ (Tevatron)

- **Indirect searches**
  - $M_H = 87^{+35}_{-26} \text{ GeV}$ and $M_H < 157 \text{ GeV}$

- **Future at the Tevatron**
  - Increase data sets (roughly factor of 2–3)
  - Try to improve NN selection and systematic errors
  - See first evidence for a Higgs boson or try to exclude the Higgs boson over the whole mass range from 115–200 GeV

- **Future at the LHC**
  - Start looking for the Higgs boson with the ATLAS and CMS detectors

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Search for the Higgs Boson with the ATLAS–Detector
LHC

- pp collisions @ 14 TeV (design)
- First collisions hopefully before Christmas
- Plan for 2010
  - Few month of collision data at $E_{\text{cms}} = 7$ TeV
  - Increase energy to 10 TeV for rest of the year
  - Collect $\sim 100 \text{ pb}^{-1}$ of data
Search Strategy

- Perform Higgs search in two separated channels
  - Gluon fusion: electron + muon + $E_T + 0$ jets
    - Two high $p_T$ leptons
    - Large $E_T$ to account for neutrinos
    - Reject events with any high $p_T$ jet
  - Vector boson fusion: electron + muon + $E_T + 2$ forward jets
    - Two high $p_T$ leptons
    - Large $E_T$ to account for neutrinos
    - Two hard jets in forward region
    - Construct NN based on several jet quantities

- Signal and background contributions are extracted by performing a 2–dimensional fit to the data
H→WW Sensitivity

- Expected sensitivity in the H→WW channel using 10 fb\(^{-1}\) of data (a few years of running)

Gluon fusion analysis

Vector boson fusion analysis

\[ \begin{align*}
\text{Median Significance} & \quad \text{(ATLAS)} \\
\int L \, dt = 10 \, \text{fb}^{-1} & \\
\end{align*} \]

\begin{align*}
5 \sigma \text{ discovery for } M_H &= 140–185 \text{ GeV} \\
5 \sigma \text{ discovery for } M_H &= 150–185 \text{ GeV}
\end{align*}
Overall ATLAS Sensitivity

- Combination of several channels
  \[ \Delta H \rightarrow WW, H \rightarrow ZZ, H \rightarrow \tau\tau \text{ and } H \rightarrow \gamma\gamma \]

Discovery potential (10 \( fb^{-1} \))

Exclusion limit (2 \( fb^{-1} \))

5 \( \sigma \) discovery for \( M_H = 125–400 \text{ GeV} \)

95% CL exclusion for \( M_H = 115–460 \text{ GeV} \)
Overall ATLAS Sensitivity

- Combination of several channels
  - $H \rightarrow WW$, $H \rightarrow ZZ$, $H \rightarrow \tau\tau$ and $H \rightarrow \gamma\gamma$

Discovery potential

Exclusion limit

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• The $H \rightarrow WW$ channel is one of the main search channels for a low mass Higgs ($M_H < 200 \text{ GeV}$)
• With $10 \text{ fb}^{-1}$ of data and a combination of all channels ATLAS can discover the Higgs with a mass above 125 GeV
• A low mass Higgs in the favored region around 115 GeV is very challenging and requires much more data
• With $2 \text{ fb}^{-1}$ ATLAS can rule out a Higgs boson over the complete allowed mass range
Conclusion and Outlook

- The Higgs boson is the only missing particle in the Standard Model
- The search for the Higgs boson was, is and will be the most important task in High Energy Physics
- The (non)observation of the Higgs boson will shed light on the origin of electro–weak symmetry breaking and lead the way to new physics beyond the SM

- Tevatron
  - So far no hints for a Higgs boson
  - Start to exclude the mass range around 160 GeV

- LHC
  - Start of data taking hopefully by the end of this year
  - If the Higgs boson exists it should be observed at the LHC
    - Although it may take some time in the most favored region
BACKUP SLIDES