Higgs Physics at the Large Hadron Collider

Michael Krämer

(RWTH Aachen)

- Electroweak symmetry breaking
- The profile of the Standard Model Higgs boson
- Higgs searches at the LHC
I have used the following references to prepare these lectures:

- Lectures from Maria Laach schools, in particular those by S. Dawson and M.L. Mangano;
- Lectures from previous Lecce schools, in particular those by C. Oleari and D. Zeppenfeld;
- Lectures by D. Ross at the Scottish University Summer School SUSSP57;
- textbooks, mainly: Peskin & Schroeder, Barger & Phillips.
The SM Lagrangian is determined by

- the particle content
- Poincare invariance
- local gauge invariance under $SU(3)$, $SU(2)$ and $U(1)$
- renormalizability
- and the mechanism of electroweak symmetry breaking

\[
\mathcal{L}_{SM} = -\frac{1}{4} F^{a}_{\mu\nu} F_{a}^{\mu\nu} + i \bar{\psi} D\psi \\
+ \psi_i \lambda_{ij} \psi_j H + h.c. \\
+ |D H|^2 - V(H) \\
+ N_i M_{ij} N_j
\]

gauge sector
flavour sector
EWSB sector
$\nu$-mass sector
The SM Lagrangian looks a bit more complicated when you spell it out (typed by T.D.Gutierrez from Diagrammatica by M.Veltman)
From $WW$-scattering to the Higgs boson

**Fermi**: weak interactions described by effective Lagrangian eg. for $\mu$ decay $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} [\bar{\nu}_\mu \gamma^\lambda (1 - \gamma_5) \mu] [\bar{e} \gamma^\lambda (1 - \gamma_5) \nu_e]$$

with $G_F \approx 1.17 \times 10^{-5}$ GeV$^{-2}$ (Fermi coupling)

**Fermi theory at high energies**: $\mathcal{M} [\bar{\nu}_\mu e^- \rightarrow \mu^- \nu_e] \sim \frac{G_F}{2\sqrt{2}\pi} s$

$\implies$ violates unitarity

**Solution**: interaction mediated by heavy vector boson $W^\pm$

$$\mathcal{M} [\bar{\nu}_\mu e^- \rightarrow \mu^- \nu_e] \rightarrow \frac{G_F s}{2\sqrt{2}\pi} \frac{M_W^2}{M_W^2 - s} \quad \text{ (with } M_W \approx 100 \text{ GeV)}$$
From $WW$-scattering to the Higgs boson

Consider $WW \rightarrow WW$

$\mathcal{M}[W_L W_L \rightarrow W_L W_L] \propto s$ ⇒ violates unitarity

Solution: − strong $WW$ interaction at high energies or
− new scalar particle $H$ with $g_{WWH} \propto M_W$

$\mathcal{M} \rightarrow \frac{G_F M_H^2}{4\sqrt{2}\pi}$

Unitarity ⇒ properties of $H$: − coupling $g_{XXH} \propto$ particle mass $M_X$
− $M_H \lesssim 1$ TeV
Spontaneous symmetry breaking I: the ABEGHHK’tH Mechanism

(Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble, ’t Hooft)

Generating particle masses requires breaking the gauge symmetry

\[ M_{W,Z} \neq 0 \quad \Leftrightarrow \quad \langle 0 | X | 0 \rangle \neq 0 \]

Standard Model: Spontaneous symmetry breaking through scalar isodoublet \( \Phi \)

\[
\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}
\]

with scalar potential

\[ V = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 \]

If \( \mu^2 < 0 \) (why?), then the minimum of the potential is at

\[
\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}
\]

where \( v = \sqrt{-\mu^2/|\lambda|} \)

→ spontaneous symmetry breaking

→ 3 Goldstone bosons → mass for \( W^\pm, Z \)
→ 1 physical scalar (Higgs) particle
Spontaneous symmetry breaking I: U(1)-Example

Or: How to generate masses for gauge bosons without violating gauge invariance?

Recall structure of $U(1)$ local gauge theory with single spin-1 gauge field $A_\mu$:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \quad \text{where} \quad F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

$\rightarrow$ mass term $\propto m^2 A^\mu A_\mu$, not gauge invariant $\rightarrow$ massless gauge boson $A$

Possible solution: add complex scalar field $\phi$ with charge $-e$:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + |D_\mu \phi|^2 - V(\phi) \quad \text{where} \quad V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

If $\mu^2 > 0$: unique minimum at $\phi = 0 \rightarrow$ QED with $M_A = 0$ and $M_\phi = \mu$

Reverse sign of $\mu^2$ so that $V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$

$\rightarrow$ minimum of potential at $\sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{\nu}{\sqrt{2}}$

Expand $\phi$ around vacuum expectation value: $\phi = \frac{1}{2} (v + H + i\chi)$

$$\Rightarrow \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \partial_\mu H \partial^\mu H + \partial_\mu \chi \partial^\mu \chi + \frac{1}{2} e^2 v^2 A_\mu A^\mu + ev A^\mu \partial_\mu \chi$$

$$-e A^\mu (\chi \partial_\mu H - H \partial_\mu \chi) + \frac{1}{2} e^2 A_\mu A^\mu (H^2 + \chi^2) - V(\phi)$$
Spontaneous symmetry breaking I: U(1)-Example

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \partial_\mu H \partial^\mu H + \partial_\mu \chi \partial^\mu \chi + \frac{1}{2} e^2 v^2 A_\mu A^\mu + e v A^\mu \partial_\mu \chi \\
- e A^\mu (\chi \partial_\mu H - H \partial_\mu \chi) + \frac{1}{2} e^2 v^2 A_\mu A^\mu (H^2 + \chi^2) - V(\phi)
\]

The theory now has:

- a photon of mass \( M_A = e v \)
- a scalar field \( H \) with \( M_H^2 = -2 \mu^2 > 0 \)
- a massless scalar field \( \chi \) (Goldstone boson)

The mixed \( A - \chi \) propagator can be removed by a gauge transformation:

\[ A_\mu \rightarrow A_\mu - \frac{1}{e v} \partial_\mu \chi \quad \text{and} \quad \phi \rightarrow e^{-i \frac{\chi}{v}} \phi \quad \text{(unitary gauge)} \]

→ the \( \chi \) field has been absorbed by a redefinition of \( A \)

(jargon: \( \chi \) has been “eaten” to give photon mass)

Counting of degrees of freedom:

before symmetry breaking: massless gauge boson (2 dof) and complex scalar (2 dof)

after symmetry breaking: massive gauge boson (3 dof) and physical scalar (1 dof)
Spontaneous symmetry breaking I: the ABEGHHK’tH Mechanism?

John Earman, Philosopher, on the need to choose a specific gauge to suppress Goldstone bosons and generate masses for gauge bosons:

“A genuine property like mass cannot be gained by eating descriptive fluff, which is just what gauge is”
ACCIDENTAL BIRTH OF A BOSON

1964

Thu. 16 July

F. 24 July
Broken Symmetries, Messerschmidt Particles and Gauge Fields (P.W.H) sent to Physics Letters editor at CERN.

F. 31 July
Broken Symmetries and the Masses of Gauge Bosons (P.W.H.) sent to Physics Letters editor at CERN.

REJECTED

August
Paper revised by adding (italics)
"It is worth noting that an essential feature of this type of theory is the prediction of incomplete multiplets of vector bosons"

31 August
Revised paper received by Physical Review Letters.
ACCEPTED

Referee (Member) draws to attention of PWH the paper by T. Englert & R Brout, Broken Symmetries and the mass of Gauge Vector Mesons (received by Phys. Rev. Letters 22 June, published 31 August).
Spontaneous symmetry breaking II: superconductivity


Ginzburg-Landau description: \( F_{\text{super}}(B = 0) = F_{\text{free}}(B = 0) + \alpha |\Psi|^2 + \beta |\Psi|^4 \)

![Graphs showing free energy as a function of order parameter for temperatures above and below \( T_c \)]

\( T > T_c : \alpha > 0 \Rightarrow \Psi_0 = 0 \)

\( T < T_c : \alpha < 0 \Rightarrow \Psi_0 \neq 0 \)

Microscopic mechanism (Bardeen, Cooper, Schrieffer):

Electromagnetic gauge invariance is broken by Cooper pairs of electrons with \( \langle 0 | \bar{e} e | 0 \rangle \neq 0 \)

Weisskopf, Cornell seminar (recalled by Brout), 1960:

“Particle physicists are so desperate these days that they have to borrow from the new things coming up in many-body physics - like BCS. Perhaps something will come of it…”
Spontaneous symmetry breaking III: chiral symmetry in QCD

- For $m_{\text{up}}, m_{\text{down}} = 0$:

$$\mathcal{L}_{\text{QCD}} = \bar{q}_L \not{D} q_L + \bar{q}_R \not{D} q_R \quad (q_{L,R} = (1 \mp \gamma) q/2)$$

→ independent left and right rotations permitted: $U(2)_L \otimes U(2)_R$ (chiral) symmetry

- Spontaneous breaking of chiral symmetry through quark condensate:

$$\langle 0 | \bar{q}q | 0 \rangle \equiv \langle 0 | \bar{q}_L q_R + \bar{q}_R q_L | 0 \rangle \simeq \Lambda_{\text{QCD}}^3 \simeq (250 \text{ MeV})^3 \neq 0$$

→ 3 massless Goldstone bosons: $\pi^0, \pi^\pm$

→ dynamical quark masses → heavy nucleons

- **QCD lite**™ (2 massless quarks and gluons)

  90% of mass of ordinary matter (without the Higgs particle...)

- In the real world $m_{\text{up}}, m_{\text{down}} \neq 0$ and chiral symmetry is not exact.

  But $m_{\text{up}}, m_{\text{down}} \ll \Lambda_{\text{QCD}}$ and $m_\pi \ll m_{\text{proton, neutron}}...$
Dynamical electroweak symmetry breaking: Technicolour

- SSB in condensed matter physics and QCD through fermion condensate

\[ \langle 0 | F^a F | 0 \rangle \neq 0 \]

\[ \Rightarrow \text{EWSB through new strong interactions of new massless fermions ("technicolour")}: \]

\[ \langle 0 | \bar{T} T | 0 \rangle \simeq \Lambda_{TC}^3 \simeq (1 \text{ TeV})^3 \neq 0 \]

- massless technipions \rightarrow masses for $W^\pm$, $Z$ via Brout-Englert-Higgs mechanism
- new bound states ("technihadrons") with $M \approx 1$ TeV

To give masses to the Standard Model quarks and leptons must add interactions between $T, q, l$ ("extended technicolour")

- Features
  - no fundamental scalar needed
  - dynamical generation of hierachy $\Lambda_{TC}/M_{\text{Planck}} \approx 10^{-17}$ through RGE running
    - What breaks extended technicolour?
    - How to accommodate FCNC and electroweak precision tests? (\rightarrow "walking technicolour")
    - How to accommodate the large top quark mass? (\rightarrow "topcolour assisted technicolour")
EWSB: fundamental Higgs boson or fermion condensate?

**fundamental Higgs boson**

+ simple and predictive
+ consistent with precision data

- no dynamical explanation of EWSB
- fundamental scalar has never been observed in nature
- Higgs mass unstable under radiative corrections: why is $M_{\text{Higgs}} \ll M_{\text{Planck}}$?
  (naturalness problem)

**fermion condensate**

+ analogous to existing mechanisms (BCS, QCD)
+ no fundamental scalar $\rightarrow$ no naturalness problem

- less predictive (strongly interacting theorie)
- no realistic and compelling models(?)

Michael Peskin, EPS 99:

“The idea that the data drives us to a weak-coupling picture of the Higgs boson was controversial at HEP99. Among the people arguing vocally on the other side were Holger Nielsen and Gerard ’t Hooft. So if you do not wish to accept this argument, you are in good company (but still wrong).”
Consider first the Higgs kinetic term

$$\mathcal{L} \supset |D_\mu \Phi|^2$$

with the covariant derivative of the $SU(2) \times U(1)$ gauge theory

$$D_\mu = \partial_\mu + i \frac{g_W}{2} \sigma^i W^i_\mu + i \frac{g'_W}{2} B_\mu$$

Expanding $\Phi$ about its vacuum expectation value

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

the covariant derivative may be written (in unitary gauge)

$$D_\mu \Phi = \frac{1}{\sqrt{2}} \left( \partial_\mu + i \frac{g_W}{2} \begin{pmatrix} W^0_\mu & \sqrt{2} W^-_\mu \\ \sqrt{2} W^+_\mu & -W^0_\mu \end{pmatrix} + i \frac{g'_W}{2} B_\mu \right) \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

which leads to

$$\mathcal{L} \supset |D_\mu \Phi|^2 = \frac{1}{2} (\partial_\mu H)^2 + \frac{g_W^2 v^2}{4} W^{+\mu} W^-_\mu + \frac{v^2}{8} (g_W W^0_\mu - g'_W B_\mu)^2 + \text{interaction terms}$$
The profile of the Standard Model Higgs boson

\[ \mathcal{L} \supset |D_\mu \Phi|^2 = \frac{1}{2} (\partial_\mu H)^2 + \frac{g^2 W^2}{4} W^+ \mu W^-_{\mu} + \frac{v^2}{8} (g_W W^0_\mu - g'_W B_\mu)^2 + \text{interaction terms} \]

→ massive gauge bosons: \( W^\pm_\mu \) and \( Z_\mu = \frac{1}{\sqrt{(g^2_W + g'^2_W)}} (g_W W^0_\mu - g'_W B_\mu) \)

with masses: \( M^\pm_W = \frac{1}{2} g_W v \) and \( M_Z = \frac{1}{2} \sqrt{(g^2_W + g'^2_W)} v \)

Orthogonal superposition to \( Z \): massless photon \( A_\mu = \frac{1}{\sqrt{(g^2_W + g'^2_W)}} (g'_W W^0_\mu + g_W B_\mu) \)

Introduce the electroweak mixing angle

\[ \sin \theta_W = \frac{g'_W}{\sqrt{(g^2_W + g'^2_W)}} \quad \text{and} \quad \cos \theta_W = \frac{g_W}{\sqrt{(g^2_W + g'^2_W)}} \]

so that

\[ g'_W = g_W \tan \theta \quad \text{and} \quad M_W = M_Z \cos \theta_W \]

The Higgs vacuum expectation value can be determined from the Fermi constant \( G_F \):

\[ \frac{G_F}{\sqrt{2}} = \left( \frac{g_W}{2 \sqrt{2}} \right)^2 \frac{1}{M^2_W} \quad \Longrightarrow \quad v = \sqrt{\frac{1}{\sqrt{2} G_F}} \approx 246.22 \text{ GeV} \]
The Higgs kinetic term

\[ \mathcal{L} \ni |D_\mu \Phi|^2 \]

also includes Higgs–gauge-boson interactions:

\[
|D_\mu \Phi|^2 \ni \left( \frac{g_W^2}{4} W^+_\mu W^{-\mu} + \frac{g_W^2}{8 \cos^2 \theta_W} Z^\mu Z_\mu \right)(H^2 + 2vH)
\]

\[
= g_W M_W W^+_\mu W^{-\mu} H + \frac{g_W}{2 \cos \theta_W} M_Z Z^\mu Z_\mu H
\]

\[
+ \frac{g_W^2}{4} W^+_\mu W^{-\mu} H^2 + \frac{g_W^2}{8 \cos^2 \theta_W} Z^\mu Z_\mu H^2
\]

The Higgs potential \( V = \mu^2 |\phi|^2 + \lambda |\phi|^4 \) expanded around the vacuum state \( \langle \Phi \rangle = 1/\sqrt{2}(0, v) \) becomes

\[
V = \frac{1}{2} (2\lambda v^2) H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 - \frac{\lambda}{4} v^4
\]

yielding a Higgs mass

\[
M_H = 2\lambda v^2
\]

and cubic and quartic Higgs self-couplings.
Fermion masses are generated through so-called Yukawa interactions, e.g. for electrons

$$\mathcal{L} \supset -G_e \bar{l}_L \Phi_i e_R + \text{h.c.}$$

which, in unitary gauge, is

$$\mathcal{L} \supset -\frac{G_e}{\sqrt{2}} \left( \begin{array}{c} \bar{\nu}_L \\ \bar{e}_L \end{array} \right)^T \left( \begin{array}{c} 0 \\ v + H \end{array} \right) e_R + \text{h.c.}$$

This yields an electron mass term

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

The Yukawa coupling $G_e$ is related to the electron mass $m_e$ by

$$G_e = g_W \frac{m_e}{\sqrt{2} M_W}$$

There is also an interaction between the electron and the Higgs

$$\mathcal{L} \supset -g_W \frac{m_e}{2 M_W} \bar{e} H e$$
The profile of the Standard Model Higgs boson

Quark masses are also generated through Yukawa interactions

\[
\mathcal{L} \supset -G_d \bar{q}_L^i \Phi_i d_R + \text{h.c.} - G_u \epsilon_{ij} \bar{q}_L^i \Phi^\dagger_j u_R + \text{h.c.}
\]

with masses

\[
m_d = \frac{G_d}{\sqrt{2}} v = \sqrt{2} \frac{G_d M_W}{g W} \quad \text{and} \quad m_u = \frac{G_u}{\sqrt{2}} v = \sqrt{2} \frac{G_u M_W}{g W}
\]

There is also an interaction between the quarks and the Higgs:

\[
\mathcal{L} \supset -g_W \frac{m_u}{2M_W} \bar{u} H u - g_W \frac{m_d}{2M_W} \bar{d} H d
\]

Adding more generations will introduce mixing in the Yukawa interactions, e.g.

\[
\mathcal{L} \supset -G_{dS} \begin{pmatrix} \bar{u}_L \\ \bar{d}_L \end{pmatrix}^T \Phi S_R
\]
The profile of the Standard Model Higgs boson

Three-point couplings with Higgs bosons

\[ H \rightarrow W \rightarrow W \]
\[ H \rightarrow Z \rightarrow Z \]
\[ H \rightarrow f \rightarrow f \]
\[ H \rightarrow H \rightarrow H \]

\[ = i g_W M_W g_{\mu\nu} \]
\[ = i \frac{g_W}{\cos^2 \theta_W} M_W g_{\mu\nu} \]
\[ = -i g_W m_f \]
\[ = -\frac{3i g_W M_H^2}{2M_W} \]

Four-point couplings with Higgs bosons

\[ H \rightarrow W \rightarrow W \]
\[ H \rightarrow Z \rightarrow Z \]
\[ H \rightarrow H \rightarrow H \]

\[ = \frac{1}{2} i g_W^2 g_{\mu\nu} \]
\[ = \frac{i g_W^2}{2 \cos^2 \theta_W} g_{\mu\nu} \]
\[ = -\frac{3i g_W M_H^2}{4M_W^2} \]
The profile of the Standard Model Higgs boson

SM Higgs decay modes and branching ratios

\[ \text{HDECAY: Djouadi, Kalinowski, Spira} \]

\[ \Rightarrow \text{dominant decay into} \]

\[ \begin{cases} 
\bar{b}b & \text{for } M_H \lesssim 130 \text{ GeV} \\
WW, ZZ & \text{for } M_H \gtrsim 130 \text{ GeV} 
\end{cases} \]
The profile of the Standard Model Higgs boson

**SM Higgs total decay width**

![Graph showing the total decay width of the Higgs boson as a function of its mass](image)
The SM Higgs mechanism is testable because all couplings are known:

fermions: \[ g_{ffH} \propto m_f / v \]

\[ g_{ffH} \propto \frac{m_f}{v} \]

gauge bosons: \[ g_{VVH} \propto \frac{M_V^2}{v} \]

\[ g_{VVH} \propto \frac{M_V^2}{v} \]

with vacuum expectation value \( v^2 = 1 / \sqrt{2} G_F \approx (246 \text{ GeV})^2 \) (from \( \mu \)-decay)

The Higgs sector and the properties of the Higgs particle
(lifetime, decay branching ratios, cross sections)
are fixed in terms of the Higgs boson mass \( M_H \).

[Express the Higgs potential in terms of \( (\mu, \lambda) \rightarrow (v^2, M_H) \)]

Extended Higgs models (eg. 2-Higgs-doublet models like the MSSM) have a more complicated structure
Theoretical constraints on the Higgs boson mass

Running of the Higgs coupling:

\[
\frac{d\lambda}{d\ln \mu^2} = \frac{3}{8\pi^2} \left[ \lambda^2 + \lambda G_t^2 - G_t^4 \right]
\]

with \( \lambda = M_H^2/v^2 \) and \( G_t = \sqrt{2} m_t/v \).

For \( M_H > m_t \) one has \( d\lambda/d\ln \mu^2 \sim \lambda^2 \)

and thus

\[
\lambda(\mu^2) = \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\pi^2} \ln \frac{\mu^2}{v^2}}
\]

Requiring \( \lambda(\Lambda) < \infty \) yields

\[
M_H^2 \lesssim \frac{8\pi^2 v^2}{3 \ln (\Lambda^2/v^2)}
\]
Higgs boson hunting: indirect search

Quantum corrections to precision observables give access to high mass scales:

\[ \propto m_{\text{top}}^2 \]

More precisely: calculate \( M_W \) from \( M_Z \) and \( G_F \) including quantum corrections

\[
\frac{M_W^2}{M_Z^2} \left( 1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_F M_Z^2 (1 - \Delta r)}
\]

where the quantum correction \( \Delta r \) is composed of

\[
\Delta r = \Delta \alpha - \cot \theta_W \Delta \rho_{\text{top}} + \Delta r^{\text{Higgs}} + \ldots
\]

The leading top contribution is quadratic in \( m_{\text{top}} \):

\[
\Delta \rho_{\text{top}} = \frac{3 G_F m_{\text{top}}^2}{8 \pi^2 \sqrt{2}} + \ldots
\]

The Higgs contribution is screened, depending only logarithmically on \( M_{\text{Higgs}} \)

\[
\Delta r^{\text{Higgs}} = \frac{G_F M_W^2}{8 \pi^2 \sqrt{2}} \frac{1 + 9 \sin^2 \theta_W}{3 \cos^2 \theta_W} \ln \left( \frac{M_{\text{Higgs}}^2}{M_W^2} \right) + \ldots
\]
Higgs boson hunting: indirect search

Indirect top hunting works well:

\[ m_{\text{top}} = 172.7 \pm 2.9 \text{ GeV (CDF & D0)} \]

\[ m_{\text{top}} = 179.4 \pm 11 \text{ GeV (LEP & SLD)} \]
Indirect Higgs hunting is harder:

High $Q^2$ except $m_t$

68% CL

Excluded

$m_t$ (Tevatron)
Higgs boson hunting: indirect search

Indirect Higgs hunting is harder:

\[ m_H < 219 \text{ GeV} \] (95% CL)

\( m_W \) (LEP2 prel., pp)

\( \Rightarrow \) Data consistent with SM

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**Higgs boson hunting: indirect search**

Precision SM measurements are important to constrain the Higgs sector

... what we hope to see (maybe?)

Repeat the electroweak fit with smaller uncertainties

- $\delta M_W = 15$ MeV
- $\delta M_{\text{top}} = 1$ GeV
- same central values
Higgs boson hunting: past and present colliders

- search at the CERN LEP2  
  \[ (e^+e^- \text{ collider with } \sqrt{s} \lesssim 200 \text{ GeV}) \]
  \[ e^+e^- \rightarrow ZH \quad \Rightarrow M_H > 114.4 \text{ GeV (95\% CL)} \quad \text{(LEPHIGGSWG)} \]

- search at the Fermilab Tevatron  
  \[ (p\bar{p} \text{ collider with } \sqrt{s} = 2 \text{ TeV}) \]

\[
\begin{array}{c}
\text{combined CDF/D0 thresholds} \\
\text{integrated luminosity/expr.} \\
\text{Higgs mass (GeV/c}^2) \\
\end{array}
\]

- current \( \int \mathcal{L} \approx 1 \text{ fb}^{-1} \)
- expectation in 2008: \( \int \mathcal{L} = 4 - 6 \text{ fb}^{-1} \)
Higgs Physics at the Large Hadron Collider

Michael Krämer
(RWTH Aachen)

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[Express the Higgs potential in terms of \( (\mu, \lambda) \to (v^2, M_H) \)]

Extended Higgs models (eg. 2-Higgs-doublet models like the MSSM) have a more complicated structure
Summary of lecture 1: SM Higgs boson properties

Three-point couplings with Higgs bosons

\[ H \rightarrow WW = ig_W M_W g_{\mu\nu} \]
\[ H \rightarrow ZZ = ig_W \frac{g_W}{\cos^2 \theta_W} M_W g_{\mu\nu} \]
\[ H \rightarrow Wf = -ig_W \frac{m_f}{2M_W} \]
\[ H \rightarrow HH = -\frac{3ig_W M_H^2}{2M_W} \]

Four-point couplings with Higgs bosons

\[ HH \rightarrow WW = \frac{1}{2} ig_W^2 g_{\mu\nu} \]
\[ HH \rightarrow ZZ = \frac{ig_W^2}{2 \cos^2 \theta_W} g_{\mu\nu} \]
\[ HH \rightarrow HH = -\frac{3ig_W M_H^2}{4M_W^2} \]
Summary of lecture 1: SM Higgs boson properties

SM Higgs decay modes and branching ratios

\[ \text{BR}(H) \]

\[ M_H \text{ [GeV]} \]

\( M_H \lesssim 130 \text{ GeV} \)

\( M_H \gtrsim 130 \text{ GeV} \)

\( \Rightarrow \) dominant decay into

\[ \begin{cases} 
  b\bar{b} & \text{for } M_H \lesssim 130 \text{ GeV} \\
  WW, ZZ & \text{for } M_H \gtrsim 130 \text{ GeV}
\end{cases} \]
Higgs boson hunting

Ellis, Gaillard, Nanopoulos, *A Phenomenological Profile of the Higgs Boson*, 1976:

“We should perhaps finish with an apologie and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson... and for not being sure of its couplings to other particles except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson...”
The Large Hadron Collider LHC
The days of the Higgs boson are numbered!
Higgs boson production at the LHC

\[\sigma(pp \rightarrow H + X) [pb]\]

\[\sqrt{s} = 14 \text{ TeV}\]

NLO / NNLO

\[\text{gg} \rightarrow H\]

\[\text{qq} \rightarrow Hqq\]

\[\text{gg/qq} \rightarrow t\bar{t}H\]

\[\text{q}\bar{q} \rightarrow HZ\]

MRST
Higgs production cross sections: theoretical status

- Higgs production in gluon-gluon fusion

- NLO corrections: $K_{\text{NLO}} \approx 1.7$
  [Spira, Djouadi, Graudenz, Zerwas; Dawson, Kauffman]

- NNLO corrections:
  $$K_{\text{NNLO}}(m_{\text{top}} \gg M_H) \approx 2$$
  [Harlander, Kilgore; Anastasiou, Melnikov '02; Ravindran et al. '03]

  $\rightarrow$ NNLO scale dependence $\lesssim 15\%$

- Soft-gluon summation $\approx 5\%$
  [MK, Laenen, Spira; Catani, de Florian, Grazzini]

- Electroweak corrections $\approx 5\%$
  [Aglietti, Bonciani, Degrassi, Vicini; Degrassi, Maltoni]
Higgs production cross sections: theoretical status

- Vector boson fusion

\[
\begin{array}{c}
q \\
\rightarrow \ \\
W, Z \\
\rightarrow H \\
\rightarrow q
\end{array}
\]

- discovery channel & measurement of Higgs couplings
  [Zeppenfeld, Kauer, Plehn, Rainwater]

- NLO QCD corrections (cf DIS) \( \approx +10\% \)
  [Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; Berger, Campbell]

- Associated VH production

\[
\begin{array}{c}
q \\
\rightarrow \ \\
W, Z \\
\rightarrow H
\end{array}
\]

- crucial for Tevatron search \( (M_H \lesssim 130 \text{ GeV}) \)

- NLO QCD corrections \( \approx + (30 \,-\,40)\% \)
  [Han, Willenbrock]

- NNLO QCD corrections \( \approx + 10\% \)
  [Brein, Djouadi, Harlander]

- NLO electroweak corrections \( \approx - 10\% \)
  [Ciccolini, Dittmaier, MK]
Higgs production cross sections: theoretical status

- Small cross section but distinctive final state
- Direct measurement of top-Higgs Yukawa coupling
  → Need precise theoretical cross section prediction
- NLO scale dependence $\lesssim 15\%$

[Beenakker, Dittmaier, MK, Plümpner, Spira, Zerwas; Dawson, Jackson, Orr, Reina, Wackeroth]
Higgs boson search at the LHC

\[ \sigma_{\text{tot}} \]

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

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

\[ \sigma_{\text{Higgs}}(M_H = 150 \text{ GeV}) \]

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

QCD background: \( \sigma_{bb} \approx 10^8 \text{ pb} \)

Higgs signal: \( \sigma_{H+X} \approx 10 \text{ pb} \)

\[ \approx 3 \times 10^5 \text{ Higgs bosons/year} \]

\[ (\int \mathcal{L} = 30 \text{ fb}^{-1}) \]

Higgs-search through rare decays or/and associate production
Higgs boson search at the LHC

**Inclusive channels**

- $pp \rightarrow H(\rightarrow \gamma\gamma) + X$ important for $M_H \lesssim 150$ GeV
- $pp \rightarrow H(\rightarrow WW^* \rightarrow l^+\nu l^-\bar{\nu}) + X$ important for $140$ GeV $\lesssim M_H \lesssim 200$ GeV
- $pp \rightarrow H(\rightarrow ZZ^* \rightarrow l^+l^-l^+l^-) + X$ important for $M_H \gtrsim 130$ GeV and $M_H \neq 2M_W$

**Associated production**

- $pp \rightarrow t\bar{t}H(\rightarrow b\bar{b}) + X$ important for $M_H \lesssim 140$ GeV
- $pp \rightarrow q\bar{q}H(\rightarrow \tau\tau, b\bar{b}, \gamma\gamma, WW, ZZ) + X$ important for whole Higgs mass range
Inclusive search channels: $H \rightarrow \gamma\gamma$

- small branching ratio $\text{BR}(H \rightarrow \gamma\gamma) \approx 10^{-3}$
- large background from QCD processes
- excellent photon-energy resolution in CMS and ATLAS
  
  $\rightarrow$ Higgs discovery through resonance peak

+ determine background from sideband of data

$$S/\sqrt{B} = 2.8 \text{ to } 4.3 \sigma \quad (\int \mathcal{L} = 30 \text{ fb}^{-1})$$
Inclusive search channels: $H \rightarrow WW^* \rightarrow l^+\nu l^-\bar{\nu}$

- Neutrinos in final state
  - No invariant Higgs mass peak

- Large background from QCD process
  $q\bar{q} \rightarrow WW$

+ Exploit lepton rapidity distributions and angular correlations to suppress background
  (Dittmar, Dreiner)

$S/\sqrt{B} = 3$ to $15\sigma$ ($\int L = 30$ fb$^{-1}$)
Inclusive search channels: \( H \to ZZ^* \to l^+l^-l^+l^- \)

+ most important and clean search channel
  for \( M_H > 2M_Z \)
+ only limited background from QCD processes
+ reconstruction of Higgs mass peak

\[ \Rightarrow \frac{S}{\sqrt{B}} \approx 20 \sigma \left( \int L = 30 \text{ fb}^{-1} \right) \]

for 180 GeV \( \gtrsim M_H \lesssim 400 \) GeV
Associated production: \( pp \rightarrow t\bar{t}H(\rightarrow b\bar{b}) \)

- small cross section: \( \sigma(t\bar{t}H)/\sigma(H + X) \approx 1/100 \rightarrow \) only relevant for \( M_H \lesssim 140 \) GeV
- distinctive final state: \( pp \rightarrow t(\rightarrow W^+b) \ \bar{t}(\rightarrow W^-\bar{b}) \ H(\rightarrow b\bar{b}) \)
- cross section \( \propto g^2_{ttH} \rightarrow \) unique way to measure top-Higgs Yukawa coupling
Associated production: $pp \rightarrow qqH(\rightarrow \tau^+\tau^-, b\bar{b}, \gamma\gamma, WW, ZZ)$

- Identify signal with forward jet tagging and central jet veto
- Relevant for many Higgs decay channels
  - Measurement of Higgs couplings
    
    $H \rightarrow \tau^+\tau^-, b\bar{b}$ \hspace{1cm} $M_H \lesssim 140$ GeV
    
    $H \rightarrow \gamma\gamma$ \hspace{1cm} $M_H \lesssim 150$ GeV
    
    $H \rightarrow WW^*$ \hspace{1cm} $M_H \gtrsim 130$ GeV
    
    $H \rightarrow ZZ$ \hspace{1cm} $M_H \gtrsim 500$ GeV

[Eboli, Hagiwara, Kauer, Plehn, Rainwater, Zeppenfeld; Mangano, Moretti, Piccinini, Pittau, Polosa…]
Higgs boson search at the LHC: signal significance

\[ M_H \lesssim 2M_Z \rightarrow \]
\[ \begin{align*}
  gg &\rightarrow H & (H \rightarrow \gamma\gamma, ZZ^*, WW(\ast)) \\
  gg/\bar{q}\bar{q} &\rightarrow t\bar{t}H & (H \rightarrow b\bar{b}, \tau\tau) \\
  qq &\rightarrow qqH & (H \rightarrow \gamma\gamma, WW^*, \tau\tau) \\
  qq' &\rightarrow WH & (H \rightarrow \gamma\gamma) \\
\end{align*} \]

\[ M_H \gtrsim 2M_Z \rightarrow \]
\[ \begin{align*}
  gg &\rightarrow H & (H \rightarrow ZZ, WW) \\
  qq &\rightarrow qqH & (H \rightarrow ZZ, WW) \\
\end{align*} \]

[ + diffractive Higgs production]
Higgs boson search at the LHC: signal significance

![Graph showing the discovery luminosity for different Higgs boson decay channels at the LHC. The graph plots the 5σ discovery luminosity (fb⁻¹) against the Higgs boson mass (GeV/c²). Different decay channels are represented by various symbols and colors.]

- **qqH, H→WW→lνjj**
- **qqH, H→ZZ→lνlν**
- **H→WW*/WW→lνlν, NLO**
- **H→ZZ*/ZZ→4 leptons, NLO**
- **H→γγ, τ⁺τ⁻**
- **H→γγ inclusive, NLO**
- **tH, WH, H→b¯b**
- **Combined channels**
Higgs boson search at the Tevatron (revisited)

For $M_H \ \begin{cases} < 140 \text{ GeV} \\ > 140 \text{ GeV} \end{cases}$ use $\begin{cases} p\bar{p} \rightarrow WH/ZH \text{ and } H \rightarrow b\bar{b} \\ p\bar{p} \rightarrow H \text{ and } H \rightarrow WW \end{cases}$

current $\int \mathcal{L} = 0.8 \text{ fb}^{-1}$

expectation in 2008: $\int \mathcal{L} = 4 - 6 \text{ fb}^{-1}$
To test the Higgs mechanism we have to determine the profile of the Higgs boson:

- mass and lifetime
- external quantum numbers
- couplings to gauge bosons and fermions
- Higgs self-couplings
The Higgs mass

Expected precision $\Delta M / M \approx 10^{-3}$ for $M_{\text{Higgs}} \lesssim 500$ GeV
Higgs boson physics at the LHC: the Higgs profile

The Higgs width

Remember:

$\Gamma(H)$ [GeV]

$M_H$ [GeV]

$\Rightarrow$ measurement of $\Gamma$ possible only for $M_H \gtrsim 200$ GeV
The Higgs width

Expected precision $\Delta \Gamma / \Gamma \approx 5 - 10\%$ for $M_{\text{Higgs}} \gtrsim 250$ GeV
Higgs boson physics at the LHC: the Higgs profile

- The Higgs spin and parity quantum numbers

- Discovery of $H \rightarrow \gamma\gamma \Rightarrow J \neq 1$ and $C' = +1$ (Landau-Yang)

- Angular-correlations, e.g. in $H \rightarrow VV(*)$: 

\[
\begin{align*}
\theta_3 & \quad \phi_3 & \quad \theta_1 \\
\overline{f}_4 & \quad f_3 & \quad f_1 \\
V & \quad H & \quad V \\
V & \quad \overline{f}_2 & \quad \overline{f}_3
\end{align*}
\]
The Higgs spin and parity quantum numbers

- Angular-correlations in $H \rightarrow VV^{(*)}$:

![Graph showing angular correlations](image_url)
The measurement of Higgs couplings:

The LHC measures \( \sigma(pp \rightarrow H) \times \operatorname{BR}(H \rightarrow X) = \sigma(pp \rightarrow H) \times \Gamma(H \rightarrow X)/\Gamma_{\text{tot}} \)
The measurement of Higgs couplings:

Different production and decay channels provide measurements of combinations of partial decay widths, for example

\[ X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma_{\text{tot}}} \quad \text{from} \quad qq \rightarrow qqH, \ H \rightarrow \gamma\gamma \]

\[ Y_\gamma = \frac{\Gamma_g \Gamma_\gamma}{\Gamma_{\text{tot}}} \quad \text{from} \quad gg \rightarrow H \rightarrow \gamma\gamma \]

\[ X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma_{\text{tot}}} \quad \text{from} \quad qq \rightarrow qqH, \ H \rightarrow \tau\tau \]

\[ Y_Z = \frac{\Gamma_g \Gamma_Z}{\Gamma_{\text{tot}}} \quad \text{from} \quad gg \rightarrow H \rightarrow ZZ(*) \]

\[ X_W = \frac{\Gamma_W^2}{\Gamma_{\text{tot}}} \quad \text{from} \quad qq \rightarrow qqH, \ H \rightarrow WW(*) \]

\[ Y_W = \frac{\Gamma_g \Gamma_W}{\Gamma_{\text{tot}}} \quad \text{from} \quad gg \rightarrow H \rightarrow WW(*) \]

Problem: no direct measurement of \( \Gamma_{\text{tot}} \)

no observation of some decay modes (e.g. \( H \rightarrow gg \))

→ consider ratios of \( X \) or \( Y \)’s
Higgs boson physics at the LHC: the Higgs profile

- Ratios of Higgs couplings can be measured with an accuracy of 10-40%
- Partial widths can be extracted with additional theoretical assumptions

[Dührssen et al.]

**width ratios**

**(partial) widths**

![Graph showing width ratios and (partial) widths vs. m_H (GeV)](image-url)
Reconstructing the Higgs potential at the LHC is difficult (impossible)

Recall:

\[ V = \frac{M_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 \]

In the SM we have

\[ \lambda_3 = \lambda_4 = \frac{M_H^2}{2v^2} \]

To determine \( \lambda_3 \) and \( \lambda_4 \) need to measure multi-Higgs production, e.g.
Higgs boson physics at the LHC: the Higgs profile

The measurement of $\lambda_3$ appears to be very difficult

The problem is the low cross section and large backgrounds

- $M_{\text{Higgs}} \lesssim 140$ GeV: $HH \to b\bar{b}b\bar{b}$
  overwhelming QCD background

+ $150$ GeV $\lesssim M_{\text{Higgs}} \lesssim 140$ GeV:
  $HH \to (WW)(WW) \to (jjl\nu)(jjl\nu)$
  $\rightarrow$ can determine whether $\lambda_3 = 0$
The measurement of $\lambda_4$ appears to be impossible
Higgs boson physics at the LHC: beware of backgrounds!

- Consider Higgs search in $pp \rightarrow H \rightarrow WW \rightarrow l\bar{l}l'\nu'$ channel
  
  - $WW$ pair production is the dominant background: $\sigma \times \text{BR} \approx 5$ times larger than signal
  
  - a Higgs mass peak cannot be reconstructed from leptonic $W$ decays

  $\Rightarrow$ theoretical control of the background is important

- experimental selection cuts may enhance the importance of higher-order corrections for background processes

- example: $gg \rightarrow WW \rightarrow l\bar{l}l'\nu'$
  
  [Binoth, Ciccolini, Kauer, MK; Dührssen, Jakobs, van der Bij, Marquard]

  $\Rightarrow$ formally NNLO
  
  $\Rightarrow$ but enhanced by Higgs search cuts
**Higgs boson physics at the LHC: beware of backgrounds!**

- **Consider search in VBF channel** \( pp \to qqH \)
  - important discovery channel
  - provides measurement of \( HVV \) couplings

![VBF diagram](image)

- **large Higgs + 2 jets background from** \( gg \to ggH \)
  
  [Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld]

![Higgs background diagram](image)

- **need additional kinematic cuts**

![Kinematic cuts](image)
The hierarchy problem: why is $M_{\text{Higgs}} \ll M_{\text{Planck}}$?

- Quantum corrections to the Higgs mass have quadratic UV divergencies
  \[
  \delta m_H^2 \sim \frac{\alpha}{\pi} (\Lambda^2 + m_F^2)
  \]
  
  The cutoff $\Lambda$ represents the scale up to which the Standard Model remains valid.
  
  $\to$ need $\Lambda$ of $\mathcal{O}(1 \text{ TeV})$ to avoid unnaturally large corrections

- Most popular new physics models
  - Supersymmetry
  - Extra dimensions
  - Dynamical EWSB
  - Little Higgs models

- Quantum corrections due to superparticles cancel the quadratic UV divergences
  \[
  \delta m_H^2 \sim -\frac{\alpha}{\pi} (\Lambda^2 + \tilde{m}_F^2)
  \]

  $\delta m_H^2 \sim \frac{\alpha}{\pi} (m_F^2 - \tilde{m}_F^2) \to$ no fine-tuning if $\tilde{m} \lesssim \mathcal{O}(1 \text{ TeV})$
A crucial test of the MSSM: the light Higgs

MSSM Higgs sector: two Higgs doublets to give mass to up- and down-quarks

→ 5 physical states: $h$, $H$, $A$, $H^\pm$

The MSSM Higgs sector determined by $\tan \beta = v_2/v_1$ and $M_A$.

The couplings in the Higgs potential and the gauge couplings are related by supersymmetry. At tree level one finds $M_h \leq M_Z$. This relation is modified by radiative corrections so that

$$M_h \lesssim 130 \text{ GeV} \text{ (in the MSSM)}$$

The existence of a light Higgs boson is a generic prediction of SUSY models.
A crucial test of the MSSM: the light Higgs

One of the SUSY Higgs bosons will be seen at the LHC

but it may look like the SM Higgs…
Higgs boson physics at the LHC: summary

- The LHC will find the (or a?) Higgs boson (or something similar).

- The LHC will measure some of the Higgs boson properties.
  For a more precise and model independent determination of decay widths
  and a measurement of quantum numbers we will need the ILC.

- Higgs physics is exciting:
  - reveals the mechanism of electroweak symmetry breaking
  - points towards physics beyond the SM (hierarchy problem)