Higgs boson searches at hadron colliders

Part 2

- SM Higgs search at the Tevatron
  - Low and high mass channels
  - Statistical combination
  - Prospects for the next years

- Test of Monte Carlo generators
Cross Sections and Production Rates

Rates for $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$: (LHC)

- Inelastic proton-proton reactions: $10^9 / \text{s}$
- $b\bar{b}$ pairs: $5 \times 10^6 / \text{s}$
- $t\bar{t}$ pairs: $8 / \text{s}$
- $W \rightarrow e \nu$: $150 / \text{s}$
- $Z \rightarrow e^+ e^-$: $15 / \text{s}$
- Higgs (150 GeV): $0.2 / \text{s}$
- Gluino, Squarks (1 TeV): $0.03 / \text{s}$

Large production rates, however, overwhelmed by large backgrounds from:

- jet production via QCD processes
- $t\bar{t}$ production (for lepton final states)
- $W/Z +$ jet production (lepton final states)
**Higgs Boson Production cross sections**

**LHC**

M. Spira et al.

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

- \( \sqrt{s} = 14 \text{ TeV} \)
- \( M_H = 175 \text{ GeV} \)
- CTEQ4M

**Tevatron**

\[ \sigma(p\bar{p} \rightarrow H + X) \] [pb]

- \( \sqrt{s} = 1.96 \text{ TeV} \)
- MSTW2008
- \( m_t = 173.1 \text{ GeV} \)

General Observations:

- \( q\bar{q} \rightarrow W/Z + H \) cross sections
- \( gg \rightarrow H \)

- \( \sim 10 \times \) larger at the LHC
- \( \sim 70-80 \times \) larger at the LHC

K. Jakobs, Universität Freiburg

CERN Academic Training Lectures, June 2010
Useful Higgs Boson Decays at Hadron Colliders

**at high mass:**
- **Lepton** final states
  - (via $H \rightarrow WW$, $ZZ$)

**at low mass:**
- **Lepton and Photon** final states
  - (via $H \rightarrow WW^*, ZZ^*$)
- **Tau** final states

The dominant **bb decay mode** is only useable in the associated production mode ($ttH$, $W/Z H$)

(due to the huge QCD jet background, leptons from $W/Z$ or $tt$ decays)
Detector requirements for Higgs 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 $\eta \sim 5$

- Jet tagging in the forward regions (Vector boson fusion process)

- Efficient $b$-tagging and $\tau$ identification (silicon strip and pixel detectors)
The accelerators
The Tevatron Collider at Fermilab

• **Proton antiproton collider**
  - 6.5 km circumference
  - Beam energy 0.98 TeV, $\sqrt{s} = 1.96$ TeV
  - 36 bunches, 396 ns separation (time between crossings)

• **2 Experiments:** CDF and DØ

• **Main challenges:**
  - Antiproton production and storage
    → luminosity, stability of operation

Collider is running in so called Run II (since 2001)
[Run I from 1990 – 1996, int. luminosity: 0.125 fb⁻¹, Top quark discovery]

* March 2001 – Feb 2006: Run II a, $\int L \, dt = 1.2$ fb⁻¹
* July 2006 - 2010 (11 / 12)?: Run II b, $\int L \, dt = 10 - 12$ fb⁻¹
Peak luminosities of the machine as a function of time

- Peak luminosity of $4.02 \cdot 10^{32}$ cm$^{-2}$ s$^{-1}$
- Corresponds to $\sim 10$ interactions per bunch crossing (superposition of minimum bias events on hard collision)
The integrated Tevatron luminosity (until June 2010)

- After a slow start-up (2001 – 2003), the Tevatron accelerator has reached an excellent performance
- Today, Tevatron delivers a data set equal to Run I (~100 pb⁻¹) every 2 weeks
- Integrated luminosity delivered to the experiments so far ~ 8.8 fb⁻¹
- Anticipate an int. luminosity of ~10 fb⁻¹ until end of 2010, with a potential increase to 12 - 13 fb⁻¹, if Tevatron will run until end of 2011

Data corresponding to an int. luminosity of up to 5.4 fb⁻¹ analyzed…
Challenges with high luminosity

Min. bias pileup at the Tevatron, at $0.6 \cdot 10^{32}$ cm$^2$s$^{-1}$ ... and at $2.4 \cdot 10^{32}$ cm$^2$s$^{-1}$

Average number of interactions:

LHC: initial “low” luminosity run (L=$2 \cdot 10^{33}$ cm$^2$s$^{-1}$): $\langle N \rangle = 3.5$

TeV: (L=$3 \cdot 10^{32}$ cm$^2$s$^{-1}$): $\langle N \rangle = 10$
The Large Hadron Collider

... became a reality in 2008 after ~15 years of hard work

Beam energy          7 TeV
(nominal)
SC Dipoles              1232, 15 m, 8.33T
Stored Energy          362 MJ/Beam
Bunch spacing          25 ns
Particles/Bunch        1.15 \cdot 10^{11}
Design luminosity    10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1}
Comparison of the LHC and Tevatron machine parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC (design)</th>
<th>Tevatron (achieved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>14 TeV</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
<td>36</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns</td>
<td>396 ns</td>
</tr>
<tr>
<td>Energy stored in beam</td>
<td>360 MJ</td>
<td>1 MJ</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>$10^{33}$-$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$4 \times 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Integrated Luminosity / year</td>
<td>10-100 fb$^{-1}$</td>
<td>$\approx 2$ fb$^{-1}$</td>
</tr>
</tbody>
</table>

- 7 times more energy (after initial 3.5 TeV phase)
- Factor 3-30 times more luminosity
- Physics cross sections factor 10-100 larger
The Search for

The Higgs boson at the Tevatron
Searches for a low mass Higgs boson at the Tevatron

$m_H < 135$ GeV:
Associated production WH and ZH with $H \rightarrow bb$ decay
Main low mass search channels

$\ell + E_T^{\text{miss}} + b\bar{b}$: $WH \rightarrow \ell \nu b\bar{b}$

Largest $VH$ production cross section, however, severe backgrounds

$\ell \ell + b\bar{b}$: $ZH \rightarrow \ell \ell b\bar{b}$

Less background than $WH$

Smallest Higgs signal

$E_T^{\text{miss}} + b\bar{b}$: $ZH \rightarrow \nu \nu b\bar{b}$

3x more signal than $ZH \rightarrow \ell \ell b\bar{b}$

($+WH \rightarrow \ell \nu b\bar{b}$ when lepton non-identified)

Large backgrounds which are difficult to handle
Number of produced events (incl. decays) per 1 fb⁻¹

**WH (H→bb) Signal, m_H = 115 GeV:**
\[ \sigma \times \text{BR} = 14 \text{ fb} \] (per lepton)

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

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

+ multijet QCD background
General Search Strategy

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

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

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

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

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

Example: \( WH \rightarrow \ell \nu bb \)
**b tagging**

- Several methods have been established at the Tevatron during the past years:
  - lifetime tags, signed impact parameters
  - reconstructed secondary vertices

- Most powerful methods combine information using neural networks

- Typical performance figures:
  
  D0: Neural net (Impact parameter, sec. vertex)
  - “Tight”: 70% b-tag efficiency, 3.5% mistag
  - “Loose”: 50% b-tag efficiency, 0.3% mistag

  Similar results for CDF
DØ: WH→lv bb (l=e,μ) neural net

\[ p_{T}(j_1), \]
\[ p_{T}(j_2), \]
\[ \Delta R(jj), \]
\[ \Delta \phi(jj), \]
\[ p_{T}(jj), \]
\[ M(jj), \]
\[ p_{T}(l, E_{T \text{ Miss}}) \]
(iv) Split data into several sub-samples with different final state topologies
- maximize sensitivity due to S:B variations
- different background composition in the different classes
  (e.g. 1 b-tag, 2 b-tags)

(v) Final step: Statistical combination of all sub-samples in each experiment and of both experiments
Sensitivity in the low mass region

- Limits for individual channels a factor of 5-10 away from SM cross section at $m_H = 115$ GeV
- The combination of all contributing channels is crucial

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

Excluded cross section:
(95% C.L., $m_H = 115$ GeV)

D0: $\sigma_{95} = 6.9 \cdot \sigma_{SM}$
CDF: $\sigma_{95} = 4.3 \cdot \sigma_{SM}$
Searches for a high mass Higgs boson at the Tevatron

$m_H > 135$ GeV:

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

**Signal, $m_H = 160$ GeV:**

- $gg \rightarrow H \rightarrow WW \rightarrow ll\nu\nu$: $\sigma \times BR = 40$ fb
- Associated WH and qqH production increase signal by $\sim 30\%$

**Significant di-boson backgrounds:**

- **Di-Boson**
  - $WW$: $\sigma \times BR = 13$ pb
  - $WZ$: $\sigma \times BR = 4.0$ pb
  - $ZZ$: $\sigma \times BR = 1.5$ pb

**Additional backgrounds:**

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

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

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

To increase sensitivity:

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

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

Veto events with tight b-tagged jet
$H \rightarrow \ell^+ \ell^- \nu \nu$

Excluded cross section per experiment:

Expected limits:
- CDF: $\sigma_{95} = 1.03 \cdot \sigma_{SM}$
- D0: $\sigma_{95} = 1.36 \cdot \sigma_{SM}$

Observed limits:
- CDF: $\sigma_{95} = 1.13 \cdot \sigma_{SM}$
- D0: $\sigma_{95} = 1.55 \cdot \sigma_{SM}$
Combination → limit setting

Combination of all channels and of the two experiments:
(note that exclusion is not possible in a single channel / experiment)
List of final states considered

- 90 mutually exclusive final states
- New analyses have been added during 2009
- Acceptance improvements, e.g. loose lepton ID or high p_T tracks

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity (fb⁻¹)</th>
<th>m_H range (GeV/c²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH → ℓνbb 2-jet channels</td>
<td>3×(TDT,LDT,ST,LDTX)</td>
<td>4.3</td>
<td>100-150</td>
</tr>
<tr>
<td>WH → ℓνbb 3-jet channels</td>
<td>2×(TDT,LDT,ST)</td>
<td>4.3</td>
<td>100-150</td>
</tr>
<tr>
<td>ZH → ℓ⁺ℓ⁻bb</td>
<td>(TDT,LDT,ST)</td>
<td>3.6</td>
<td>105-150</td>
</tr>
<tr>
<td>ZH → ℓ⁺ℓ⁻bb</td>
<td>(low,high s/b)×(TDT,LDT,ST)</td>
<td>4.1</td>
<td>100-150</td>
</tr>
<tr>
<td>H → W⁺W⁻</td>
<td>(low,high s/b)×(0,1 jets)+(2+ jets)+Low-m_ℓℓ</td>
<td>4.8</td>
<td>110-200</td>
</tr>
<tr>
<td>WH → WW⁺W⁻ → ℓ±νℓ±ν</td>
<td>4.8</td>
<td>110-200</td>
<td>8</td>
</tr>
<tr>
<td>H + X → ℓ⁺τ⁻ + 2 jets</td>
<td>2.0</td>
<td>110-150</td>
<td>9</td>
</tr>
<tr>
<td>WH + ZH → jjbb</td>
<td>2.0</td>
<td>100-150</td>
<td>10</td>
</tr>
</tbody>
</table>

---

TABLE III: Luminosity, explored mass range and references for the different processes and final state (ℓ = e, μ) for analyses

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity (fb⁻¹)</th>
<th>m_H range (GeV/c²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH → ℓνbb</td>
<td>2×(ST,DST)</td>
<td>5.0</td>
<td>100-150</td>
</tr>
<tr>
<td>VH → ττbb/qqττ</td>
<td>4.9</td>
<td>105-145</td>
<td>12, 13</td>
</tr>
<tr>
<td>ZH → ℓνbb</td>
<td>(ST,LDT)</td>
<td>5.2</td>
<td>100-150</td>
</tr>
<tr>
<td>ZH → ℓ⁺ℓ⁻bb</td>
<td>2×(ST,DST)</td>
<td>4.2</td>
<td>100-150</td>
</tr>
<tr>
<td>WH → WW⁺W⁻ → ℓ±νℓ±ν</td>
<td>3.6</td>
<td>120-200</td>
<td>16, 17</td>
</tr>
<tr>
<td>H → W⁺W⁻</td>
<td>ℓ±νℓ±ν</td>
<td>5.4</td>
<td>115-200</td>
</tr>
<tr>
<td>H → γγ</td>
<td>4.2</td>
<td>100-150</td>
<td>19</td>
</tr>
<tr>
<td>tH → tbb</td>
<td>2×(ST,DST,TT)</td>
<td>2.1</td>
<td>105-155</td>
</tr>
</tbody>
</table>
“Tevatron exotic” channels

$H \rightarrow \gamma \gamma$

WH $\rightarrow \tau \nu$ bb
“Tevatron exotic” channels

W/Z H $\rightarrow$ qq bb
List of channels that enter the combination (cont.)

- Channels difficult to add (for comparison of data vs. expectations)
  → use bins in S/B
Hypothesis testing

The observed data are subjected to a likelihood ratio test of two hypothetical scenarios: Background scenario (no Higgs signal assumed)
Signal + Background scenario (Higgs signal with assumed mass added)

Compute likelihood for B and (S+B) hypothesis

Likelihood ratio  \( Q : = \frac{L_{S+B}}{L_B} \)

Test statistics: \( LLR : = -2 \ln Q \)  
(log-likelihood ratio (LLR))

Distribution (pdf) of \(-2 \ln Q\) can be calculated in MC experiments for (S+B) and B-hypothesis
Example from LEP: Likelihood ratio distributions for different assumed Higgs boson mass values

$m_H = 110 \text{ GeV/c}^2$  \hspace{1cm}  $m_H = 115 \text{ GeV/c}^2$  \hspace{1cm}  $m_H = 120 \text{ GeV/c}^2$

Difference between the median values between the S+B and B hypothesis is a measure of the sensitivity
LEP: Observed and expected behavior of $-2 \ln Q$

Broad minimum around 115 GeV/c$^2$

Neg. value of $-2 \ln Q$ in data indicates that the (S+B) hypothesis is more favored than the B-hypothesis, however, at low significance.
- Sensitivity is largest around 165 GeV
- Observed LLR is consistent with background hypothesis, although at low mass, S+B is slightly favoured
Systematic uncertainties

Analyses are affected by significant systematic uncertainties; Example: The two most significant DØ analyses:

<table>
<thead>
<tr>
<th>Source</th>
<th>$WH \rightarrow e\nu b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6.1</td>
</tr>
<tr>
<td>Normalization</td>
<td>-</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>3.0</td>
</tr>
<tr>
<td>Jet ID</td>
<td>5.0</td>
</tr>
<tr>
<td>Jet Triggers</td>
<td>-</td>
</tr>
<tr>
<td>Electron ID/Trigger</td>
<td>4.0</td>
</tr>
<tr>
<td>Muon ID/Trigger</td>
<td>-</td>
</tr>
<tr>
<td>$b$-Jet Tagging</td>
<td>3.9</td>
</tr>
<tr>
<td>Background $\sigma$</td>
<td>7-20</td>
</tr>
<tr>
<td>Multijet</td>
<td>14</td>
</tr>
<tr>
<td>Shape-Dependent Bkgd Modeling</td>
<td>2-10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$H \rightarrow W^+W^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6.1</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>3.0</td>
</tr>
<tr>
<td>Jet ID</td>
<td>1-2</td>
</tr>
<tr>
<td>Tau Energy Scale/ID</td>
<td>-</td>
</tr>
<tr>
<td>Electron ID/Trigger</td>
<td>3-10</td>
</tr>
<tr>
<td>Muon ID/Trigger</td>
<td>7.7-10</td>
</tr>
<tr>
<td>$b$-Jet Tagging</td>
<td>-</td>
</tr>
<tr>
<td>Background $\sigma$</td>
<td>7-10</td>
</tr>
<tr>
<td>Signal $\sigma$</td>
<td>11</td>
</tr>
<tr>
<td>Multijet</td>
<td>2-20</td>
</tr>
<tr>
<td>Shape-Dependent Bkgd Modeling</td>
<td>5-20</td>
</tr>
</tbody>
</table>

- Systematic uncertainties for background rates are generally several times larger than the signal expectation itself
- To minimize the degrading effect of systematic uncertainties on the search sensitivity, the individual background contributions are fitted to the data observation by maximizing a likelihood function
  Nuisance parameters allow for variations within errors
- Each systematic uncertainty (incl. uncertainty on signal cross section) is folded into the signal and background expectation via Gaussian distributions (correlations preserved)
Combined Tevatron limits

Tevatron experiments set a 95% CL exclusion of a SM Higgs boson in the mass region 162–166 GeV (first direct exclusion since LEP)

At $m_H = 115$ GeV

- Expected limit: $1.8 \times \sigma_{SM}$
- Observed limit: $2.7 \times \sigma_{SM}$
**Comments on this combination**

- Use best knowledge on signal cross sections
  - NNLO + NNLL calculations for the gluon fusion
  - NLO cross sections for VBF + W/ZH associated production

- Background cross sections normalized using either experimental data or NLO calculations (e.g. MCFM for W+heavy flavour processes)
  Finally constrained via nuisance parameters in a likelihood fit

- Assessment of systematic uncertainties is difficult!

In particular treatment of signal cross section uncertainties might be considered to be optimistic
Conclusions on the Tevatron Higgs search

• The Tevatron experiments have reached sensitivity (expected limit) for the SM Higgs boson in the mass range around 160 GeV.

• With increased luminosity the sensitivity in this region is expected to reach the $3\sigma$ level.
  → Either a large mass region can be excluded with 95% C.L. or first evidence ($3\sigma$) for a SM Higgs boson can be found;

However: not a single “evidence channel” available needs the combination of many channels and of the two experiments.

• The Higgs search in the mass range below $\sim130$ GeV is difficult (also at the LHC);

Search for the $b\bar{b}$ final state at the Tevatron will provide important complementary information to the LHC Higgs search in the $H \rightarrow \gamma\gamma$ and $qqH \rightarrow qq\tau\tau$ channels.
For 10 fb\textsuperscript{-1}, expect 95% C.L. exclusion for a Higgs boson mass of 115 GeV
- Can be reached faster, if analysis improvements can be achieved
Expected Tevatron sensitivity (cont.)

Possible improvements:  
- improved $m_{bb}$ mass resolution  
- improved b-tagging, c-tagging, lepton ID, .....  

- With improvements, 95% C.L. exclusion might be reached over mass range up to ~200 GeV
What can be learned on Test of Monte Carlo Models?
- W/Z production as an example -
QCD Test in $W/Z + \text{jet}$ production

- LO predictions fail to describe the data;
- Jet multiplicities and $p_T$ spectra in agreement with NLO predictions within errors;
  NLO central value $\sim 10\%$ low

Jet multiplicities in $Z + \text{jet}$ production

$p_T$ spectrum of leading jet
• Comparison of $p_T$ spectra of leading, second and third jet in Z+jet events to
  - PYTHIA and HERWIG (parton shower based Monte Carlos)
  - ALPGEN and SHERPA (explicit matrix elements (tree level) matched to parton showers)

....they might have to try harder