Higgs boson searches at LHC

- LHC physics goals
- Standard Model and a Higgs boson
- Experimental challenges
- Prospects for SM Higgs
- Prospects for MSSM Higgs
- Summary on the road path
**LHC a brief history**

The most ambitious project in high-energy physics ever, and one of the most ambitious in science.

1983 : $W^\pm/Z$ detected at SPS proton-antiproton collider  
Tevatron becomes operational  

1984 : **First studies for a high-energy pp collider in the LEP tunnel**  
1989 : Start of SLC and LEP e+e- colliders  
1993 : SSC is cancelled  

1994 : **LHC approved by the CERN Council**  
1995 : Top-quark discovery at the Tevatron  
1996 : **Construction of LHC machine and experiments start**  
2000 : End of LEP2  
2003 : **Start of the accelerator and experiments installation**

**Summer 2008**

Expect First collisions at $\sqrt{s} = 10\text{TeV}$ (14 TeV)  
Start a ~15-year long physics program
In the experiments:

- $10^9$ pp interactions per second
- $\sim 1500$ particles ($p, n, \pi$) produced in the detectors at each bunch-crossing
LHC physics goals (pp collision)

Higgs boson is a keystone of Standard Model construction. Elusive itself though interactions is expected to define properties of all known particles. That is why search for the Standard Model Higgs boson over mass range $\sim 115 < m_H < 1000 \text{ GeV}$ is focusing point of LHC experiments.

Explore the highly-motivated TeV-scale, search for physics beyond the SM (Supersymmetry (more than one Higgs boson), Extra-dimensions, q/l compositness, leptoquarks, $W'/Z'$, heavy q/l, etc.)

Precise measurements

-- W mass
-- Top mass, couplings and decay properties
-- Higgs mass, spin, couplings (if Higgs found)
-- B-physics (mainly LHCb): CP violation, rare decays,.....
-- QCD jet cross-section and $\alpha_s$
-- etc....
ATLAS and CMS detectors

- Multi-purpose: able to detect all known particles
- Fast response: \(~50 \text{ ns}\)
- \(10^8\) electronic channels
- Radiation hard (up to \(10^6\) Gy in the hottest regions after 10 years of operation)
Why do we like the Standard Model?

All the SM predictions (but one ...), in terms of particles and features of their interactions, have been verified by many experiments at many machines.

1983: \( W, Z \) discovered at CERN pp Collider
\( m \approx 100 \text{ GeV} \) as predicted by theory

1989-2000: LEP \( e^+e^- \) collider at CERN
several precise measurements of Z particle
\( \rightarrow \) agreement theory-data at the permil level!

1994: top quark discovered at Fermilab pp Collider: \( m \approx 175 \text{ GeV} \)
Heaviest elementary particle!

Production and decay of a top-quark pair from CDF data

1994:

\( e^+e^- \) collider at CERN
several precise measurements of Z particle
\( \rightarrow \) agreement theory-data at the permil level!
But still many open questions... first of all

What is the origin of the particle masses?

Mass of quark top (heaviest elementary particle observed)
  ∼ mass of Gold atom.
Electron mass = 1 000 000 times smaller than top-quark mass
Photon mass = 0

The mass mystery could be solved by the “Higgs mechanism”, which predicts the existence of a new elementary scalar particle: **the Higgs boson**

This particle has been searched for 20 years at accelerators all over the world and has not been observed yet.

The Higgs particle has a mass between 2 times the mass of an Iron atom and 4 times the mass of an Uranium atom. **The LHC has sufficient energy to produce it.**

If the Higgs particle is not found at the LHC, the Higgs mechanism is wrong and we will have to find another solution to the mass problem.
SM Higgs mass constraints

**Experiment**

Indirect constraints from precision EW data
- $M_H < 260$ GeV at 95% CL (2004)
- $M_H < 166$ GeV (2006, ICHEP06)

Direct limit from LEP: $M_H > 114.4$ GeV

**SM theory**

The triviality (upper) bound and vacuum stability (lower) bound as function of the cut-off scale $\Lambda$

- $m_t = 175$ GeV
- $\alpha_s(M_Z) = 0.118$

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E. Richter-Was  
The experimental challenges

Don’t know how New Physics will manifest
- detectors must be able to detect as many particles and signatures as possible: \(e, \mu, \tau, \nu, \gamma, \text{jets}, \text{b-quarks} \ldots\)
- ATLAS and CMS are general-purpose experiments.

Lepton measurement:
\(p_T \approx \) GeV \(\rightarrow 5\) TeV \((b \rightarrow l+X, W'/Z',\ldots)\)

Mass resolutions:
- \(\approx 1\%\) decays into leptons or photons (Higgs, new resonances)
- \(\approx 10\%\) \(W \rightarrow jj, H \rightarrow bb\) (top physics, Higgs, ...)

Particle identification:
- \(b/\text{jet separation}: \varepsilon(b) \approx 50\%\) \(R(\text{jet}) \approx 100\) (H \(\rightarrow bb, \text{SUSY, 3rd generation !!})
- \(\tau/\text{jet separation}: \varepsilon(\tau) \approx 50\%\) \(R(\text{jet}) \approx 100\) (A/H \(\rightarrow \tau\tau, \text{SUSY, 3rd generation !!})
- \(\gamma/\text{jet separation}: \varepsilon(\gamma) \approx 80\%\) \(R(\text{jet}) > 103\) (H \(\rightarrow \gamma\gamma\))
- \(e/\text{jet separation}: \varepsilon(e) > 70\%\) \(R(\text{jet}) > 105\) (inclusive electron sample)
The experimental challenges

2 Event rate and pile-up (high luminosity...)

Event rate in ATLAS, CMS:

\[ N = L \times \sigma_{\text{inelastic}}(\text{pp}) \approx 10^{34} \text{ cm}^{-2} \text{s}^{-1} \times 70 \text{ mb} \]

\[ \approx 10^9 \text{ interactions/s} \]

Proton bunch spacing: 25 ns

Protons per bunch: \(10^{11}\)

~ 20 inelastic (low-\(p_T\)) events (“minimum bias”) produced simultaneously in the detectors at each bunch crossing → pile-up

Impact of pile-up on detector requirements and performance:

-- fast response: \(\sim 50 \text{ ns}\)
-- granularity: > \(10^8\) channels
-- radiation resistance
  (up to \(10^{16}\) n/cm\(^2\)/year in forward calorimeters)
-- event reconstruction much more challenging than at previous colliders

H → bb event

ATLAS tracking

Track density in jet >> pile-up

H → bb event @ high luminosity
The experimental challenges

Huge (QCD) backgrounds (high energy ...)

No hope to observe light objects (W, Z, H ?) in fully-hadronic final states \( \rightarrow \) rely on \( l, \gamma \).

Fully-hadronic final states (e.g. \( q^* \rightarrow qg \)) can be extracted from backgrounds only with hard \( O(100 \text{ GeV}) p_T \) cuts \( \rightarrow \) works only for heavy objects.

Mass resolutions of \( \sim 1\% (10\%) \) needed for \( l, \gamma \) (jets) to extract tiny signals from backgrounds.

Excellent particle identification: e.g. \( e/jet \) separation.

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### Expected data samples (examples) with 100 pb\(^{-1}\)

<table>
<thead>
<tr>
<th>Channels (examples ...)</th>
<th>Events to tape for 100 pb(^{-1}) (ATLAS)</th>
<th>Total statistics from LEP and Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td>W (\rightarrow) (\mu\nu)</td>
<td>(\sim 10^6)</td>
<td>(\sim 10^4) LEP, (\sim 10^{6-7}) Tevatron</td>
</tr>
<tr>
<td>Z (\rightarrow) (\mu\mu)</td>
<td>(\sim 10^5)</td>
<td>(\sim 10^6) LEP, (\sim 10^{5-6}) Tevatron</td>
</tr>
<tr>
<td>(\tt\rightarrow WbWb\rightarrow\mu\nu+X)</td>
<td>(\sim 10^4)</td>
<td>(\sim 10^{3-4}) Tevatron</td>
</tr>
<tr>
<td>QCD jets (p_T &gt; 1) TeV</td>
<td>(&gt; 10^3)</td>
<td>(---)</td>
</tr>
<tr>
<td>(gg\ m = 1) TeV</td>
<td>(\sim 50)</td>
<td>(---)</td>
</tr>
</tbody>
</table>

#### Goals in 2008-2009:

1. **Commission and calibrate the detector in situ using physics samples**
   - e.g. - Z \(\rightarrow ee\), \(\mu\mu\) tracker, ECAL, Muon chamber calibration and alignment, etc.
   - \(\tt\rightarrow bl\nu bjj\) jet scale from W \(\rightarrow jj\), b-tag performance, etc.

2. **“Rediscover” and measure SM physics at \(\sqrt{s} = 14\) TeV (10TeV?)**
   - W, Z, \(tt\), QCD jets ... (also backgrounds to New Physics)

3. **Early discoveries?**
   - Potentially accessible: \(Z'\), SUSY, .... surprises?
$m_H < 130 \text{ GeV} : H \to bb, \tau\tau$ dominate

$\rightarrow$ best search channels at the LHC : $qqH \to qq\tau\tau, H \to \gamma\gamma, ttH \to lbbX$

$m_H > 130 \text{ GeV} : H \to WW^{(*)}, ZZ^{(*)}$ dominate

$\rightarrow$ best search channels at the LHC : $H \to ZZ^{(*)} \to 4l$ (gold-plated)
$H \to WW^{(*)} \to l\nu l\nu
Discovery potential in a complete mass range

\[ m_H \text{ (GeV)} \]

\[
\begin{align*}
L &\geq 1 \text{ fb}^{-1} \text{ for 95\% C.L. exclusion} \\
&\leq 5 \text{ fb}^{-1} \text{ for } 5\sigma \text{ discovery} \\
&\text{over full allowed mass range}
\end{align*}
\]

Final word about Higgs mechanism by 2010?

\[ \text{CMS, 30 fb}^{-1} \]

\[ \text{2003} \]

\[ \text{ATLAS + CMS} \]

(March 2006)

Needed \( |L dt| \text{ (fb}^{-1}) \)

of well-understood data

per experiment
The “gold plated” channel: $H \rightarrow ZZ(*) \rightarrow \ell\ell\ell\ell$

$\int L = 9.2 \, \text{fb}^{-1}$

Signal and background at $5\sigma$ discovery
The most difficult low-mass region: \( m_H \sim 115-150 \text{ GeV} \ldots \)

### ATLAS: \( m_H \sim 115 \text{ GeV} \)

- \( 10 \text{ fb}^{-1} : \frac{S}{\sqrt{B}} \approx 4-5.5 \)

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3 (complementary) channels with (similar) small significances:

1. **\( H \rightarrow \gamma\gamma \)**
   - \( S=130, B=4300, \frac{S}{\sqrt{B}}=2 \text{ - } 4.4 \)

2. **\( \text{ttH} \rightarrow \text{ttbb} \rightarrow \text{bl\ell} b\text{jjjb} \)**
   - \( \frac{S}{\sqrt{B}} \approx 2, \text{ being re-evaluated} \)

3. **\( \text{qqH} \rightarrow \text{qq}\tau\tau \)**
   - \( S=10, B=10, \frac{S}{\sqrt{B}}=2.7 \)

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- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - ECAL crucial for \( H \rightarrow \gamma\gamma \) (in particular response uniformity): \( \sigma/m \sim 1\% \) needed
  - b-tagging crucial for \( \text{ttH} \): 4 b-tagged jets needed to reduce combinatorics (background being re-evaluated)
  - efficient jet reconstruction over \( |\eta| < 5 \) crucial for \( \text{qqH} \rightarrow \text{qq}\tau\tau \):
    - forward jet tag and central jet veto needed against background

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All three channels require very good understanding of detector performance and background control to 1-10\% \( \rightarrow \) convincing evidence likely to come mid-end 2009 ...
More difficult channels

\[ qqH \rightarrow qq\tau\tau \rightarrow qq\ell\nu \tau\text{-had }\nu \]

Experimental challenges:

- identification of hadronic taus
- good \( p_T^{\text{miss}} \) resolution (tau mass reconstruction in collinear approximation)
- control of the \( Z\rightarrow\tau\tau \) background shape in the high mass region

\[ H \rightarrow \gamma\gamma \]

Experimental challenges:

- photon identification and \( \gamma\text{/jet} \) separation (calorimeter + tracker)
- mass resolution of the photon system
- low signal-to-background ratio
Measurements of the SM Higgs boson couplings

Mass will be measured with precision of 0.1% in mass range 130-450 GeV (gg, H→4l).

Angular distributions in H→4l sensitive to spin and CP eigenvalue.

Relative couplings will be measured with precision of 20% at 300fb-1.
What about the Tevatron experiments?

Today ~ 3 fb\(^{-1}\) /experiment

2009 expect 6-7 fb\(^{-1}\) /experiment

With 4 (8) fb\(^{-1}\):

~ no 5\(\sigma\) sensitivity 3\(\sigma\) evidence up to 120 (130) GeV
95\% C.L. exclusion up to ~ 130 (180) GeV
MSSM Higgs sector: $h, H, A, H^\pm$

$m_h < 135$ GeV, $m_A \approx m_H \approx m_{H^\pm}$

$A, H, H^+$ cross-sections $\sim \tan^2 \beta$

Best sensitivity from $A/H \rightarrow \tau\tau, H^+ \rightarrow \tau\nu$

Not easy the first year

$A/H \rightarrow \mu\mu$ experimentally easier specially for the beginning

Here only SM-like observable

If SUSY particles neglected

Also reevaluated with different SUSY "benchmark scenarios", CPX scenario, etc.
MSSM Higgs sector: $h, H, A, H^\pm$

$m_h < 135$ GeV, $m_A \approx m_H \approx m_{H^\pm}$

$H, A \rightarrow \mu\mu, \tau\tau$

$H^\pm \rightarrow \tau\nu, tb$

Here only $h$ (SM-like) observable at LHC, unless $A, H, H^\pm \rightarrow$ SUSY
$\rightarrow$ LHC may miss part of the MSSM Higgs spectrum
Observation of full spectrum may require high-$E$ ($\sqrt{s} \approx 2$ TeV) Lepton Collider

Assuming decays to SM particles only
What about the Tevatron experiments?

MSSM Higgs bosons
\( b\bar{b}\psi \rightarrow b\bar{0}, \; \phi = h, H, A \)

LHC prospects (10 fb\(^{-1}\))
The road path for Higgs boson discovery

The large number of channels and scenarios studied demonstrate the detector sensitivity to many signatures \(\rightarrow\) robustness, ability to cope with unexpected scenarios

**With the very first collision data (\(\leq 100 \text{ pb}^{-1}\))**

Commission/calibrate the detectors in situ in the LHC environment, tune the software tools (simulation, reconstruction, etc.)

Perform first physics measurements of Standard Model processes: e.g. cross-sections for W, Z, top, QCD jets with 10-30% precision;

**Much more luminosity (at least 1 fb-1) will be needed to:**

Discover a SM Higgs boson (<10 fb-1) [watch the Tevatron ...]

Completely cover parameter space of the MSSM Higgs bosons
The LHC experiments are well set up to explore the existence of a Standard Model or MSSM Higgs bosons and are well prepared for unexpected scenarios.

The full Standard Model mass range and the full MSSM parameter space can be covered (CP conserving case).

In addition, important parameter measurements (mass, spin, ratio of couplings) can be performed (vector boson fusion processes important).

More difficult:
- invisible Higgs boson decays or NMSSM models
- measurement of the Higgs boson self–coupling

LHC data will hopefully soon give guidance to the theory and to future experiments.
The first Higgs in ATLAS ... (4th April 2008)

P.W.Higgs