8. Physics of the Higgs Boson

8.1 The Higgs boson in the Standard Model

8.2 Properties of the Higgs boson

8.3 Higgs boson production at hadron colliders

8.4 The search for the Higgs boson at the Tevatron

8.5 Status and prospects for Higgs boson searches at the LHC
8.1 The Higgs boson in the Standard Model

(a brief summary, for more details, see lecture notes)
Fundamental principle:  Local gauge invariance
Prototype:  Quantum Electrodynamics (QED)

Free Dirac equation:  \[ i\gamma^\mu \partial_\mu \psi - m\psi = 0 \]

Lagrangian formalism:  \[ L = i\bar{\psi} \gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi \]

Local gauge transformation:  \[ \psi(x) \rightarrow e^{i\alpha(x)}\psi(x) \]

(derivative:  \[ \partial_\mu \psi \rightarrow e^{i\alpha(x)}\partial_\mu \psi + ie^{i\alpha(x)}\psi\partial_\mu \alpha \]
\[ \delta_\mu \alpha \text{ term breaks the invariance of } L \]

Invariance of \( L \) under local gauge transformations can be accomplished by introducing a gauge field \( A_\mu \), which transforms as:

\[ A_\mu \rightarrow A_\mu + \frac{1}{e} \partial_\mu \alpha \]

where \( e = g_e/4\pi \) = coupling strength

Can be formally achieved by the construction of a “modified” derivative

\[ \partial_\mu \rightarrow D_\mu = \partial_\mu - ieA_\mu \quad \text{(covariant derivative)} \]
Lagrangian of QED:

\[ L = i \bar{\psi} \gamma^\mu \partial_\mu \psi - m \bar{\psi} \psi + e \bar{\psi} \gamma^\mu A_\mu \psi - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} \]

where \( F_{\mu \nu} \) is the usual field strength tensor:

\[ F_{\mu \nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \]

Note:

(i) Imposing local gauge invariance leads to the interacting field theory of QED

(ii) A mass term \( \frac{1}{2} m^2 A_\mu A^\mu \) for the gauge field \( A_\mu \) would violate gauge invariance
Similar for the Standard Model interactions:

**Quantum Chromodynamics (QCD):**

SU(3) transformations, 8 gauge fields,
8 massless gluons, Gluon self-coupling
- $T_a$ ($a = 1, \ldots, 8$) generators of the SU(3) group
  (independent traceless 3x3 matrices)
- $G_\mu$ gluon fields
- $g$ = coupling constant

**Electroweak Interaction** (Glashow, Salam, Weinberg):

SU(2)$_L \times$ U(1)$_Y$ transformations,
4 gauge fields, ($W^1_\mu$, $W^2_\mu$, $W^3_\mu$, $B_\mu$)

**Physical states:**

$$ W^\pm_\mu = \frac{1}{\sqrt{2}} \left( W^1_\mu \pm iW^2_\mu \right) $$

$$ Z_\mu = -\sin \theta_W B_\mu + \cos \theta_W W^3_\mu $$

$$ A_\mu = \cos \theta_W B_\mu + \sin \theta_W W^3_\mu $$
Problems at that stage:

- Masses of the vector bosons W and Z:
  
  Experimental results: \( M_W = 80.399 \pm 0.023 \) GeV / c\(^2\)  
  \( M_Z = 91.1875 \pm 0.0021 \) GeV / c\(^2\)  

  A local gauge invariant theory requires massless gauge fields

- Divergences in the theory (scattering of W bosons)

\[-iM (W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \text{ for } s \rightarrow \infty\]
Solution to both problems:

- create mass via spontaneous breaking of electroweak symmetry
- introduce a scalar particle that regulates the $WW$ scattering amplitude

⇒ Higgs Mechanism
The Higgs mechanism

Spontaneous breaking of the SU(2) x U(1) gauge symmetry

- Scalar fields are introduced
  \[ \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i \phi_2 \\ \phi_3 + i \phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \]

- Potential:
  \[ V(\phi) = \mu^2 (\phi \ast \phi) + \lambda (\phi \ast \phi)^2 \]

- Lagrangian for the scalar fields:
  \[ L_2 = \left| i \partial_\mu - g T \cdot W_\mu - g' \frac{Y}{2} B_\mu \right| \phi^2 - V(\phi) \]

- For \( \mu^2 < 0, \lambda > 0 \), minimum of potential:
  \[ \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2 \quad v^2 = -\frac{\mu^2}{\lambda} \]

- Perturbation theory around ground state:
  \[ \phi_0(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \]
Particle content and masses

- Mass terms for the $W^\pm$ bosons:

$$M_{W^\pm} = \frac{1}{2}\nu g$$

- Remaining terms off-diagonal in $W^3_\mu$ and $B_\mu$:

$$\frac{1}{8}\nu^2 (W^3_\mu, B_\mu) \left( \begin{array}{cc} g^2 & -gg' \\ -gg' & g'^2 \end{array} \right) \left( \begin{array}{c} W^3_\mu \\ B_\mu \end{array} \right) = \frac{1}{8}\nu^2 \left[ gW^3_\mu - g'B_\mu \right]^2 + 0 \left[ g'W^3_\mu + gB_\mu \right]^2$$

- Massless photon:

$$A_\mu = \frac{g'W^3_\mu + gB_\mu}{\sqrt{g^2 + g'^2}} \quad \text{with} \quad M_A = 0$$

- Massive neutral vector boson:

$$Z_\mu = \frac{gW^3_\mu - g'B_\mu}{\sqrt{g^2 + g'^2}} \quad \text{with} \quad M_Z = \frac{1}{2}\nu\sqrt{g^2 + g'^2}$$
Masses of the gauge bosons:

\begin{align*}
\left| \left( -ig \frac{\tau}{2} \mathbf{w}_\mu - i \frac{g'}{2} B \right) \phi \right|^2
= & \frac{1}{8} \left| \begin{pmatrix}
g W^3_\mu + g' B_\mu & g (W^1_\mu - iW^2_\mu) \\
g (W^1_\mu + iW^2_\mu) & -g W^3_\mu + g' B_\mu
\end{pmatrix}
\begin{pmatrix}0 \\ v\end{pmatrix}\right|^2 \\
= & \frac{1}{8} v^2 g^2 \left[ (W^1_\mu)^2 + (W^2_\mu)^2 \right] + \frac{1}{8} v^2 (g' B_\mu - g W^3_\mu)(g' B^\mu - g W^3_\mu) \\
= & \left( \frac{1}{2} vg \right)^2 W^+ \mathbf{w}^{-\mu} + \frac{1}{8} v^2 (W^3_\mu, B_\mu) \begin{pmatrix}g^2 & -gg' \\ -gg' & g'^2\end{pmatrix} \begin{pmatrix}W^3_\mu \\ B^\mu\end{pmatrix}
\end{align*}
Important relations in the Glashow-Salam-Weinberg model:

• Relation between the gauge couplings:
  \[ \frac{g'}{g} = \tan \theta_w \]

→ Important prediction of the GSW with a Higgs doublet:
  \( \frac{M_W}{M_Z} = \cos \theta_w \)

or expressed in terms of the \( \rho \) parameter:
  \[ \rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1 \]

• From the \( M_W \) relation the value of the vacuum expectation value of the Higgs field can be calculated:
  \[ \frac{1}{2v^2} = \frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}} \]
  \[ \rightarrow v = 246 \text{ GeV} \]

where \( G_F = \) Fermi constant, known from low energy experiments (muon decay)
Masses of the Fermions:

- The same Higgs doublet which generates $W^\pm$ and $Z$ masses is sufficient to give masses to the fermions (leptons and quarks):
e.g. for electrons: use an arbitrary coupling $G_e$

$$L_3 = -G_e \left[ (\bar{\nu}_e, \bar{e})_L (\phi^0) e_R + \bar{e}_R (\phi^+, \phi^0) (\nu_e)_L \right]$$

- Spontaneous symmetry breaking:

$$L_3 = -\frac{G_e v}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) - \frac{G_e}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) h$$

  mass term  interaction term with the Higgs field

- Important relation: coupling of the Higgs boson to fermions is proportional to their mass

$$G_f = \frac{\sqrt{2} m_f}{v}$$
and finally...... a massive scalar with self-coupling, the **Higgs boson**:

- **Mass:** 
  \[ m_h^2 = 2v^2 \lambda \]

  (since \( \lambda \) is not predicted by theory, the mass of the Higgs boson is unknown)

- **Self-coupling:** 
  \[ -\lambda v h^3 - \frac{1}{4} \lambda h^4 \]

..... and:

- The additional diagram, with Higgs boson exchange, regulates the divergences in the longitudinal WW scattering
The Higgs boson as a UV regulator

Scattering of longitudinally polarized W bosons

$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{m_W^2} \quad \text{for} \quad s \rightarrow \infty$$

Higgs boson guarantees unitarity (if its mass is < ~1 TeV)

$$-iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty$$
8.2 Higgs boson properties

(a) \( \frac{-ig_f}{2m_W} \) (b) \( ig_m g_{\mu\nu} \) (c) \( \frac{ig_Z}{\cos \theta_W} g_{\mu\nu} \)
Higgs Boson Decays

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

\[
\begin{align*}
H & \rightarrow W^+, Z, t, b, c, \tau^+, \ldots, g, \gamma \\
H & \rightarrow W^-, Z, t, b, c, \tau, \ldots, g, \gamma
\end{align*}
\]

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

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

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

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

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

Total width

\[
\Gamma(H) [GeV] = \frac{G_F}{4\sqrt{2}\pi} m_f^2 (M_H^2 - M^2) M_H
\]
Higgs Boson Decays

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

\[
\begin{align*}
W^+, Z, t, b, c, \tau^+, \ldots, g, \gamma \\
W^-, Z, t, b, c, \tau, \ldots, g, \gamma
\end{align*}
\]
Constraints on the Higgs boson mass

1. Constraints from theory
2. Indirect limits from electroweak precision data (theory and experiment)
3. Limits from Direct Searches (LEP, Tevatron)
(i) Theory Constraints on the Higgs boson mass

- Unitarity limit:

  If Higgs boson too heavy, the regulation of the WW cross section is less effective and unitarity is violated again

  \[ m_H < \sim 1 \text{ TeV} \]  (as just discussed)

- Stricter limits from the energy dependence of the Higgs boson self coupling \( \lambda \):
  - Stability of the vacuum
  - Diverging coupling \( \lambda(Q^2) \)

  \[ \rightarrow \text{ next slides} \]
Tighter Higgs mass constraints:

Stronger bounds on the Higgs-boson mass result from the energy dependence of the Higgs coupling $\lambda(Q^2)$ (if the Standard Model is assumed to be valid up to some scale $\Lambda$)

$$\lambda(Q^2) = \lambda_0 \left\{ 1 + \frac{3\lambda_0}{2\pi^2} \log \left( 2 \frac{Q^2}{v^2} \right) + \ldots - \frac{3g_t^4}{32\pi^2} \log \left( 2 \frac{Q^2}{v^2} \right) + \ldots \right\}$$

where $\lambda_0 = \frac{m_h^2}{v^2}$

Upper bound: diverging coupling (Landau Pole)

Lower bound: stability of the vacuum
(negative contribution from top quark dominates)

Mass bounds depend on scale $\Lambda$ up to which the Standard Model should be valid

Hambye, Risselmann et al.
(ii) Indirect limits from electroweak precision data \( (m_W \text{ and } m_t) \)

**Motivation:**

\( W \) mass and top quark mass are fundamental parameters of the Standard Model; The standard theory provides well defined relations between \( m_W, m_t \) and \( m_H \)

Electromagnetic constant measured in atomic transitions, \( e^+e^- \) machines, etc.

\[
m_W = \left( \frac{\pi \alpha_{EM}}{\sqrt{2} G_F} \right)^{1/2} \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}}
\]

- \( G_F \), \( \alpha_{EM} \), \( \sin \theta_W \) are known with high precision
- Precise measurements of the \( W \) mass and the top-quark mass constrain the Higgs-boson mass (and/or the theory, radiative corrections)

\( m_W = \left( \frac{\pi \alpha_{EM}}{\sqrt{2} G_F} \right)^{1/2} \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}} \)
Results of the precision el.weak measurements: (LEWWG-2009):

\[ m_H = 87^{+35}_{-26} \text{ GeV} \]

\[ m_H = 108^{+6}_{-6} \text{ GeV} \]
(iii) Constraints from direct searches at LEP
**Higgs bosons searches at LEP**

**Higgs-Strahlung:**  $e^+ e^- \rightarrow Z H$

**WW-Fusion:**  $e^+ e^- \rightarrow \nu \nu H$

Higgs decay branching ratios for $m_H=115$ GeV/c$^2$:
- $BR (H \rightarrow bb) = 74\%$
- $BR (H \rightarrow \tau\tau, WW, gg) = 7\%$ each
- $BR (H \rightarrow cc) = 4\%$

**Decay modes searched for:**

- **Four Jet channel:**  $HZ \rightarrow bb\ qq$
- **Missing energy channel:**  $bb\ \nu\nu$
- **Leptonic channel:**  $bb\ ee, \ bb\ \mu\mu$
- **Tau channels:**  $bb\ \tau\tau$, and $\tau\tau\ qq$
Results of the final LEP analysis:

Final results have been published: CERN-EP / 2003-011:

Based on final calibrations of the detectors, LEP-beam energies, final Monte Carlo simulations and analysis procedures.

The reconstructed bb mass for two levels of signal purity (loose and tight cuts):

Clear peak in the background prediction in the vicinity of $m_Z$ due to the $e^+e^- \rightarrow ZZ$ background, which is consistent with the data.
Final combined LEP result

Likelihood ratio \( Q : = \frac{L_{S+B}}{L_B} \)
Test statistics: \(-2 \ln Q\)

\[ 1 - CL_B = 0.09 \quad \leftrightarrow \]

Signal significance = 1.7 \( \sigma \)

\[ M_H > 114.4 \text{ GeV/c}^2 \quad (95\% \text{ CL}) \]

expected mass limit: 115.3 GeV/c\(^2\)
(sensitivity)
8.3 Higgs boson production at Hadron Colliders
Higgs Boson production processes at Hadron Colliders

Relative importance of the various processes is different at the LHC and at the Tevatron

Gluon Fusion

Vector boson fusion

tt associated production

WH/ZH associated production
Production cross sections at the LHC

(for $\sqrt{s} = 14$ TeV, difference between 14 and 7 TeV to be discussed tomorrow)
Production cross sections at the LHC

(for $\sqrt{s} = 14$ TeV, difference between 14 and 7 TeV to be discussed tomorrow)
Production cross sections at the LHC

(for $\sqrt{s} = 14$ TeV, difference between 14 and 7 TeV to be discussed tomorrow)
Production cross sections at the LHC

(for $\sqrt{s} = 14$ TeV, difference between 14 and 7 TeV to be discussed tomorrow)
Production cross sections at the Tevatron

1. Gluon fusion

2./3. W/Z H associated production
Vector boson fusion

4. ttH (very small cross section)

qq → W/Z + H  cross sections  ~10 x larger at the LHC (\(\sqrt{s} = 14\) TeV)

gg → H  ~70-80 x larger at the LHC (\(\sqrt{s} = 14\) TeV)

J. Baglio, A. Djouadi, arXiv:1003.4266


Gluon fusion:

- Dominant production mode

- Sensitive to heavy particle spectrum ... (e.g. 4\textsuperscript{th} generation quarks)
  ...and the corresponding Yukawa couplings (important for coupling measurements, top Yukawa coupling)

- Large K-factors (NLO, NNLO corrections)
  - Difficult to calculate, loop already at leading order
    (calculation with infinite top mass is used as an approximation, however, this seems to be a good approximation)
  - Nicely converging perturbative series
Higher order corrections:

Independent variation of renormalization and factorization scales (with $0.5 \ m_H < \mu_F, \mu_R < 2 \ m_H$)
Vector boson fusion:

- Second largest production mode, Distinctive signature (forward jets, little jet activity in the central region)

- Sensitivity to W/Z couplings

- Moderate K-factors (NLO corrections)

  Both NLO QCD and el.weak have been calculated

- Effective K-factor depends on experimental cuts

  Example: typical VBF cuts
  \( P_T(jet) > 20 \text{ GeV} \)
  \( \eta < 4.5, \Delta\eta > 4, \eta_1 \cdot \eta_2 < 0 \)

Ciccolini, Denner, Dittmaier (2008)
WH / ZH associated production:

- Weak at the LHC, relatively stronger at the Tevatron
- Allows for a Higgs-decay-independent trigger: $W \rightarrow l\nu$, $Z \rightarrow ll$
- Sensitivity to W/Z couplings
- Moderate K-factors (NLO corrections)
  
  Both NLO QCD and el. weak corrections available

Han, Willenbrock (1990)
Ciccolini, Dittmaier, Krämer (2003)
ttH associated production:

- Weak and difficult at the LHC
- Sensitivity to top-Yukawa coupling
- Moderate K-factors (NLO corrections)
  
  NLO QCD corrections available, scale uncertainty drastically reduced

scale: $\mu_0 = m_t + m_H/2$

LHC: $K \sim 1.2$
Tevatron: $K \sim 0.8$

Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas (2001)
8.4 The Search for the Higgs Boson at the Tevatron
Useful Higgs Boson Decays at Hadron Colliders

**at high mass:**
Lepton final states
(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 ($ttH, W/Z H$)

(due to the huge QCD jet background, leptons from $W/Z$ or $tt$ decays)
Searches for a low mass Higgs boson at the Tevatron

$m_H < 135 \text{ GeV}$:

Associated production $WH$ and $ZH$ with $H \to bb$ decay
Main low mass search channels

\( \ell + E_T^{\text{miss}} + bb: \ WH \to \ell vbb \)
Largest VH production cross section, however, severe backgrounds

\( \ell\ell + bb: \ ZH \to \ell\ell bb \)
Less background than WH
Smallest Higgs signal

\( E_T^{\text{miss}} + bb: \ ZH \to vvbb \)
3x more signal than \( ZH \to \ell\ell bb \)
(+\( WH \to \ell v bb \) when lepton non-identified)
Large backgrounds which are difficult to handle
WH (H→bb) Signal, \( m_H = 115 \text{ GeV} \):
\[ \sigma \times \text{BR} = 14 \text{ fb} \] (per lepton)

Large backgrounds:
- W+jet production
  - W+bb: \( \sigma \times \text{BR} = 4 \times 10^4 \text{ fb} \)
  - W+cc: \( \sigma \times \text{BR} = 1 \times 10^5 \text{ fb} \)
  - W+qq: \( \sigma \times \text{BR} = 2 \times 10^6 \text{ fb} \)

Additional backgrounds:
- WW: \( \sigma \times \text{BR} = 13 \text{ pb} \)
- tt: \( \sigma \times \text{BR} = 7 \text{ pb} \)
- single top: \( \sigma \times \text{BR} = 3 \text{ pb} \)

+ multijet QCD background
General Search Strategy

(i) Select events consistent with Z/W + 2 jets (large W+jet and Z+jet backgrounds)

(ii) Apply b-tagging (most discriminating variable: dijet inv. mass)

   even after b-tagging S:B ratio remains small, needs advanced (multivariate) analysis tools

(iii) Optimize separation power by multivariate discrimination (neutral networks, matrix elements, ...)

Major input variables:
- dijet mass
- $P_T$ of the dijet system
- $P_T$ of W/Z
- Sphericity
- $\Delta R_{jj}, \Delta \phi_{jj}, \Delta \eta_{jj}$

Example: $WH \rightarrow \ell\nu bb$

- Pre-b-tag $S/B = 1/4000$
- 1b-tag $S/B = 1/400$
- 2b-tag $S/B = 1/100$
DØ: WH→lν bb (l=e,μ) neural net

- $p_T(j_1)$
- $p_T(j_2)$
- $\Delta R(jj)$
- $\Delta \phi(jj)$
- $p_T(jj)$
- $M(jj)$
- $p_T(l, E_T\text{ Miss})$
Sensitivity in the low mass region

- Limits for individual channels a factor of 5-10 away from SM cross section at \( m_H = 115 \text{ GeV} \)
- The combination of all contributing channels is crucial

Excluded cross section:
(95% C.L., \( m_H = 115 \text{ GeV} \))

- **D0**: \( \sigma_{95} = 6.9 \cdot \sigma_{SM} \)
- **CDF**: \( \sigma_{95} = 4.3 \cdot \sigma_{SM} \)

Main systematic uncertainties for low mass channels:
- Signal (total 15%): cross section, b-tagging, ID efficiencies
- Background (total 25-30%): normalization of W/Z+jets heavy flavour samples, modelling of the multijet and W/Z+jet backgrounds, b-tagging
Searches for a high mass Higgs boson at the Tevatron

$m_H > 135 \text{ GeV}$:

$gg \rightarrow H \rightarrow WW \rightarrow \ell \nu \ell \nu$
Number of produced events (incl. decays) per 1 fb$^{-1}$

$gg \rightarrow H \rightarrow WW \rightarrow l\nu l\nu$) Signal, $m_H = 160$ GeV:
$\sigma \times \text{BR} = 40$ fb
Associated WH and qqH production increase signal by $\sim 30$

**Significant di-boson backgrounds:**

- WW: $\sigma \times \text{BR} = 13$ pb
- WZ: $\sigma \times \text{BR} = 4.0$ pb
- ZZ: $\sigma \times \text{BR} = 1.5$ pb

**Additional backgrounds:**

- $tt$: $\sigma \times \text{BR} = 7$ pb
- Single top: $\sigma \times \text{BR} = 3$ pb

+ multijet QCD background
$H \rightarrow \ell^+\ell^- \nu\nu$

- Dominant decay for $m_H > 135$ GeV: $H \rightarrow W^*W$
- Leptons in final state
  → exploitation of $gg\rightarrow H$ is possible
- Signal contribution also from $W/Z+H$ and $qqH$ production
  → Consider all sources of opposite sign di-lepton + $E_T^{\text{miss}}$
    Split analysis in $ee$, $\mu\mu$, and $e\mu$ final states
- Backgrounds: Drell-Yan, dibosons, $tt$, $W$+jet, multijet production
Dominant Drell-Yan background can be reduced with cuts on $E_T^{\text{miss}}$ and its isolation (distance to nearest object).

Spin correlation gives main discrimination against irreducible background from non-resonant $WW$ production.

$H \rightarrow \ell^+ \ell^- \nu \nu$

Cut at 25 (15 for $\mu \mu$) already applied.
To increase sensitivity:

**DØ:** Split the samples according to lepton flavour and combines the result.

**CDF:** Split samples into jet multiplicity and lepton ID criteria: different signal and background composition.

Veto events with tight b-tagged jet.
Tevatron experiments set a 95% CL exclusion of a SM Higgs boson in the mass region 158–173 GeV  (first direct exclusion since LEP)

At $m_H = 115$ GeV  
Expected limit: $1.8 \times \sigma_{SM}$

Observed limit: $2.7 \times \sigma_{SM}$
Systematic uncertainties

Analyses are affected by significant systematic uncertainties;

Example: The two most significant DØ analyses:

<table>
<thead>
<tr>
<th>Source</th>
<th>$WH \rightarrow e\nu b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6.1</td>
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<tr>
<td>Normalization</td>
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<tr>
<td>Jet Energy Scale</td>
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<tr>
<td>Jet ID</td>
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<td>Jet Triggers</td>
<td>-</td>
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<td>Electron ID/Trigger</td>
<td>-</td>
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<td>Muon ID/Trigger</td>
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<tr>
<td>$b$-Jet Tagging</td>
<td>-</td>
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<td>Background $\sigma$</td>
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<tr>
<td>Multijet</td>
<td>7-20</td>
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<td>Shape-Dependent Bkgd Modeling</td>
<td>14</td>
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<td>Multijet</td>
<td>2-20</td>
</tr>
<tr>
<td>Shape-Dependent Bkgd Modeling</td>
<td>5-20</td>
</tr>
</tbody>
</table>

- Systematic uncertainties for background rates are generally several times larger than the signal expectation itself

- To minimize the degrading effect of systematic uncertainties on the search sensitivity, the individual background contributions are fitted to the data observation by maximizing a likelihood function
  Nuisance parameters allow for variations within errors

- Each systematic uncertainty (incl. uncertainty on signal cross section) is folded into the signal and background expectation via Gaussian distributions (correlations preserved)