Lecture 9:

The search for the (SM) Higgs Boson

- theoretical basics
- Higgs production and decay
- Higgs search in $e^+e^-$ annihilation
  - direct search
  - indirect mass limits from electroweak radiation corrections
- Higgs searches in hadron collisions
  - Tevatron
  - LHC (-> next lecture)
The Standard Model Higgs Boson:
theoretical basics and expectations

• gauge field theory with gauge symmetry in weak isospin/hyper charge [SU(2) x U(1)]
to describe electromagnetic and weak interactions of quarks and leptons:
includes massless gauge bosons (γ, Z⁰, W⁺, W⁻) and fermions

• any attempt to include mass terms breaks gauge symmetry and destroys
renormalizability of the theories

• Englert, Brout and Higgs (1964): spontaneous symmetry breaking (generates mass,
keeps renormalizability):

• introduction of complex SU(2) doublets of scalar fields with a potential
of \( V(\phi) = \lambda (\phi^*\phi)^2 - \mu^2 \phi^*\phi \); with \( \lambda, \mu^2 > 0 \);
\[
\phi = \begin{pmatrix}
\phi_1 + i\phi_2 \\
\phi_3 + i\phi_4
\end{pmatrix}
\]

• \( V \) does not have minimum at \( \phi = 0 \), but at
\[
|\phi| = \sqrt{\frac{\mu^2}{2\lambda}} = \frac{\nu}{\sqrt{2}}
\]

• 3 of the 4 real degrees of freedom are used to generate
the longitudinal spin d.o.f. of \( Z^0 \) and \( W^\pm \);
4. d.o.f. \( \rightarrow \) physical Higgs particle!
theoretical basis and expectations

• inserting $\phi$ in Lagrange function results in 3 massive vector fields, 1 massless vector-field, plus one massive scalar field with

$$M_W = \frac{1}{2} g v \quad \Rightarrow \quad v = 246 \ \text{GeV}$$

$$M_Z = M_W / \cos \theta_w \quad (g = e / \sin \theta_w)$$

$$M_\gamma = 0$$

$$M_H = 2 \mu^2 = 2 \lambda v^2$$

• introduction of Yukawa-couplings $g_f$ between $\phi$ and the fermion fields: generates fermion masses

$$m_f = \frac{g_f v}{\sqrt{2}}$$

• fundamental fermion-Higgs couplings:

$$g_{f\bar{f}H} = \frac{e m_f}{2 M_w \sin \theta_w}$$

$$g_{WWH} = \frac{e M_w}{\sin \theta_w}$$

$$g_{ZZH} = \frac{e M_Z}{\sin \theta_w \cos \theta_w}$$
theoretical basis and expectations

theoretical bounds for $M_H$ from self-consistency arguments of the Standard-Model:

- upper bounds: perturbativity
- lower bounds: vacuum stability

n.b.: if SM is valid only up to $\Lambda = O(1 \text{ TeV})$, then $M_H = 50 \ldots 1000 \text{ GeV}$

n.b.: if SM is valid up to $\Lambda = O(M_{\text{Planck}})$, then $M_H \sim 125 \ldots 180 \text{ GeV}$

$\Lambda$: energy scale up to which SM is valid
Higgs: production and decays

**Higgs-radiation**

\[ e^+ e^- \rightarrow Z^* \rightarrow H \]

**Gluon - Fusion**

\[ g g \rightarrow t t \rightarrow H \]

**W- (Z-) fusion**

\[ q q' \rightarrow W (Z) \rightarrow H \]

**Higgs-radiation ("associate production")**

\[ g g \rightarrow Z^*, W^* \rightarrow H \]

**Higgs-decay:**

predominantly into heaviest, kinematically accessible pair of leptons or bosons

\[ q, \ell^+, W^+, Z^0 \]

\[ \bar{q}, \ell^-, W^-, Z^0 \]
**Higgs: decays**

$$\text{Br}(H \rightarrow \gamma\gamma) \sim 10^{-3}$$

- **$M_H < \sim 135 \text{ GeV}$:** dominanter Zerfallskanal  \( H \rightarrow b \, b \)
- **$M_H > \sim 135 \text{ GeV}$:** dominanter Zerfallskanal  \( H \rightarrow W^+W^- \)
Higgs: decays

Low mass region, e.g. $m_H = 125$ GeV:
- $\gamma\gamma$, 0.2%
- $ZZ$, 3.0%
- $\tau\tau$, 5.9%
- $WW$, 21.8%
- $bb$, 56.4%

High mass region, e.g. $m_H = 300$ GeV:
- $ZZ$, 30.7%
- $WW$, 69.2%
- other, 0.1%

Ordered by the sensitivity to the signal:
- $H \to ZZ \to (\ell^+\ell^-)(\ell^+\ell^-)$
- $H \to \gamma\gamma$
- $H \to WW \to (\ell^+\nu)(\ell^-\nu)$
- $H \to \tau^+\tau^-$ (large background)
- $H \to b\bar{b}$ (large background)

Ordered by the sensitivity to the signal:
- $H \to ZZ \to (\ell^+\ell^-)(\ell^+\ell^-)$
- $H \to ZZ \to (\ell^+\ell^-)(\nu\nu)$
- $H \to ZZ \to (\ell^+\ell^-)(q\bar{q})$
- $H \to WW \to (\ell^+\nu)(\ell^-\nu)$
- $H \to WW \to (\ell^+\nu)(qq)$
**Higgs: production**

\[ e^+e^- \text{ annihilation} \]

\[
\begin{array}{c}
\sigma \text{ (pb)} \\
\hline
10^5 \\
10^4 \\
10^3 \\
10^2 \\
10 \\
1 \\
10^{-1} \\
10^{-2} \\
10^{-3} \\
10^{-4} \\
10^{-5}
\end{array}
\]

\[
\begin{array}{c}
e^+e^- \rightarrow \text{hadrons} \\
\text{Born} \\
e^+e^- \rightarrow \mu^+\mu^- \\
e^+e^- \rightarrow HZ \\
WW \\
ZZ \\
m_h = 70 \text{ GeV} \\
90 \\
110
\end{array}
\]

\[ \sqrt{s} \text{ [GeV]} \]

\[ 60 \quad 80 \quad 100 \quad 120 \quad 140 \quad 160 \quad 180 \quad 200 \]
Higgs: production

Standard Model Higgs Boson @ Tevatron

\[
\sigma(pp \to H + X) \text{ [pb]}
\]

\[
\sqrt{s} = 2 \text{ TeV}
\]

- \(gg \to H\)
- \(Hqq\)
- \(H\bar{b}\bar{b}\)
- \(H\tau\tau\)
- \(WW, ZZ\) fusion
- \(WW, ZZ\) bremsstrahlung
Higgs: production

Standard Model Higgs Boson @ LHC (7 TeV)

![Graph showing Higgs production at the LHC](image)
Higgs: production

Standard Model Higgs Boson @ LHC (14 TeV)

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

- \( gg \rightarrow H \)
- \( q\bar{q}' \rightarrow HW \)
- \( gg, q\bar{q} \rightarrow H\ell \)
- \( gg, q\bar{q} \rightarrow H\ell \)
- \( gg, q\bar{q} \rightarrow Hbb \)
- \( q\bar{q} \rightarrow HZ \)
- \( W, Z \) bremsstrahlung
Higgs production cross-sections

proton - (anti)proton cross sections

\[ \sigma(\text{nb}) \]

\[ \sigma_\text{tot} \]

\[ \sigma_\text{b} \]

\[ \sigma_\text{W} \]

\[ \sigma_\text{Z} \]

\[ \sigma_\text{jet}(E_T > \sqrt{s}/20) \]

\[ \sigma_\text{jet}(E_T > 100 \text{ GeV}) \]

\[ \sigma_{\text{Higgs}}(M_H = 120 \text{ GeV}) \]

\[ \sigma_{\text{Higgs}}(200 \text{ GeV}) \]

\[ \sigma_{\text{Higgs}}(500 \text{ GeV}) \]

\[ \text{events/sec for } L = 10^{33} \text{ cm}^{-2}\text{s}^{-1} \]
Higgs search
Higgs-search in $e^+e^-$ annihilation: direct

production:

\[
\begin{align*}
e^+ & \rightarrow Z^* \rightarrow ZH \\
e^- & \rightarrow Z^* \rightarrow ZH \\
W^+ & \rightarrow \nu \rightarrow \ell^+ \\
W^- & \rightarrow \bar{\nu} \rightarrow \ell^-
\end{align*}
\]

deck channel ($e^+e^- \rightarrow HZ$):

\[
\begin{align*}
H & \rightarrow b\bar{b}, \quad Z \rightarrow q\bar{q} \quad \text{4-Jet-Kanal} \\
H & \rightarrow b\bar{b}, \quad Z \rightarrow \nu\bar{\nu} \quad \text{Neutrino-Kanal} \\
H & \rightarrow b\bar{b}, \quad Z \rightarrow \tau^+\tau^- \quad \text{Tau-Kanal} \\
H & \rightarrow \tau^+\tau^-, \quad Z \rightarrow q\bar{q} \quad \text{Lepton-Kanal}
\end{align*}
\]

background:

\[
\begin{align*}
WW & \rightarrow q\bar{q}q\bar{q}, ZZ \rightarrow b\bar{b}q\bar{q} \quad \text{QCD 4jets} \\
WW & \rightarrow q\bar{q}\ell\nu, ZZ \rightarrow b\bar{b}\nu
\end{align*}
\]

search includes ~ 80% of all final states with ~ 40 - 50% selection efficiency
Higgs-search in $e^+e^-$ annihilation: direct

L3: Candidate event for $ee \rightarrow HZ \rightarrow eeqq$

LEP: from direct search $M_H > 114.1$ GeV
Higgs-search in e^+e^- annihilation: indirect

radiation corrections in SM:

photonic corrections:

\[ \sin^2 \theta_{\text{eff}}(s) \]

corrections \( \sim 100\% \), selection dependent;
factorisable: \( (1 + \delta_{\text{rad}}) \)

non-photonic corrections:

\[ N_{\text{cf}} \left( 1 + \frac{\alpha_s}{\pi} + 1.4 \left( \frac{\alpha_s}{\pi} \right)^2 + \ldots \right) \] (für Quarks)

\[ \frac{M_W^2}{M_Z^2} = \rho \cdot \cos^2 \theta_w \] mit \( \rho = \frac{1}{1 - \Delta \rho} \); \( \Delta \rho = 0.0026 \frac{M_t^2}{M_Z^2} - 0.0015 \ln \left( \frac{M_H}{M_W} \right) \)
Higgs-search in $e^+e^-$ annihilation: indirect

Insertion of running couplings into "Born"-approximation:

Partial decay widths of $Z$: \[ \Gamma_f = \frac{G_f M_Z^3}{6\pi\sqrt{2}} \left[ g_{a,f}^2 + g_{v,f}^2 \right] \] (and thus, also the cross sections) become dependent on:

- $M_t$
- $M_H$
- $\alpha_s$

$\Rightarrow$ indirect determination (fit) of $M_t$, $M_H$, und $\alpha_s$ from combination of all available electro-weak observables (differential cross sections, partial decay widths, forward-backward asymmetries, $\tau$-polarisation, ...)

$g_{a,f} = I_{3,f}$ (3. Komponente schw. Isospin; = ±1/2)

$g_{v,f} = I_{3,f} - 2Q\sin^2 \theta_w$
Higgs-search in $e^+e^-$ annihilation: indirect

indirect
(adjuncting radiative corrections):
$m_H = 84^{+34}_{-26}$ GeV
(68% c.l.)

direct searches
(exclusion)
$m_H > 114.1$ GeV

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$114.1$ GeV < $m_H < 154$ GeV (1-sided 95% c.l.)

$n.b.$: at the end of LEP (2000), indication for few events with $m_H \sim 115$ GeV (~2.3 std. dev.)
Higgs-Search at Hadron colliders: Tevatron

$M_H < \sim 135 \text{ GeV}$: dominant decay $H \rightarrow b \bar{b}$ ($\sim 90\%$)
$H \rightarrow \tau^+\tau^-$ ($\sim 8\%$)

$M_H > \sim 135 \text{ GeV}$: dominant decay $H \rightarrow W^+W^-$

hadron collider: $b \bar{b}$ background from QCD processes dominates; irreducible;
$g g \rightarrow H \rightarrow b \bar{b}$ cannot be used

therefore:

focus on associate production $(ZH, WH)$ and analyse
e.g. $Z \rightarrow l^+l^-; H \rightarrow bb$

$\tau \tau$ decay suitable for all production channels
Higgs-Search at Hadron colliders: Tevatron

example: $M_H = 120$ GeV and $30$ fb$^{-1}$ (model study!)

very difficult measurement; background must be known extremely well!
Tevatron was shut down on Sept. 29, 2011, after 26 years of colliding p and $\bar{p}$
definition of significance

- $N_s$: number of signal events
- $N_b$: number of background events

$\sqrt{N_b} = \text{uncertainty on number of background events}$

discovery: $S > 5$

- probability to observe background fluctuation: $\approx 10^{-7}$

aim for high significance

- minimize mass resolution $\sigma_m$: $S \sim 1/\sqrt{\sigma_m}$
- maximize luminosity $L$: $S \sim \sqrt{L}$

$S = \frac{N_s}{\sqrt{N_b}}$
Expected Tevatron sensitivity

Tevatron at end-of-run (Sept. 2011): $< 12 \text{ fb}^{-1} / \text{experiment}$

$\rightarrow$ exclusion ($3 \sigma$) expected: 100 - 117 und 150 - 179 GeV;
5 $\sigma$ discovery possible to be reached at 160 - 167 GeV.
H→WW→lνlν

- Basic event selection is two reconstructed leptons and missing $E_T$
- Presence of two neutrinos in final state prevents complete Higgs mass reconstruction
- Separate potential signal from large backgrounds using kinematic event information
H→WW→lνlν

- Results from thirteen independent search samples are combined to obtain the best possible sensitivity.
- No significant, observed excesses in data above predicted SM background contributions.
• Tevatron searches in this decay mode are still the world’s most sensitive
• Basic event selection is 0, 1, or 2 leptons and/or missing $E_T$ plus two high $E_T$ jets
• Challenge is separating the small number of potential signal events from the much larger SM background contributions
Pre-tagged events

Focus on

Increasing lepton reconstruction and selection efficiencies

Improving the efficiency for tagging bottom quark jets

Optimizing dijet mass resolution
CDF/D0 combined conclusion (July 2012):

- SM Higgs exclusion in the range 147-180 (and 100-103) GeV @95% CL
- Expected exclusion range 139-184 GeV
- $2.5 \sigma$ excess in region 115-135 GeV ($3.0 \sigma$ at $M_H=125$ GeV)

observed signal strength:
Summary SM Higgs-search w/o LHC data (2012):

Precision measurements of electroweak observables, accounting for radiative corrections \( \propto \log m_H^2 \):

- \( m_H = 94^{+20}_{-24} \text{ GeV} \) (68% C.L.) and
- \( m_H < 171 \text{ GeV} \) (95% C.L.)

Direct searches at LEP:
- \( m_H > 114.4 \text{ GeV} \) at (95% C.L.)

Direct searches at Tevatron:
- \( m_H < 147 \text{ GeV} \) at (95% C.L.) and
- \( m_H > 180 \text{ GeV} \) at (95% C.L.)
Higgs-search and discovery at LHC (preview):

(see next lecture; 16.1.2017)
Literatur:


- Updated Combination of CDF and D0 Searches for Standard Model Higgs Boson Production with up to 10.0 fb-1 of Data, http://arxiv.org/abs/1207.0449.