... what we hope to see

Repeat the electroweak fit changing the uncertainties

- $\delta M_W = 15 \text{ MeV}$
- $\delta M_{\text{top}} = 1 \text{ GeV}$
- same central values
Physics at the Large Hadron Collider

Michael Krämer

(RWTH Aachen)

- Lecture 1: Review of the Standard Model
- Lecture 2: SM physics at hadron colliders
- Lecture 3: Higgs and SUSY searches at the LHC
The Higgs mechanism is testable because all couplings are known:

- fermions: \( g_{ffH} = \sqrt{2}m_f/v \)
- gauge bosons: \( g_{VVH} = 2M_V/v \)

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

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 Higgs potential in terms of \((\mu, \lambda) \rightarrow (v^2, M_H)\)
Higgs boson mass

- Higgs search at LEP in associated $ZH$ production $e^+e^- \rightarrow Z^* \rightarrow ZH$

  ![Diagram of $e^+e^- \rightarrow Z^* \rightarrow ZH$]

  provide a lower limit on the SM Higgs mass: $M_H > 114.4 \text{ GeV}$ (95% CL)

- Electroweak precision tests

  ![Diagram of $W^+W^-$]

  provide an upper limit on the SM Higgs mass: $M_H < 219 \text{ GeV}$ (95% CL)
Running of the Higgs coupling:

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

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 decays

Higgs decay modes and branching ratios

$\Rightarrow$ dominant decay into

$$\begin{cases} 
    bb & \text{for } M_H \lesssim 130 \text{ GeV} \\
    WW, ZZ & \text{for } M_H \gtrsim 130 \text{ GeV}
\end{cases}$$
Higgs boson decays

![Higgs decay width]

$\Gamma(H) \text{[GeV]}$

$M_H \text{[GeV]}$

$\rightarrow$ direct measurement of $\Gamma$ only for $M_{\text{Higgs}} \gtrsim 300 \text{ GeV}$
Higgs boson production at the LHC

\[ \sigma(pp \rightarrow H + X) \text{ [pb]} \]
\[ \sqrt{s} = 14 \text{ TeV} \]
NLO / NNLO

\[ gg \rightarrow H \text{ (NNLO)} \]
\[ q\bar{q} \rightarrow Hq\bar{q} \]
\[ gg/q\bar{q} \rightarrow t\bar{t}H \text{ (NLO)} \]

MRST

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

Michael Krämer
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Herbstschule Maria Laach, September 2005
Higgs boson production at the LHC

- Precision calculations are needed for signal and background processes
  - for Higgs discovery in $WW$ decay channels (no reconstruction of mass peak possible)
  - for a reliable determination of the discovery/exclusion significance
  - for a precise measurement of the Higgs couplings
    \(\leftrightarrow\) test of the Higgs mechanism
    \(\leftrightarrow\) discrimination between SM and BSM (eg. SUSY)

- Recent progress for SM Higgs production includes
  - NNLO QCD calculations for $pp \rightarrow H$
    [Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven; Anastasiou, Melnikov, Petriello; \ldots (02-04)]
  - NNLO QCD calculations for $pp \rightarrow HZ, HW$
    [Brein, Djouadi, Harlander (04)]
  - (N)NLO QCD calculations for $pp \rightarrow Q\bar{Q}H$
    [Beenakker, Dittmaier, MK, Plümer, Spira, Zerwas; Dawson, Jackson, Orr, Reina, Wackeroth; Harlander, Kilgore; Campbell, Ellis, Maltoni, Willenbrock; \ldots (01-05)]
  - NLO QCD calculations for $pp \rightarrow qqH$
    [Figy, Oleari, Zeppenfeld; Berger, Campbell (03-04)]
  - NLO EWK calculations for $pp \rightarrow HZ, HW$
    [Ciccolini, Dittmaier, MK (03)]
  - (N)NLL resummation for $pp \rightarrow H$
    [Kulesza, Sterman, Vogelsang; Berger, Qiu; Catani, de Florian, Grazzini; \ldots (03-04)]
  - matching of NLO calculation with parton shower MC Herwig for $pp \rightarrow H$
    [Frixione, Webber (04)];
  - NNLO splitting functions and PDF fits, error estimates for PDF fits
    [Moch, Vermaseren, Vogt; MRST; CTEQ (02-05)].
Higgs boson production at the LHC

- Higgs production in gluon-gluon fusion

- NLO corrections: $K_{\text{NLO}} \approx 1.7$

- NNLO corrections:
  \[ K_{\text{NNLO}}(m_{\text{top}} \gg M_H) \approx 2 \]

- NNLO scale dependence $\lesssim 15\%$

[Harlander, Kilgore '02]
Higgs boson search at the LHC

Higgs bosons/year \( (\int \mathcal{L} = 30 \text{ fb}^{-1}) \)

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

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

Higgs-search through associate production or/and through rare decays
The days of the Higgs boson are numbered!

![Graph showing signal significance vs. mass (m_H) for various Higgs boson decay modes: H → γγ, ttH (H → bb), H → ZZ(*) → 4l, H → WW(*) → lνlν, H → ZZ → lνlν, H → WW → lνjj. The total significance is also shown with a line. The integration over luminosity (L dt = 30 fb^{-1}) is noted, and the ATLAS experiment is mentioned with a note on no K-factors.]
Higgs boson search at the LHC: signal significance

\[ \int L \, dt = 30 \text{ fb}^{-1} \]
(no K-factors)

ATLAS

\[ m_H (\text{GeV/c}^2) \]

Signal significance

\[ 10^{-2} \]

\[ 10 \]

\[ 1 \]

\[ \int L \, dt = 30 \text{ fb}^{-1} \]
(no K-factors)

ATLAS

\[ M_H \lesssim 2M_Z \rightarrow \]

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

\[ M_H \gtrsim 2M_Z \rightarrow \]

\[ \begin{cases} 
    gg \rightarrow H & (H \rightarrow ZZ, WW) \\
    qq \rightarrow qqH & (H \rightarrow ZZ, WW) \\
\end{cases} \]

[ + diffractive Higgs production]
Higgs boson search at the Tevatron

search at the Fermilab Tevatron

For $M_H \begin{cases} < 140 \text{ GeV} \\ > 140 \text{ GeV} \end{cases}$ use

\begin{align*}
\begin{cases}
pp &\to WH/ZH \text{ and } H \to b\bar{b} \\
p\bar{p} &\to H \text{ and } H \to WW
\end{cases}
\end{align*}

\begin{equation*}
\text{current } \int \mathcal{L} = 0.8 \text{ fb}^{-1}
\end{equation*}

\begin{equation*}
\text{expectation in 2008: } \int \mathcal{L} = 4 - 6 \text{ fb}^{-1}
\end{equation*}
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
Higgs boson physics at the LHC: the Higgs profile

The Higgs mass

The expected precision on $M_{\text{Higgs}}$ at the LHC is $\Delta M/M \approx 10^{-3}$ (for $M_{\text{Higgs}} \lesssim 500$ GeV)
Higgs boson physics at the LHC: the Higgs profile

The measurement of Higgs couplings:

The LHC measures $\sigma(pp \rightarrow H) \times \text{BR}(H \rightarrow X) = \sigma(pp \rightarrow H) \times \frac{\Gamma(H \rightarrow X)}{\Gamma_{\text{tot}}}$

Different production and decay channels provide measurements of combinations of partial decay widths

- $X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma_{\text{tot}}}$ from $qq \rightarrow qqH, H \rightarrow \gamma\gamma$
- $Y_\gamma = \frac{\Gamma_g \Gamma_\gamma}{\Gamma_{\text{tot}}}$ from $gg \rightarrow H \rightarrow \gamma\gamma$
- $X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma_{\text{tot}}}$ from $qq \rightarrow qqH, H \rightarrow \tau\tau$
- $Y_\tau = \frac{\Gamma_g \Gamma_Z}{\Gamma_{\text{tot}}}$ from $gg \rightarrow H \rightarrow ZZ(\ast)$
- $X_W = \frac{\Gamma_W^2}{\Gamma_{\text{tot}}}$ from $qq \rightarrow qqH, H \rightarrow WW(\ast)$
- $Y_W = \frac{\Gamma_g \Gamma_W}{\Gamma_{\text{tot}}}$ from $gg \rightarrow H \rightarrow WW(\ast)$

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%:
Higgs boson physics at the LHC: the Higgs profile

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.

The measurement of \( \lambda_3 \) appears to be very difficult, the measurement of \( \lambda_4 \) impossible(?)
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)
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.

$\rightarrow$ need $\Lambda$ of $\mathcal{O}(1 \text{ TeV})$ to avoid unnaturally large corrections

In comparison: $\delta m_e \sim \frac{\alpha}{\pi} m_e \ln(\Lambda/m_e) \approx 0.25 m_e$

$\rightarrow$ electron mass is stabilized ("protected") by the chiral symmetry

An elegant way to solve the hierarchy problem is to introduce an additional symmetry that transforms fermions into bosons and vice versa: supersymmetry

Quantum corrections due to superparticles cancel the quadratic UV divergences

$$\delta m_H^2 \sim -\frac{\alpha}{\pi} (\Lambda^2 + \tilde{m}_F^2)$$

$$\delta m_H^2 \sim \frac{\alpha}{\pi} (m_F^2 - \tilde{m}_F^2) \rightarrow \text{no fine-tuning if } \tilde{m} \lesssim \mathcal{O}(1 \text{ TeV})$$
The Minimal Supersymmetric Standard Model

The MSSM particle spectrum

<table>
<thead>
<tr>
<th>Gauge Bosons $S = 1$</th>
<th>Gauginos $S = 1/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluon, $W^\pm, Z, \gamma$</td>
<td>gluino, $\tilde{W}, \tilde{Z}, \tilde{\gamma}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fermions $S = 1/2$</th>
<th>Sfermions $S = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(u_L)$ $(\nu^c_L)$</td>
<td>$(\tilde{u}_L)$ $(\tilde{\nu}^c_L)$</td>
</tr>
<tr>
<td>$(d_L)$ $(e_L)$</td>
<td>$(\tilde{d}_L)$ $(\tilde{e}_L)$</td>
</tr>
<tr>
<td>$u_R, d_R, e_R$</td>
<td>$\tilde{u}_R, \tilde{d}_R, \tilde{e}_R$</td>
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</tbody>
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<th>Higgs</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$(H_2^0)$ $(H_1^+)$</td>
<td>$(\tilde{H}_2^0)$ $(\tilde{H}_1^+)$</td>
</tr>
<tr>
<td>$(H_2^-)$ $(H_1^0)$</td>
<td>$(\tilde{H}_2^-)$ $(\tilde{H}_1^0)$</td>
</tr>
</tbody>
</table>
SUSY particle production at the LHC

In the MSSM one imposes a symmetry

\[ R = (-1)^{3B+L+2S} \begin{cases} 
= +1 & \text{SM} \\
= -1 & \text{SUSY} 
\end{cases} \]

to avoid proton decay

→ SUSY particles produced pairwise

→ lightest SUSY particle stable (dark matter candidate)

The interactions of MSSM particles are determined by gauge symmetry and SUSY

example: gluon \( \mu, a \) squark \( p, i \) squark \( q, j \)

\[ = -i g_s (T_a)_{ij} (p + q)^\mu \]

→ no new coupling!

SUSY particles would be produced copiously at the LHC through QCD processes, e.g.
SUSY particle production at the LHC

Cross section predictions

\[ \sigma_{\text{tot}} \text{[pb]}: \text{pp} \rightarrow \tilde{g} \tilde{g}, \tilde{q} \tilde{q}, \tilde{t}_1 \tilde{\bar{t}}_1, \tilde{\chi}_2^0 \tilde{\chi}_1^+, \tilde{\nu} \tilde{\nu}, \tilde{\chi}_2^0 \tilde{g}, \tilde{\chi}_2^0 \tilde{\bar{q}} \]

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

\[ \begin{align*}
\text{m [GeV]} & \quad 100 & 150 & 200 & 250 & 300 & 350 & 400 & 450 & 500 \\
\sigma_{\text{tot}} \text{[pb]} & \quad 10^{-3} & 10^{-2} & 10^{-1} & 1 & 10 & 10^2 & 10^3 \\
\end{align*} \]

e.g. \( \sigma(pp \rightarrow \tilde{g} \tilde{g}) \approx 1 \text{ pb for } M_{\text{gluino}} = 1 \text{ TeV} \rightarrow 10^4 \text{ events/year} \)
**SUSY searches at the LHC**

**Distinctive signature due to cascade decays:**

- multiple jets (and/or leptons) with large amount of missing energy

\[
\tilde{g} \rightarrow \tilde{q} \rightarrow \chi_2^0, \chi_1^\pm \rightarrow \tilde{l} \rightarrow \text{(high-} p_T \text{) jets} \\
\chi_1^0 \rightarrow \text{high-} p_T \text{ jets and/or leptons} \\
\text{missing } E_T
\]

→ discovery reach for squarks and gluinos: \( M_{\tilde{q}, \tilde{g}} \lesssim 2.5 \text{ TeV} \)
SUSY searches at the LHC

- SUSY is broken: SUSY-masses $\neq$ SM-masses

$$\mathcal{L} = \mathcal{L}(\text{SUSY}) + \mathcal{L}(\text{SUSY-breaking})$$

“soft-breaking”-terms: $\rightarrow$ 124 parameters in the MSSM

(SUSY is not to blame. The large number of the MSSM parameters is a consequence of our ignorance of the dynamics of SUSY-breaking)

$\Rightarrow$ What is the mechanism of SUSY-breaking?

- The bottom-up approach: Measure the parameters of the SUSY Lagrangian at the LHC and test models of SUSY breaking.

- Will the accuracy of SUSY measurements at the LHC be sufficient to discriminate among different models of SUSY-breaking?
A crucial test of SUSY models: 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

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

The existence of a light Higgs boson with mass $M_h \lesssim 200 \text{ GeV}$ is a generic prediction of SUSY models.
One of the SUSY Higgs bosons will be seen at the LHC
A crucial test of SUSY models: the light Higgs

but it may look like the SM Higgs...

Consider

\[
\frac{\sigma^{\text{MSSM}}(gg\rightarrow h\rightarrow \gamma\gamma)}{\sigma^{\text{SM}}(gg\rightarrow h\rightarrow \gamma\gamma)}
\]

→ differences \( \lesssim 10\% \)

Needs precision measurements & calculations for production cross sections and \( b \) ranching ratios
Summary

- The LHC will find a Higgs boson or something that does its job

- The LHC should find signatures of BSM physics (SUSY?)

  Fundamental questions:
  
  - How is SUSY broken?
  - Does SUSY provide a viable dark matter candidate?
  
  → link between collider physics and cosmology

- Exploring BSM physics may be difficult and will require input from

  - collider physics
  - low energy physics ($g - 2$, $B$ decays, EDMs, ...)
  - $\nu$ physics
  - astroparticle physics (cosmic rays, ...)
  - cosmology