Higgs Boson Searches at Hadron Colliders

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• Introduction
  - The Standard Model Higgs boson and its properties

• Higgs boson production at Hadron Colliders

• Search for the Standard Model Higgs boson
  - Overview on the LHC potential
  - Status and prospects at the Tevatron

• Measurement of Higgs boson parameters

• Higgs bosons in the MSSM
  - Potential at the LHC, various benchmark scenarios
  - Status and prospects at the Tevatron
  - Can invisibly decaying Higgs bosons be seen?

The Higgs Boson

„The last missing piece of the Standard Model..., the only particle not detected yet.“

“Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics”

„Particle Physicists know everything about this particle, the only thing they don’t know is whether it exists.”

Peter Higgs
Preface / Disclaimer:

1. The subject I am talking about is sort of an “old topic”
   many talks about this subject, extensively discussed in the literature,
   many theorists and experimentalists working on it,
   overwhelming wealth of material
   → selection of material, will not be complete,.....
   → tutorial

2. LHC is only 1.5 years away !!!  (Detectors + machine → Steinar Stapnes)
   Focus of experimental studies is shifting
   → more full simulations, need to understand backgrounds,
     more sophisticated studies, incl. NLO calculations / Monte Carlos
   → point to new studies

3. Review the Tevatron situation in situ (Detectors, data taking, more physics,...
   Discuss LHC first,  → John Womersley)
   where relevant, compare to the situation at the Tevatron
   → what can be done there?

Where do we stand today?

e⁺e⁻ colliders LEP at CERN and SLC at SLAC + the Tevatron pp collider
+ many other experiments (HERA, fixed target........)
have explored the energy range up to ~100 GeV with incredible precision

• The Standard Model is consistent with all experimental data !

• No Physics Beyond the SM observed

• No Higgs boson seen (yet)
Why do we need the Higgs Boson?

The Higgs boson enters the Standard Model to solve two fundamental problems:

- **Masses of the vector bosons W and Z:**
  
  Experimental results:  
  \[ M_W = 80.426 \pm 0.034 \text{ GeV} / c^2 \]
  \[ M_Z = 91.1875 \pm 0.0021 \text{ GeV} / c^2 \]
  
  A local gauge invariant theory requires massless gauge fields

- **Divergences in the theory** (scattering of W bosons)

  \[-i M (W^+W^- \rightarrow W^+W^-) \sim s / M_W^2\]

The Higgs mechanism

**Spontaneous breaking of the SU(2) \times 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:  
  \[ U(\phi) = \mu^2 (\phi^* \phi) + \lambda (\phi^* \phi)^2 \]

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

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

  Mass terms result from interaction of gauge bosons with Higgs field

  3 massive vector fields:  
  \[ M_{W \pm} = \frac{1}{2} v g \]
  \[ M_Z = \frac{1}{2} v g / \cos \theta_W = M_W / \cos \theta_W \]

  1 massless vector field:  
  \[ M_Z = 0 \]

  1 massive scalar field: **The Higgs boson** \( H \)

  \[ M_H = \sqrt{\lambda} v^2 \]

  \[ v = \text{vacuum expectation value} \quad v = (\sqrt{2} G_F)^{-1/2} = 246 \text{ GeV} \]
The Higgs mechanism (cont.)

- Coupling terms of W- and Z-bosons and fermions to the Higgs field:

  ![Diagram of Higgs coupling](image)

  \[ g_{fH} = (\sqrt{2}G_F)^{1/2} m_f \]

  \[ g_{VVH} = 2 (\sqrt{2}G_F)^{1/2} M_W \]

- The introduced scalar fields can also be used to generate fermions masses

  \[ m_f = g_f v / \sqrt{2} \quad \Rightarrow \quad g_f = m_f \sqrt{2} / v \]

  (where \( g_f \) is the coupling of the Higgs field to the fermion)

- Higgs boson self-coupling

  \[ L = \ldots - \lambda \nabla h^3 - \frac{1}{4} \lambda h^4 \]

  and finally:

- Higgs boson regulates divergences in the WW scattering cross section

Properties of the Higgs Boson

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

- \( H \rightarrow W^+ W^- \), \( H \rightarrow Z Z \), \( H \rightarrow W^+ t \), \( H \rightarrow W^- b \), \( H \rightarrow Z c \), \( H \rightarrow Z t \), \( H \rightarrow c b \), \( H \rightarrow \gamma \gamma \)

\[ \Gamma(H \rightarrow f f) = N_c \frac{G_F}{4 \sqrt{2} \pi} m_f^3 (M_H^2) M_B \]

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

where: \( \delta_V = 1, \delta_W = 2, \varepsilon = M_W^2 / M_B^2, \beta = \text{velocity} \)

\[ \Gamma(H \rightarrow gg) = \frac{G_F}{36 \sqrt{2} \pi} m_f^3 (M_H^2) \left[ 1 + \left( \frac{5}{4} - \frac{7 \alpha_s}{6} \right) \omega \right] \]

\[ \Gamma(H \rightarrow \gamma \gamma) = \frac{G_F}{128 \sqrt{2} \pi} M_B^2 \left[ \frac{4 \pi \alpha_s^2}{\sqrt{2}} - \gamma^2 \right] W\text{-loop contributions} \]

Upper limit on Higgs boson mass, from unitarity of WW scattering: \( M_H < 1 \text{ TeV/}c^2 \)
Higgs mass constraints (from theory):

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

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

Upper bound: diverging coupling (Landau Pole)
Lower bound: stability of the vacuum (neg. contribution from top quark dominates)

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

Indirect Limits via radiative corrections (exp + theory):

W-mass depends on top-quark mass and Higgs boson mass via radiative corrections:

$$\Delta M_W \sim m_t^2 \quad \Delta M_W \sim \ln M_H$$

Results of the precision electroweak measurements: (LEWWG-2005):

$$M_H = 91 \, (+45) \, (-32) \text{ GeV/c}^2$$

$$M_H < 186 \text{ GeV/c}^2 \quad (95 \% \text{ CL})$$
Results on Direct Higgs bosons searches at LEP (exp)

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

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

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

Decay modes searched for:

- Four Jet channel: $HZ \rightarrow bb qq$
- Missing energy channel: $\rightarrow bb \nu \nu$
- Leptonic channel: $\rightarrow bb ee, bb \mu \mu$
- Tau channels: $\rightarrow bb \tau \tau$, 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

1 - $\text{CL}_B = 0.09$ ↔

Signal significance $= 1.7 \sigma$

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

expected mass limit: 115.3 GeV/c²
(sensitivity)

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19th Nordic Particle Physics Meeting, Spatind/Norway, Jan. 2006

The Large Hadron Collider (LHC)

- Proton-proton accelerator in the LEP tunnel at CERN

\[ p \leftrightarrow p \]
7 TeV

- Four experiments:
  ATLAS, CMS (pp physics)
  LHC-B (physics of b-quarks)
  ALICE (Pb-Pb collisions)

- Startup planned for 2007

- Luminosities: Early phase, “low luminosity”:
  \[ L = 1 \times 10^{33} \text{ cm}^2 \text{ sec}^{-1} \]
  10 fb⁻¹ / year

After 2-3 years, “high luminosity”:
  \[ L = 1 \times 10^{34} \text{ cm}^2 \text{ sec}^{-1} \]
  100 fb⁻¹ / year

K. Jakobs
19th Nordic Particle Physics Meeting, Spatind/Norway, Jan. 2006
Official LHC installation schedule – “a piece of art” -

Proton-Proton Collisions at the LHC

Proton – Proton:

2835 x 2835 bunches
separation: 7.5 m (25 ns)

10^{11} Protons / bunch
Bunch crossing rate: 40 MHz
Luminosity: L = 10^{34} cm^{-2} sec^{-1}

Proton-Proton collisions: \sim 10^9 / sec
(superposition of 23 pp-interactions per bunch crossing)

\sim 1600 charged particles in the detector

\Rightarrow high particle densities
high requirements on the detectors
Detector requirements from physics

• Good measurement of leptons and photons with large transverse momentum $P_T$

• Good measurement of missing transverse energy ($E_{T \text{miss}}$) and energy measurements in the forward regions $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

• Efficient b-tagging and $\tau$ identification (silicon strip and pixel detectors)

The ATLAS experiment

• Solenoidal magnetic field (2T) in the central region (momentum measurement)

  High resolution silicon detectors:
  - 6 Mio. channels (80 $\mu$m x 12 cm)
  - 100 Mio. channels (50 $\mu$m x 400 $\mu$m)

  space resolution: $\sim 15 \mu$m

• Energy measurement down to 1° to the beam line

• Independent muon spectrometer (supercond. toroid system)

Diameter 25 m
Barrel toroid length 26 m
End-cap end-wall chamber span 46 m
Overall weight 7000 Tons
ATLAS Installation

October 2005

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Physics during the first year(s) ?

Expected event rates in ATLAS and CMS at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$:

<table>
<thead>
<tr>
<th>Process</th>
<th>Events / sec</th>
<th>Events for 10 fb$^{-1}$ (1 year)</th>
<th>Total stat. collected at previous machines by 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e \nu$</td>
<td>15</td>
<td>$10^8$</td>
<td>$10^4$ (LEP) $10^6$ (Tevatron) $10^7$ (LEP)</td>
</tr>
<tr>
<td>$Z \rightarrow e e$</td>
<td>1.5</td>
<td>$10^7$</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$10^6$</td>
<td>$10^7$</td>
<td>$10^4$ (Tevatron) $10^5$ (BaBar/Belle)</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td></td>
<td>$10^{12}$ - $10^{13}$</td>
<td></td>
</tr>
</tbody>
</table>

Higgs
$M_H = 130$ GeV/$c^2$

0.02

$10^5$

?

Squarks, Gluinos

$M \sim 1$ TeV/$c^2$

0.001

$10^4$

--

Already in the first year:

large statistics expected from known SM processes
First goals …. (2007/08) (?)

1. Understand and calibrate detector and trigger

in situ using well-known physics samples

e.g. - Z → ee, μμ tracker, calorimeter, muon chambers calibration and alignment
- tt → bℓνbjj 10⁴ events/day after cuts

⇒ jet scale from W→jj
⇒ b-tag performance

⇒ defines t₀ !!

Early Physics: Top quark without b-tag

Extremely simple selection:
- Use tt → Wb Wb → ℓνqqb decays
- 1 isolated lepton (P_T>20 GeV/c)
- Exactly 4 jets (P_T > 40 GeV/c)
- no kinematic fit, no b-tagging (!)
- invariant mass of 3 highest P_T jets

Signal visible after few days at 10³³
- stat. error on m_{top} ~ 400 MeV after one week
- ∆m_{top} = 7 GeV (assuming 10% b-jet-scale error)
- use for jet energy calibration
- ideal to commission b-tagging!

also: hadronic W-mass peak
(→jet E-scale)
2. prepare the road for discovery

- Understand basic SM physics at $\sqrt{s} = 14$ TeV
- first checks of Monte Carlos
  (very important input from the Tevatron)
- e.g. measure cross sections for $W$, $Z$, $t\bar{t}$, QCD jets,
  and event features ($P_T$ spectra etc.)
- (tt and W/Z+ jets are omnipresent in Searches for New Physics)

Search for the Higgs Boson at Hadron Colliders

Dominant hard scattering cross section:

"QCD Jet Production"
quark/gluon scattering

Detection of Higgs boson decays into $q\bar{q}$ (bb) final states
(without associated signatures) are hopeless !!
What experimental signatures can be used?

Quark-quark scattering:

\[ p q q p \]

No leptons / photons in the initial and final state

If leptons with large transverse momentum are observed:
\[ \Rightarrow \text{interesting physics!} \]

Example: Higgs boson production and decay

Important signatures:
- Leptons und photons
- Missing transverse energy

Higgs Boson production processes at Hadron Colliders

**gg fusion**

(A) \[ q g t \rightarrow H^0 \]

(C1) \[ g g t \rightarrow H^0 \]

associated \( t t H \)

**WW/ZZ fusion**

(B) \[ q W, Z \rightarrow H^0 \]

(C2) \[ q' q W, Z \rightarrow H^0 \]

associated WH, ZH
Leading Order Higgs Boson Production cross sections

**LHC**

- Dominant production modes:
  1. Gluon fusion
  2. Vector boson fusion

**Tevatron**

- 1. Gluon fusion
- 2./3. W/Z H associated production
- 4. \(t\bar{t}H\) (very small cross section)

Note the difference in mass range!

Status of higher order corrections

NLO corrections (K-factors) have meanwhile been calculated for all Higgs production processes (huge theoretical effort!)

1. **gg fusion:**
   - large NLO QCD correction \(K \sim 1.7 - 2.0\)
   - \([\text{Djouadi, Spira, Zerwas (91)}] [\text{Dawson (91)}]\)
   - complete NNLO calculation \(\Rightarrow\)
     - evidence for nicely converging pQCD series
     - (infinite top mass limit)
     - \([\text{Harlander, Kilgore (02)}] [\text{Anastasiou, Melnikov (02)}]\)

2. **Weak boson fusion:** \(K \sim 1.1\)
   - \([\text{Han, Valencia, Willenbrock (92)}] [\text{Spira (98)}]\)
   - (similar behaviour for the Tevatron)

3. **WH associated production:** \(K \sim 1.3\)
   - (QCD corrections from Drell-Yan process)
4. **ttH associated production:**

- full NLO calculation
  
  - LHC: $K \sim 1.2$ scale: $\mu_0 = m_t + M_H/2$
  
  - Tevatron: $K \sim 0.8$
  
  - scale uncertainty drastically reduced

[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas (01)]

[Dawson, Reina (01)]

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**Higgs Boson Production cross sections at NLO**

- **LHC**
  
  M. Spira et al.

  $\sigma_{pp \rightarrow H + X}$ cross sections

  - $\sim 10 \times$ larger at the LHC

- **Tevatron**
  
  M. Spira et al.

  $\sigma_{pp \rightarrow H + X}$ (b)$b$

  - $\sqrt{s} = 2$ TeV

  - $\sim 70-80 \times$ larger at the LHC
Some important comments:

- huge theoretical effort!!

- so far, LHC experimentalists (at least from one experiment) have refrained from systematically using these higher order corrections („no K factors“)

  main arguments: K-factors are not known for all background processes, → consistent treatment between signal and background, most likely a conservative approach

- New Tools → Experimentalists are about to use/familiarize + validate them:

  (i) New (N)NLO Monte Carlos (also for backgrounds):
      - MC@NLO Monte Carlo, S. Frixione and B. Webber, www.web.phy.cam.ac.uk/theory/webber/MCatNLO

  (ii) New approaches to match parton showers and matrix elements: (based on algorithm developed by Catani, Krauss, Kuhn and Webber (CKKW)*)
      - ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
      - PYTHIA, adapted by S. Mrenna
      - SHERPA Monte Carlo, F. Krauss et al., www.physik.tu-dresden.de/~krauss/hep/index.html

  Tevatron data are extremely important for validation, work has started, see e.g., TeV4LHC workshops

Higgs boson search in the gluon fusion channel

- large production rates, compensate for small leptons / photonic branching ratios
- jet vetos can be applied to suppress large tt and other backgrounds

no accompanying particles (except high-$p_T$ Higgs + jet production)
→ lepton or photon final states (the „classical“ channels)

\[
\begin{align*}
H \rightarrow ZZ(\star) & \rightarrow \ell\ell \ell\ell \\
H \rightarrow \gamma\gamma & \\
H \rightarrow WW(\star) & \rightarrow \ell\nu \ell\nu
\end{align*}
\]

- large production rates, compensate for small leptons / photonic branching ratios
- jet vetos can be applied to suppress large tt and other backgrounds

(i) \( H \rightarrow ZZ(\star) \rightarrow \ell\ell\ell\ell \)

Signal: \( \sigma \text{BR} = 5.7 \text{ fb} \) (\( m_H = 100 \text{ GeV} \))

Background: Top production \( tt \rightarrow Wb Wb \rightarrow \ell\nu c\ell\nu c\ell\nu \) \( \sigma \text{BR} \approx 1300 \text{ fb} \)
Associated production \( Z b\bar{b} \rightarrow \ell\ell c\ell\nu c\ell\nu \)

Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: \( \sim 1.5 \text{ ps} \))
Dominant background after isolation cuts: ZZ continuum

Discovery potential in mass range from \( \sim 130 \) to \( \sim 600 \text{ GeV} / c^2 \)

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A simulated $H \to ZZ \to \ell\ell\ell\ell$ event

(ii) $H \to \gamma\gamma$

$m_H \leq 150$ GeV

- $\sigma \times \text{BR} \approx 50 \text{ fb}$ (BR $\approx 10^{-3}$)

- Backgrounds:
  - $\gamma\gamma$ (irreducible): e.g.
    \[
    \sigma_{\gamma\gamma} \approx 2 \text{ pb} / \text{GeV} \\
    \Gamma_H \approx \text{MeV}
    \]
  \[
  \rightarrow \text{need } \sigma(m)/m \approx 1\%
  \]

- $\gamma j + jj$ (reducible):

  $\sigma_{\gamma j + jj} \sim 10^6 \sigma_{\gamma\gamma}$ with large uncertainties

  $\rightarrow$ need $R_j > 10^3$ for $\varepsilon_{\gamma} \approx 80\%$ to get $\sigma_{\gamma j + jj} \ll \sigma_{\gamma\gamma}$

$\rightarrow$ most demanding channel for EM calorimeter performance: energy and angle resolution, acceptance, $\gamma$/jet and $\gamma$/\ensuremath{\pi^0} separation

ATLAS and CMS: complementary performance
Two isolated photons:
$P_T(\gamma_1) > 40 \text{ GeV/c}$
$P_T(\gamma_2) > 25 \text{ GeV/c}$
$|\eta| < 2.5$

Mass resolution: $m_H = 100 \text{ GeV/c}^2$

ATLAS: $1.1 \text{ GeV/c}^2$ (LAr-Pb)
CMS: $0.6 \text{ GeV/c}^2$ (crystals)

Signal / background $\sim 4\%$ (Sensitivity in mass range $100 - 140 \text{ GeV/c}^2$)

background (dominated by $\gamma\gamma$ events*) can be determined from side bands
important: $\gamma\gamma$-mass resolution in the calorimeters, $\gamma / \text{jet separation}$

*) detailed simulations indicate that the $\gamma$-jet and jet-jet background can be suppressed
to the level of 10-20% of the irreducible $\gamma\gamma$-background

The full allowed mass range

from the LEP limit ($\sim 114 \text{ GeV/c}^2$)
up to
theoretical upper bound of $\sim 1000 \text{ GeV/c}^2$

can be covered using the two “safe” channels

$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ and
$H \rightarrow \gamma\gamma$
(iii) \( H \rightarrow WW^{(*)} \rightarrow \ell \nu \ell \nu \)

- Branching ratio for \( H \rightarrow WW \) is nearly 98% for \( m_H \sim 160 \text{ GeV/c}^2 \)
  (dip in the \( H \rightarrow ZZ \) sensitivity)
  \[
  \text{BR} (H \rightarrow WW \rightarrow \ell \nu \ell \nu) / \text{BR} (H \rightarrow ZZ \rightarrow \ell \ell \ell \ell) \sim 100
  \]

- However: neutrinos present in final state, no mass peak can be reconstructed
  \( \rightarrow \) use transverse mass

- Large backgrounds:
  \[
  \sigma (tt \rightarrow WbWb \rightarrow \ell \nu \ell \nu + \ldots) = 32.9 \text{ pb} \\
  \sigma (WW \rightarrow \ell \nu \ell \nu + \ldots) = 4.8 \text{ pb}
  \]

Two main discriminants:

(i) Lepton-lepton angular correlation: expect small angular separation between leptons from Higgs decays

(ii) Jet veto: no jet activity \((P_T > 20 \text{ GeV/c})\) in the central detector region \((|\eta| < 3.2)\)

\[
\Delta \phi (\ell\ell) \\
\text{Spin 0} \rightarrow \text{WW} \\
\text{expect charged leptons to be close by in space}
\]

\[
m (\ell\ell) \\
\text{Transverse mass } m_T(\ell\ell\nu)
\]

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reconstructed transverse mass distribution: \( m_H = 170 \text{ GeV}/c^2 \), \( L = 30 \text{ fb}^{-1} \)

- Signal and background shapes are similar
- Background (size and shape) need to be precisely known (for high signal significance)

Sensitivity including \( H \to WW \)

ATLAS experiment: no K-factors, \( L = 30 \text{ fb}^{-1}, 5\% \) syst. uncertainty on the background

more work on the backgrounds.....

Main theoretical challenge: - need to know the shape of the WW background
   - need to know the contributions from higher orders 
     e.g., \( gg \to WW \)

\[ \sigma(gg \to WW) : \text{only } 5\% \text{ of } \sigma(WW) \text{ before cuts, but } \sim 30\% \text{ of } \sigma(WW) \text{ after cuts} \]

WW measurements at the Tevatron are important, but gg contribution too small;
**Higgs Boson Searches at Hadron Colliders**

**Lecture 2**

- Search for the SM Higgs boson at the LHC (cont.)
- Status and perspectives at the Tevatron
- Measurement of Higgs boson parameters (mass, spin, couplings, self-coupling)

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Gluon fusion

- Higgs boson can be discovered over the full mass range with 30 fb$^{-1}$
- What about the other production modes?
**Higgs boson search in the associated production modes**

require leptons from W/Z or top decays
→ Trigger, suppression of background from QCD jet production
→ $H \rightarrow bb$ decay mode becomes accessible

$ttH \rightarrow \ell\nu bb$ (not a „discovery channel“ at the LHC)

- very challenging at the LHC !!
- large tt, ttj, ttjj, ttbb,...... Wqq, Wqqq...... backgrounds
- high performing b-tagging is absolutely necessary

$\sigma \times BR \approx 300 \text{ fb}$
Complex final state: $H \rightarrow bb$, $t \rightarrow bjj$, $t \rightarrow b\ell\nu$

- Main backgrounds:
  - combinatorial from signal (4b in final state)
  - $Wjjjjjj$, $WWbbjj$, etc.
  - $ttjj$ (dominant, non-resonant)

- b-tagging performance is crucial
  ATLAS results for 2D-b-tag from full simulation
  ($e_b = 60\%$, $R_j$ (uds)~100 at low L )

- Shape of background must be known;
  60\% (from ttbb) can be measured from ttjj using anti-b tag
- LHC experiments need a better understanding of the signal and the backgrounds (K-factors for backgrounds)

S = 38 events
B = 52 events
$S/B \sim 0.73$

$S/\sqrt{B} = 3.5$
for $K = 1.0$
and finally, a new channel: \( W/Z + ttH \rightarrow \gamma\gamma + E_T^{miss} \)

**use** \( H \rightarrow \gamma\gamma \) **decay mode again**

\( \gamma\gamma \) **signature:** background suppression, trigger, good mass resolution

\( E_T^{miss} \) **signature:** additional background suppression

\( E_T^{miss} \) from \( W \rightarrow \ell\nu, \ Z \rightarrow \nu\nu \) or \( t \rightarrow \ell\nu b \) decays

Recent study:
- ATLAS fast simulation
- \( \gamma \) selection as for inclusive case
- \( E_T^{miss} > 65 \) GeV

- For 100 fb\(^{-1}\): expect

**20.9** signal events (mass peak)
**5.4** background (flat)

---

**Higgs boson search in**

**vector boson fusion**

Distinctive Signature of:
- two high \( P_T \) forward jets ("tag jets")
- little jet activity in the central region \( \Rightarrow \) central jet Veto
- leptons from Higgs decay products (WW, \( \tau\tau \))

proposed by D. Rainwater and D. Zeppenfeld et al.: (hep/ph/9712271, hep/ph/9808468 and hep/ph/9906218)
**Forward jet tagging**

Rapidity distribution of tag jets  
VBF Higgs events vs. tt background

**Rapidity separation**

Forward tag jet reconstruction has been studied in full simulation in ATLAS and CMS

ATLAS results:  
kin. eff. for tag jets = 51.9%  
(P_T > 40/20 GeV/c,  \( \Delta \eta > 3.6 \))

tag eff. per jet: around 75%  

**Background:**

QCD backgrounds:  
\( tt \) production, \( Z + 2 \) jets

el.weak background:  
WWjj production, \( Z + 2 \) jets

**Background rejection:**

- Lepton P_T cuts and tag jet requirements  
  \( (\Delta \eta, P_T) \)
- Require large mass of tag jet system  
- Jet veto (important)  
- Lepton angular and mass cuts

Higgs boson (\( m_H = 160 \) GeV)  
\( tt \) background  
\( \gamma^* / Z + jets \)  
el.weak WWjj
qq \rightarrow qq \ W \ W^* \\
\rightarrow qq \ \ell \nu \ \ell \nu

Transverse mass distributions: clear excess of events above the background from tt-production

However: background shape is similar to signal??   robustness of signal?

-how reliable is this signal?

• Factor of two uncertainty found on the tt background calculation (PYTHIA vs. ttj + ttjj matrix element calculation, issue of parton shower matching)


However: large (S : B) ratio, discovery significance is stable

• Cuts can be relaxed, to get background shape from the data:

No kinematical cuts on leptons applied: (ATLAS study)
Presence of a signal can also be demonstrated in the $\Delta\phi$ distribution (i.e. azimuthal difference between the two leptons)

Evidence for spin-0 of the Higgs boson

Spin-0 → WW → ℓνℓν expect leptons to be close by in space

Higgs decay modes visible for a SM Higgs boson in vector boson fusion (not visible in gluon fusion mode)

$H \rightarrow \tau\tau$

qq H → qq ττ
  → qq ℓνν ℓνν
  → qq ℓνν νν

• large boost (high-$P_T$ Higgs)
  → collinear approximation:
    assume neutrinos go in the direction of the visible decay products
  → Higgs mass can be reconstructed

• main background: $Zjj$, $Z \rightarrow \tau\tau$
ATLAS Higgs discovery potential for 30 fb$^{-1}$

- Full mass range can already be covered after a few years at low luminosity
- Several channels available over a large range of masses
  Vector boson fusion channels play an important role at low mass!

Comparable situation for the CMS experiment

Effects of NLO contributions are shown for several channels
Combined significance of VBF channels for 10 fb⁻¹

**For 10 fb⁻¹ in ATLAS**
(1 year -after t₀- at low luminosity):

5 σ significance for \(120 \leq m_H \leq 190\) GeV/c²

---

Remarks for a light Higgs with \(m_H < 120\) GeV/c² and 10 fb⁻¹:

Three channels with \(~ 2-3\) σ each → observation of all channels important to extract convincing signal in first year(s)

The 3 channels are complementary → robustness:

- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - ECAL crucial for \(H \rightarrow \gamma\gamma\) \((\sigma/m \sim 1\%\) needed)
  - b-tagging is crucial for \(t\bar{t}H\) : (4 b-tagged jets needed to reduce combinatorics)
  - efficient jet reconstruction over \(|\eta| < 5\) crucial for \(q\bar{q}H \rightarrow q\bar{q}\tau\tau\)

Note: -- all require "low" trigger thresholds
  e.g. \(t\bar{t}H\) analysis cuts: \(p_T (t) > 20\) GeV, \(p_T (jets) > 15-30\) GeV
  -- \(t\bar{t}H\) requires very good understanding (5 -10%) of the backgrounds
The Search for the

Standard Model

Higgs Boson

at Fermilab

Search channels at the Tevatron

• important production modes: associated WH and ZH
  gluon fusion with \( H \rightarrow WW \rightarrow l\nu l\nu \)

• hopeless:
  gluon fusion in \( H \rightarrow \gamma\gamma, 4 \ell \) (rate limited)
  \( \sigma \text{ BR} (H \rightarrow ZZ \rightarrow 4 \ell) = 0.07 \text{ fb} \) (\( M_H=150 \text{ GeV/c}^2 \))

<table>
<thead>
<tr>
<th>Mass range (110 - 130 GeV)</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( WH \rightarrow l\nu bb )</td>
<td>( (\checkmark) ) weak</td>
</tr>
<tr>
<td>( ZH \rightarrow l^+l^- bb )</td>
<td>weak</td>
</tr>
<tr>
<td>( ZH \rightarrow \nu\nu bb )</td>
<td>( \varnothing ) (trigger)</td>
</tr>
<tr>
<td>( ZH \rightarrow bb bb )</td>
<td>( \varnothing ) (trigger)</td>
</tr>
<tr>
<td>( ttH \rightarrow l\nu b jj bbb )</td>
<td>( \checkmark )</td>
</tr>
</tbody>
</table>

Mass range (150 - 180 GeV) | LHC
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow WW(*) \rightarrow l\nu l\nu )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( WH \rightarrow WWW(*) \rightarrow l\nu l\nu l\nu )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( WH \rightarrow WWW(*) \rightarrow l^+\nu l^+\nu jj )</td>
<td>( \checkmark )</td>
</tr>
</tbody>
</table>

Triggering:
- is easier at the Tevatron:
  - better \( E_T^{\text{miss}} \) resolution
  - track trigger at Level-1

Background:
- electroweak production:
  ~10 x larger at the LHC
- QCD production (e.g., tt):
  ~ 100 x larger at the LHC
**Detector acceptance:** larger at Fermilab (central production)

Signal and background ratios after detector acceptance:

<table>
<thead>
<tr>
<th></th>
<th>low mass</th>
<th>high mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$WH \rightarrow \ell\nu b\bar{b}$</td>
<td>$H \rightarrow WW^{(*)} \rightarrow \ell\nu \ell\nu$ ($M_H = 160 \text{ GeV/c}^2$)</td>
</tr>
<tr>
<td>$S_{(14 \text{ TeV})}/S_{(2 \text{ TeV})}$</td>
<td>$\approx 5$</td>
<td>$\approx 30$</td>
</tr>
<tr>
<td>$B_{(14 \text{ TeV})}/B_{(2 \text{ TeV})}$</td>
<td>$\approx 25$</td>
<td>$\approx 6$</td>
</tr>
<tr>
<td>$S/B_{(14 \text{ TeV})}/S/B_{(2 \text{ TeV})}$</td>
<td>$\approx 0.2$</td>
<td>$\approx 5$</td>
</tr>
<tr>
<td>$S\sqrt{B}<em>{(14 \text{ TeV})}/S\sqrt{B}</em>{(2 \text{ TeV})}$</td>
<td>$\approx 1$</td>
<td>$\approx 10$</td>
</tr>
</tbody>
</table>

- comparable discovery potential for $WH$ and $ZH$:
  - larger signal at the LHC
  - better S/B-ratio at the Tevatron
  - difficult at both colliders
- significantly better LHC potential for $H \rightarrow WW^{(*)} \rightarrow \ell\nu \ell\nu$

**WH Signals at the LHC and the Tevatron**

$M_H = 120 \text{ GeV}$, $30 \text{ fb}^{-1}$

most important: control of the background shapes!!
Tevatron discovery potential for a light Higgs Boson

combination of both experiments and all channels
(discovery in a single channel not possible)

For 8 fb⁻¹:
(i) 95% CL exclusion of a SM Higgs boson is possible up to 135 GeV/c² and for 150 – 180 GeV/c²
(ii) 3-σ evidence for \( M_H < 130 \) GeV/c²
(iii) Sensitivity at low mass starts with an int. luminosity of 2 fb⁻¹ (end 2006)

Results from the present Run II data

typically, data corresponding to 300 – 350 pb⁻¹ analyzed
**Low Mass: \( WH \rightarrow e/\mu \nu bb \)**

**Data sample:** 320 pb\(^{-1}\)

**Event selection:**
- 1 high \( P_T \) central e or \( \mu \)
- \( P_T^{\text{miss}} > 20 \) GeV/c
- 2 jets, at least 1 b-tagged
- veto events with > 1 lepton

**Backgrounds:**
- \( Wbb, Wcc, Wjj \) (mistags)
- \( WW, WZ, ZZ, Z \rightarrow \tau \tau \)
- \( tt, \) single top
- QCD multijet

for details, see: hep-ex / 0512051

---

**Low Mass: \( WH \rightarrow e\nu bb \)**

**Data sample:** 382 pb\(^{-1}\)

**Event selection:** 1 e, \(|\eta| < 1.1, E_T > 20 \) GeV, \( E_T^{\text{miss}} > 20 \) GeV, 2 jets \( (E_T > 20 \) GeV) add b-tags

---

**Data:**

<table>
<thead>
<tr>
<th>Data:</th>
<th>153 events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tot. expectation</td>
<td>153.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Backgrounds:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wbb: 18.1</td>
</tr>
<tr>
<td>WH: 0.4</td>
</tr>
<tr>
<td>135.5</td>
</tr>
</tbody>
</table>

**Wbb:** 18.1
**WH:** 0.4

**Backgrounds:** 135.5
**Low mass:** WH cross section limits:

Low mass: WH cross section limits:

High mass: H → WW → ℓν ℓν

- Analyses have been performed by both CDF and DØ
- Based on data corresponding to an int. luminosity of ~ 350 pb⁻¹

Search for ℓℓ + PTmiss events (ℓ = e, μ)

Additional cuts:

- E_Tmiss > 20 GeV
- M(ℓℓ) < m_H/2
- M_T (ℓℓE_Tmiss) < m_H - 10 GeV

Data are consistent with expectations from SM backgrounds
**Limits on $H \rightarrow WW \rightarrow \ell\nu \ell\nu$ cross sections**

**CDF Run II Preliminary**

- 

**Larger Higgs boson cross sections in exotic models**

Higgs boson production rates can be enhanced in Exotic Models:

- 4th SM family enhance Higgs cross sections by a factor of ~8.5 for a Higgs boson mass between 100-200 GeV

- Fermiophobic Higgs: $\text{BR} (H \rightarrow VV) > 98\%$ for $m_H \geq 100$ GeV
Summary of current results from CDF and DØ

Combination of current analyses (CDF + DØ): for ~300 – 350 pb⁻¹

- upper limit about ~ 14 times larger than SM prediction at 115 GeV/c²
- for L = 2 fb⁻¹: \[ \text{gain} = \sqrt{\frac{L}{0.3}} \] → still a factor 5 missing

- Are the estimates from 1999 / 2003 credible ?
  Can the missing factors be gained ?

Anticipated improvements: (B. Heinemann, P5-meeting, Fermilab Sep. 05)

- increase acceptance (forward leptons, forward b-tagging)
- improvements in b-tagging (neural network)
- improvements in selection efficiencies (track-only leptons, neural networks)
- improved di-jet mass resolution
- .......

based on pre-RunII analyses

95% CL exclusion:

<table>
<thead>
<tr>
<th>Integrated Luminosity (fb⁻¹)</th>
<th>m_H (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>115 GeV/c²</td>
</tr>
<tr>
<td>4</td>
<td>130 GeV/c²</td>
</tr>
<tr>
<td>8</td>
<td>135 GeV/c²</td>
</tr>
<tr>
<td>3σ evidence: ★</td>
<td>115 GeV/c²</td>
</tr>
</tbody>
</table>

improvements not demonstrated yet, no guarantee, but there is a chance......
Determination of Higgs Boson Parameters

1. Mass
2. Couplings to bosons and fermions
3. Spin
4. Higgs self coupling

Measurement of the Higgs boson mass

Dominated by 4ℓ and γγ channels (mass peak, good mass resolution)

Dominant systematic uncertainty: \( \gamma / ℓ \) E scale.
Assumed \( 1\% \)
Goal \( 0.2\% \)
Scale from \( Z \rightarrow ℓℓ \) (close to light Higgs)

Higgs boson mass can be measured with a precision of 0.1% over a large mass range (130 - ~450 GeV / c²)

Note: no theoretical error, e.g. mass shift for large \( \Gamma_H \) (interference resonant/non-resonant production) taken into account
Measurement of the Higgs boson couplings

For a given Higgs boson mass: use the full information available, i.e. rates in various production modes → global fit

<table>
<thead>
<tr>
<th>Production mode</th>
<th>decay mode</th>
<th>Mass range (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluon fusion</td>
<td>H → ZZ^{(*)} → 4ν/4ℓ</td>
<td>110 200</td>
</tr>
<tr>
<td></td>
<td>H → WW^{(*)} → 4ν/4ℓ</td>
<td>110 200</td>
</tr>
<tr>
<td></td>
<td>H → 2γ</td>
<td>110 190</td>
</tr>
<tr>
<td>Vector boson</td>
<td>H → ZZ^{(*)} → 4ν/4ℓ</td>
<td>110 200</td>
</tr>
<tr>
<td></td>
<td>H → WW^{(*)} → 4ν/4ℓ</td>
<td>110 190</td>
</tr>
<tr>
<td></td>
<td>H → 4γ</td>
<td>110 170</td>
</tr>
<tr>
<td></td>
<td>H → 4ν/4ℓ</td>
<td>110 170</td>
</tr>
</tbody>
</table>

Production cross sections:

\[ \sigma_{ggH} = \alpha_{ggH} \times g_1^2 \]
\[ \sigma_{VBF} = \alpha_{VBF} \times g_1^2 + \alpha_{ZF} \times g_Z^2 \]
\[ \sigma_{ttH} = \alpha_{ttH} \times g_1^2 \]
\[ \sigma_{WH} = \alpha_{WH} \times g_W^2 \]
\[ \sigma_{ZH} = \alpha_{ZH} \times g_Z^2 \]
\[ \alpha \text{ from theory with assumed uncertainty } \Delta \alpha \]

Relative couplings can be measured with a precision of 10-20% (for 300 fb⁻¹)
Higgs Boson spin?

- Angular distributions in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ are sensitive to spin and CP eigenvalue.
- Azimuthal angle $\phi$, defined as angle between the decay planes of the two Z-bosons in the restframe of the Higgs.
- Polar angle $\theta$, defined as angle of neg. charged lepton in the restframe of the Z to the direction of motion of the Z in the restframe of the Higgs.

$$F(\phi) = \alpha \cos(\phi) + \beta \cos(2\phi)$$
$$F(\theta) = T (1+\cos^2 \theta) + L \sin^2 \theta$$
$$R = (L-T)/(L+T)$$

(J.R. Dell’Aquila, C.A. Nelson)

Expected results:

K. Jakobs

Higgs Bosons Self-coupling?

to establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

$$\lambda_{HHH} = 3 \frac{m_H^2}{\mu}$$

Cross sections for HH production:

small signal cross sections, large backgrounds from $tt$, $WW$, $WZ$, $WWW$, $ttt$, $Wtt$, ...

$\Rightarrow$ no significant measurement possible at the LHC

need Super LHC $L = 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$, 6000 fb$^{-1}$

K. Jakobs
Most sensitive channel: $gg \rightarrow HH \rightarrow WW WW \rightarrow \ell
\nu jj \ell\nu jj$

- accessible in mass range 160 GeV - 200 GeV
- $bb$-decay mode at lower masses is hopeless

**Selection:**
- 2 isolated, high $P_T$, like sign leptons (from different Higgs bosons)
- 4 high $P_T$ jets, compatible with W-mass

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>Signal</th>
<th>$W^\pm Z$</th>
<th>$W^\pm W^\mp W^\mp$</th>
<th>$ttW^\pm$</th>
<th>$ttt\ell$</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>170 GeV</td>
<td>350</td>
<td>90</td>
<td>60</td>
<td>2400</td>
<td>1600</td>
<td>30</td>
</tr>
<tr>
<td>200 GeV</td>
<td>220</td>
<td>90</td>
<td>60</td>
<td>1500</td>
<td>1600</td>
<td>30</td>
</tr>
</tbody>
</table>

6000 fb$^{-1} \Rightarrow \Delta \lambda_{HHH}/\lambda_{HHH} = 19\%$ (stat.) (for $m_H = 170$ GeV)

$\Delta \lambda_{HHH}/\lambda_{HHH} = 25\%$ (stat.) (for $m_H = 200$ GeV)
**The Higgs Sector in the MSSM**

Two Higgs doublets: 5 Higgs particles

- H, h, A
- H^+, H^-

determined by two parameters: \( m_A, \tan \beta \)

fixed mass relations at tree level:

(Higgs self coupling in MSSM fixed by gauge couplings)

\[
m_{H, A}^2 = \frac{1}{2} \left( m_A^2 + m_H^2 \pm \sqrt{(m_A^2 + m_H^2)^2 - 4m_A^2m_H^2 \cos^2 2\beta} \right)
\]

\[
m_A^2 \leq m_H^2 \cos^2 2\beta \leq m_H^2
\]

Important radiative corrections !! (tree level relations are significantly modified)

→ upper mass bound depends on top mass and mixing in the stop sector

\[ m_h^2 \leq m_H^2 + \frac{3g^2m_t^4}{8\alpha_m m_H^2} \left( \ln \left( \frac{M_Z^2}{m_W^2} \right) + x_t^2 \left( 1 - \frac{x_t^2}{12} \right) \right) \]

where: \( M_Z^2 = \frac{1}{2} (M_W^2 + M_H^2) \) and \( x_t = (A_t - \mu \cot \beta) / M_S \)

→\( m_h < 115 \text{ GeV} \) for no mixing

→\( m_h < 135 \text{ GeV} \) for maximal mixing

i.e., no mixing scenario: in LEP reach

max. mixing: easier to address at the LHC

---

**Branching ratios of MSSM Higgs bosons**

K. Jakobs 19th Nordic Particle Physics Meeting, Spatind/Norway, Jan. 2006
Production of MSSM Higgs bosons

At large tan $\beta$: enhanced couplings of Higgs bosons $H$ and $A$ to down-type fermions

$\rightarrow$ important production processes:

$gg \rightarrow bbH/A$

$qq \rightarrow bbH/A$

$gg \rightarrow H/A$

(b, t quarks and SUSY-particles in loop)

Cross section calculation:*)

- associated $bbH$ production becomes dominant process
- NLO calculations are available
  - two approaches –long discussions among theorists–
    - four flavour scheme (bb from gluon splitting) $K \sim 1.3 - 1.5$ (Tevatron – LHC)
    - five flavour scheme (use $b$-quark parton distributions, $bb \rightarrow h, \ gb \rightarrow bh$)
  - Finally: reasonable agreement (within respective scale uncertainties) between the NLO four-** and the NNLO five-flavour*** calculation is found for the inclusive (no b-tags) cross section.


MSSM benchmark scenarios

Masses and couplings of the Higgs bosons depend –in addition to tan$\beta$ and $m_A$– on the SUSY parameters through radiative corrections

Most relevant parameters: $A_t = \text{trilinear coupling in the stop sector}$ ($X_t = A_t - \mu \cot \beta$)

$\mu = \text{Higgs mass parameter}$

$M_2 = \text{gaugino mass term}$ ($M_1$ from gauge unification)

$m_g = \text{gluino mass}$

$m_{\text{SUSY}} = \text{common scalar mass}$

$m_h$-max: SUSY parameters chosen such that max mass value for $h$ achieved;

No mixing: vanishing mixing in the stop sector, $X_t = 0$;

Gluophobic: coupling to gluons strongly suppressed, large stop mixing, cancellation between top-quark and stop loop contributions;

Small $\alpha$: effective mixing angle between CP-even Higgs bosons is small, reduced BR into $bb$ and $\tau\tau$ for large tan$\beta$ and intermediate values of $m_A$.

**LEP results for the no-mixing scenario:**

Search for $e^+e^- \rightarrow h \ A \rightarrow bb \ bb$ and $e^+e^- \rightarrow h \ Z \rightarrow bb \ \tau\tau$

No significant excess found $\Rightarrow$

set limits in MSSM Higgs boson parameter space $(M_A, \tan \beta)$

\[ \begin{align*}
M_h & > 91.5 \text{ GeV/c}^2 \\
M_A & > 92.2 \text{ GeV/c}^2 \\
0.7 & < \tan \beta < 10.5
\end{align*} \]

Excluded $\tan \beta$ range: $0.7 < \tan \beta < 10.5$

---

**Results for the m_{h-max} scenario:**

\[ \begin{align*}
M_h & > 91.0 \text{ GeV/c}^2 \\
M_A & > 91.9 \text{ GeV/c}^2 \\
0.5 & < \tan \beta < 2.4 \ (m_t = 175 \text{ GeV/c}^2) \\
& < 1.9 \ (m_t = 179 \text{ GeV/c}^2)
\end{align*} \]
MSSM Higgs Boson Search at the LHC

Important channels in the MSSM Higgs boson search:

1. The Standard Model decay channels
   - $h \rightarrow \gamma\gamma$
   - $t\bar{t}\, h, \quad h \rightarrow b\bar{b}$
   - $q\bar{q}\, h, \quad h \rightarrow \tau\tau$
   evaluation of performance is based on SM results

2. Modes strongly enhanced at large $\tan\beta$:
   - $H/A \rightarrow \tau^+\tau^- \quad H^+ \rightarrow \tau\nu$
   - $H/A \rightarrow \mu^+\mu^-$

3. Other interesting channels:
   - $H/A \rightarrow t\bar{t}$
   - $H/A \rightarrow Zh \rightarrow l\bar{l} \gamma\gamma$
   - $H \rightarrow hh$

Search for the light CP-even Higgs boson $h$

- Standard search channels can be used
- Vector boson fusion channels contribute significantly

uncovered region at small $m_A$ → look for heavier Higgs bosons
Search for the heavy Higgs bosons H and A

at large $\tan\beta$: $bb\ H/A\rightarrow bb \ \tau\tau$ plays a key role
in addition: $bb\ H/A\rightarrow \mu\mu$
$bb\ H/A\rightarrow bb\ bb$ very difficult at the LHC
(trigger, backgrounds,....)

- Selection requires excellent b and $\tau$ identification
- detailed studies $\rightarrow$ both leptonic and
  hadronic tau decays can be used
$m_{H/A} < 400\ \text{GeV}/c^2$ ($\ell^{-}\tau_{\text{had}}$) dominates
$> 400\ \text{GeV}/c^2$ ($\tau_{\text{had}}^{-}\tau_{\text{had}}$) contributes significantly

- H/A mass can be reconstructed, collinear approx.
- Dominant backgrounds: W+jet, $tt$ production

at small $\tan\beta$: add. modes: search for $H/A\rightarrow h$ decays
allows for simultaneous observation for two Higgs bosons
examples: $H\rightarrow hh, A\rightarrow Zh$

MSSM Higgs bosons $h, H, A, H^\pm$

$m_h < 135\ \text{GeV}$
$m_A = m_h = m_{H^\pm}$ at large $m_A$

A, H cross-section $\sim \tan^2\beta$ (tree level)
- best sensitivity from $A/H\rightarrow \tau\tau$, (not easy the first year ..)
- $A/H\rightarrow \mu\mu$ experimentally easier (esp. at the beginning)
Search for the Charged Higgs Boson

Detection of a charged Higgs boson → *Physics Beyond the Standard Model*

**Production:** depends strongly on $m_{H^\pm}$

1. via top decays: $t \rightarrow H^\pm b$
2. $gg \rightarrow H^\pm tb$ or $gb \rightarrow H^\pm t$
3. $gg, qq \rightarrow H^\pm W$
4. $qq \rightarrow H^+ H^-$

**Decays:** depend strongly on $m_{H^\pm}$

- $\tau \nu$ decay mode significant at large $\tan \beta$

---

**Search for the charged Higgs bosons $H^\pm$ at large mass**

Both the $tb$ and the $\tau \nu$ decay modes can be used

- $H^\pm \rightarrow tb$ decays:
  - promising channel: (i) $gb \rightarrow H^\pm t \rightarrow tb t \rightarrow \ell \nu bb qqb$
    - require three b-tags + t-reconstruction → large background suppression
  - more difficult: (ii) $gg \rightarrow H^+tb \rightarrow tb tb \rightarrow \ell \nu bb qqbb$
    - require four b-tags + t-reconstruction (larger comb. background in rec. of $H^\pm$)

- $H^\pm \rightarrow \tau \nu$ decays:
  - promising channel: (i) $gb \rightarrow H^\pm t \rightarrow \tau \nu t \rightarrow h \nu \nu qqb$
    - exploit hadronic decays of the $\tau$ and $t$ quark
      → transverse mass distribution ($m_{\tau \nu} + E_{T,\text{miss}}$)
      can be used to reconstruct the $H^\pm$ mass
  - additional channel:
    (ii) $gg \rightarrow H^+tb \rightarrow \tau \nu tb \rightarrow h \nu \nu qqbb$
    - require two b-tags

- Other decay modes ($H^\pm \rightarrow Wh, WH$)
  - marginal - hopeless in MSSM
LHC discovery potential for charged Higgs bosons

For \( m_H < m_t - m_b \):
use \( t \rightarrow H^\pm b, \ H^\pm \rightarrow \tau \nu \) decays

combined discovery reach:

- good discovery potential, except moderate tan\( \beta \) region at high mass
- transition region around \( m_t \) can also be covered

both leptonic and hadronic decays of the top quark can be used

closes gap at small \( m_A \)

---

LHC discovery potential for MSSM Higgs bosons

\( m_{\text{SUSY}} = 1 \text{ TeV}, \ m_{\text{top}} = 175 \text{ GeV/c}^2 \)

Two or more Higgs can be observed over most of the parameter space \( \rightarrow \) disentangle SM / MSSM

- Plane fully covered (no holes) at low \( L \) (30 fb\(^{-1}\))
- Main channels: \( h \rightarrow \gamma\gamma, \ th \rightarrow bb, \ \ A/H \rightarrow \mu\mu, \tau\tau, \ H^\pm \rightarrow \tau \nu \)
LHC discovery potential for MSSM Higgs bosons

- Region at large $m_A$ and moderate $\tan \beta$ only covered by $h$; difficult to detect other Higgs bosons

Possible coverage:
- via SUSY decays (model dependent, see below)
- luminosity (only moderate improvement)

MSSM discovery potential for Super-LHC

- Situation can be improved, in particular for $m_A < \sim 400$ GeV
- But: (S)LHC can not promise a complete observation of the heavy part of the MSSM Higgs spectrum .... although the observation of sparticles will clearly indicate that additional Higgs bosons should exist.
MSSM scan for different benchmark scenarios

- Vector boson channels included
- Benchmark scenarios as defined by M. Carena et al. (h mainly affected)

**ATLAS, 30 fb⁻¹, 5σ coverage for h**

**MHMAX scenario** \((M_{\text{SUSY}}=1 \text{ TeV})\)
maximal theoretically allowed region for \(m_h\)

**Nomixing scenario** \((M_{\text{SUSY}}=2 \text{ TeV})\)
(1 TeV almost excl. by LEP)
small \(m_h\) → difficult for LHC

**Gluophobic scenario** \((M_{\text{SUSY}}=350 \text{ GeV})\)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for \(g \to H, H \to \gamma\gamma\) and \(Z \to 4\ell\)

**Small \(\alpha\) scenario** \((M_{\text{SUSY}}=800 \text{ GeV})\)
coupling to \(b\) (and \(t\)) suppressed
(cancellation of sbottom, gluino loops) for
large \(\tan \beta\) and \(M_A\) 100 to 500 GeV

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MSSM discovery potential for various benchmark scenarios

- Full parameter range can be covered with modest luminosity, 30 fb⁻¹, for all benchmark scenarios!
- Only one Higgs boson, \(h\), in some regions
(moderate \(\tan \beta\) – large \(M_A\) wedge)

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K. Jakobs 19th Nordic Particle Physics Meeting, Spatind/Norway, Jan. 2006
Can **SUSY particles** be used to detect Higgs bosons ??

or

the interplay between the Higgs sector and SUSY particles

so far: SUSY particles have been assumed to be too heavy to play a role in Higgs boson decay phenomenology

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**CMS study: MSSM scenario**

\[ \text{H/A} \rightarrow \chi_2^0 \chi_2^0 \rightarrow \ell\ell\chi_1^0 \ell\ell\chi_1^0 \]

5\(\sigma\) contours

special choice in MSSM (no scan)

- \(M_1 = 60\text{ GeV}\)
- \(M_2 = 110\text{ GeV}\)
- \(\mu = -500\text{ GeV}\)

Exclusions depend on MSSM parameters (slepton masses, \(\mu\))
Search for $H^\pm$ decays into SUSY particles

$gb \rightarrow tH^+, H^\pm \rightarrow \chi_{2,3}^0 \chi_{1,2}^\pm \rightarrow 3\ell + E_T^{miss}$

special choice in MSSM (no scan)

$M_2 = 210$ GeV
$
\mu = 135$ GeV

$m(s-\ell_R) = 110$ GeV
$m(s-\tau_R) = 210$ GeV
$m_g = 800$ GeV
$m_{\text{SUSY}} = 1000$ GeV

Excursion: Search for Supersymmetry

• If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

• Squarks and Gluinos are strongly produced

They decay through cascades to the lightest SUSY particle (LSP)

⇒ Heavy Higgs bosons might appear in cascades decays,
  e.g. cascade decays of squarks and gluinos via heavy charginos and neutralinos

\[
\begin{align*}
pp &\rightarrow g\tilde{g}, q\tilde{q}, \bar{q}\bar{g} \rightarrow \chi_2^\pm, \chi_3^0, \chi_4^0 + X \\
&\rightarrow \chi_1^\pm, \chi_2^0, \chi_1^0 + h, H, A, H^\pm + X
\end{align*}
\]

\[
\begin{align*}
pp &\rightarrow g\tilde{g}, q\tilde{q}, \bar{q}\bar{g} \rightarrow \chi_2^\pm, \chi_2^0 + X \\
&\rightarrow \chi_1^0 + h, H, A, H^\pm + X
\end{align*}
\]

Search for Higgs decays in standard channels: $bb, \tau\tau, \tau\nu$
Search for $h \rightarrow bb$ in SUSY cascade decays

Applying a cut on $E_T^{miss}$ ⇒ suppresses the Standard Model background (QCD-jets), dominant background from SUSY production

$h \rightarrow bb$: CMS study, mSUGRA

important if $\chi^0_2 \rightarrow \chi^0_1 h$ is open;

bb peak can be reconstructed in many cases

Could be a Higgs discovery mode!

More complicated scenarios, an example (CMS):

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{g} \rightarrow \chi_2^\pm, \chi_3^0, \chi_4^0 + X$

$\rightarrow \chi_1^\pm, \chi_2^0, \chi_1^0 + h, H, A, H^\pm + X$

$m_{\tilde{g}} = 1200$ GeV, $m_{\tilde{q}} = 800$ GeV,

$M_2 = 350$ GeV, $\mu = 150$ GeV

reconstructed bb mass

Two Higgs ($H, h$) bosons visible
\textbf{tan}\beta \textit{measurement in the MSSM}

- Strong dependence of production cross section of heavy Higgs bosons on \(\tan\beta\) (~ \(\tan\beta^2\) at tree level) can be used to measure its value

- However, large radiative corrections at large \(\tan\beta\), depend on SUSY particles \(\Rightarrow\) will need to be entered into a global fit of SUSY parameters

\begin{center}
\includegraphics[width=0.5\textwidth]{figure.png}
\end{center}

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K. Jakobs
19th Nordic Particle Physics Meeting, Spatind/Norway, Jan. 2006

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\textbf{Status of MSSM Higgs boson searches at the Tevatron}

K. Jakobs
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Search for Heavy Neutral Higgs Bosons $\Phi \rightarrow bb$

Data sample: $260 \, \text{pb}^{-1}$

Search for $bb \, A/H \rightarrow bb \, bb$

- dedicated trigger
- select four jet final states
- require three b-tagged jets

Search for the $\Phi \rightarrow \tau \tau$ decay mode

Data sample: $310 \, \text{pb}^{-1}$

Search for $A/H \rightarrow \tau \tau$ and $bb \, A/H \rightarrow bb \, \tau \tau$

- select $\tau$-had decays with $\ell = e, \mu$
- reconstruct visible mass ($\ell$-$\tau$-had)
**Combined excluded region**

![Combined excluded region](image)

**Prospects for MSSM Higgs boson searches at the Tevatron**

![Prospects for MSSM Higgs boson searches at the Tevatron](image)

95% CL contours

K. Jakobs  
19th Nordic Particle Physics Meeting, Spatind/Norway, Jan. 2006
Search for Charged Higgs Bosons $H^{\pm}$

- Search for charged Higgs bosons in top decays,
- $H^{\pm} \rightarrow \tau \nu$ decays
- No excess of $\tau$ contributions found $\rightarrow$ limit

Invisible Higgs decays?

Possible searches:
- $t\bar{t}$ $H \rightarrow t\bar{v} q\bar{q} b + P_T^{\text{miss}}$
- $W/Z$ $H \rightarrow \ell\nu (\ell\ell) + P_T^{\text{miss}}$
- $q\bar{q}$ $H \rightarrow q\bar{q} + P_T^{\text{miss}}$

ATLAS study:

search for invisibly decaying Higgs boson in VBF mode

Event selection:
- $2$ tag jets, $(P_T, \Delta \eta, M_{jj}>1200$ GeV) $P_T^{\text{miss}} > 100$ GeV
- Lepton and Jet veto (no jets with $P_T > 20$ GeV)

Main backgrounds:
- $W$ $jj$ production ($W \rightarrow t\bar{v}$)
- $Z$ $jj$ production ($Z \rightarrow \nu\nu$)
- QCD jet production, fake $P_T^{\text{miss}}$

Requires special forward jet + $P_T^{\text{miss}}$ trigger (under study)
Discriminating variable: $\Delta \phi_{jj}$ (separation between tag jets)

expect differences due to Higgs coupling structure:

Expected rates for 10 fb$^{-1}$:

- Signal: 590 events
- W-background: 1215 events
- Z-background: 1230 events

background normalization via $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ in region $\Delta \phi > 1$ needed, to constrain the background

(estimated background uncertainty: 4-5%)

Sensitivity:

$$\xi^2 = \frac{Br(H \rightarrow Inu)}{\sigma_{gg-H}/\sigma_{qq-H}}$$

- Needs confirmation from more detailed simulation (trigger)
- Non-Standard Model background ??
- Needs confirmation in ttH and/or WH channel to demonstrate presence of a Higgs boson

Conclusions

- Should a SM Higgs boson exist, it cannot escape detection at the LHC
- MSSM parameter space can be covered for several benchmark scenarios (incl. LHC-phobic scenarios)

Maybe celebration at Spatind 2010 ??

- Tevatron might have a 3-$\sigma$ discovery windows, however, much depends on the detector and accelerator performance.
- LHC can perform first, important measurements of Higgs boson parameters or help to constrain underlying SUSY models

Exiting times ahead of us....
transparencies under:  wwwhep.physik.uni-freiburg.de/~jakobs
→ Physik-Schulen

writeup:  V. Büscher and K. Jakobs, Higgs Boson Searches at Hadron Colliders,