Higgs Searches at the LHC: Challenges, Prospects, and Developments

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March 14, 2006
University of Pennsylvania Seminar

Outline
- Introduction to SM and MSSM Higgs Sector
- Overview of progress in recent years
- LHC discovery and measurement potential
- Timeline for the Near Future and Distant Future
The *Standard Model* of particle physics is a particular Quantum Field Theory that represents our best understanding of particles and their interactions.

The standard model is very predictive and has survived numerous precise tests over the years.

The only particle of the standard model that we have not observed is the Higgs boson.

Despite its success, we have reason to believe that it is not the whole story: we expect that there will be some deviation from the standard model near the TeV energy scale.

Physics beyond the standard model includes: SuperSymmetry (SUSY), extra space-time dimensions, new high-mass resonances, etc.

The Large Hadron Collider (LHC) at CERN and the two large multi-purpose detectors (ATLAS and CMS) have been built specifically to find the standard model Higgs boson (if it exists) and explore the theoretical landscape of beyond the standard model.
The Higgs mechanism provides a gauge invariant theory of Electroweak interactions with massive $W^\pm$ and $Z$ bosons

Spontaneous Symmetry Breaking
$\Rightarrow$ Goldstone Bosons
$\Rightarrow$ longitudinal states of $W^\pm$ and $Z$

Theory predicts:
- $g_{HWW} \propto m_W$
- $g_{Hff} \propto m_f$
- $g_{HHH} \propto m^2_H/m_w$
- $g_{HHHH} \propto m^2_H/m^2_W$

$\mathcal{L}_{\text{Higgs}} = (\partial_{\mu} \phi)^\dagger (\partial^\mu \phi) - V(\phi)$

$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$

The Higgs Mass is unknown in the S.M., but expected to be $\lesssim 1$ TeV
MSSM Motivation

While the standard model Higgs gives us massive $W^\pm$ and $Z$ bosons, it also introduces quadratic divergences in the Higgs’ self energy.

One solution is to introduce Supersymmetry, which provides a fermion ↔ boson symmetry, new loops, and $\pm 1$ factors that cancel the divergences exactly.

Because we have not observed SUSY partners, SUSY must be broken in nature.

MSSM parametrizes soft SUSY-breaking terms with 105 parameters.

$m$SUGRA, $m$AMSB, $m$GMSB, etc. are specific, well-motivated theories with fewer parameters and restricted phenomenology.
The MSSM requires two Higgs doublets, which give rise to 5 physically observable Higgs bosons: $h$, $H$, $A$, and $H^\pm$.

Unlike the SM, there is a theoretical limit on the mass of the lightest Higgs $M_h < 135$ GeV

The MSSM Higgs sector is usually parametrized by $M_A$ and $\tan\beta = v_1/v_2$

The $h$ and $H$ bosons are standard-model-like with couplings modified by functions like $\cos(\beta - \alpha)$ and $\cos(\alpha)/\cos(\beta)$.

Thus, most standard model Higgs searches can be reinterpreted in the MSSM Higgs sector (using tools like FeynHiggs)
Motivation for a Light Higgs

Electroweak precision measurements are indirectly sensitive to the Higgs mass through radiative corrections that go like \( \propto \log(m_H) \).

Revised top mass measurements from Tevatron prefer a lighter Higgs.

LEP Electroweak Fits limit: \( m_H < 186 \) GeV at 95% Confidence.
Results from direct searches for the Higgs at LEP:

**ALEPH** observed an excess of events in $e^+e^- \rightarrow 4\text{jet}$ channel, but no discovery

LEP direct search limit places $M_H > 114.4$ GeV at 95% Confidence

The low mass region is very exciting and very challenging for the LHC!
CDF RunI 106 pb⁻¹
(PRL, hep-ex/0503039)

A factor of >25 from S.M.

CDF & Dφ closing in on Standard Model with RunII
Improvements Underway

Identified potential to approach SM cross section exclusions

<table>
<thead>
<tr>
<th>Improvement</th>
<th>WH→lνb̄b</th>
<th>ZH→ννb̄b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass resolution</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Continuous b-tag (NN)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Forward b-tag</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Forward leptons</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Track-only leptons</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>NN Selection</td>
<td>1.75</td>
<td>1.75</td>
</tr>
<tr>
<td>WH signal in ZH</td>
<td>1.0</td>
<td>2.7</td>
</tr>
<tr>
<td>CDF+DØ combination</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Tools common to CDF analyses

Analysis-specific improvements

And don’t forget factor of 10 more data!

Challenge to develop and apply improvements to Higgs searches

J. Nielsen
- Gluon-Gluon Fusion dominant production process.
- Vector Boson Fusion ($Hqq$) $\approx 20\%$ of $gg$ at 120 GeV
- Associated production with $W, Z$ and heavy quarks have small rate, but can provide trigger independent of $H$ decay
- For $m_H < 2m_W$ Higgs mainly decays to fermions
- Couplings $\propto m_f$, so look for $H \to bb, \tau\tau$
- $BR(H \to bb)$ dominant at low mass, but need trigger
- $H \to ZZ \to 4l$ and $H \to \gamma\gamma$ gold-plated channels
The ATLAS Detector

- Length $\approx 40$ m
- Radius $\approx 10$ m
- Weight $\approx 7000$ tons
- $\#$ Readout Channels $\approx 10^8$

Sub-detector Highlights

- Tracker: Si pixels + strips + Transition Radiation Tracker (TRT), $B=2T$
  $\sigma/p_T \approx 5 \cdot 10^{-4} p_T \oplus 0.01$
- EM Calorimeter: Pb - liquid Ar
  $\sigma/E \approx 10\%/\sqrt{E}$
- Hadronic Calorimeter:
  Fe-scint + Cu-liquid Ar ($10\lambda$)
  $\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$
- Muon Detectors:
  $\sigma/p_T \approx 10\%$ at 1 TeV
- Non-compensating calorimeter:
  $e/h \sim 1.3$

The ATLAS detector is a multipurpose detector...
flexible enough for the surprises which may lie ahead!

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Higgs Searches at the LHC:
Challenges, Prospects, and Developments  (page 12)
The CMS Detector

Superconducting Coil, 4 Tesla

Calorimeters
- ECAL
  - 76k scintillating PbWO4 crystals
  - 2007: no endcap ECAL (installed during 1st shutdown)
- HCAL
  - Plastic scintillator/brass sandwich

Iron Yoke

Tracker
- Pixels
- Silicon Microstrips
  - 210 m² of silicon sensors
  - 9.6M channels
  - 2007: no pixels (installed during 1st shutdown)

Muon Barrel
- Drift Tube Chambers (DT)
- Resistive Plate Chambers (RPC)

Muon Endcaps
- Cathode Strip Chambers (CSC)
- Resistive Plate Chambers (RPC)

Level-1 Trigger Output
- 2007: 50 kHz (instead of 100)
- 2007: RPC $|\eta| < 1.6$ instead of 2.1 & 4th endcap layer missing

W. Smith, U. Wisconsin, ILC Workshop, Snowmass, August 17, 2005

LHC & SLHC Physics & Detectors - 4
The LHC

- 26 km in circumference
- p-p @ $\sqrt{s} = 14$ TeV
- Instantaneous Luminosity
  $\approx 10^{33} - 10^{34}$ cm$^{-2}$s$^{-1}$
- “pile-up” : 2-20 inelastic collisions per bunch crossing
- 40 MHz bunch crossings
The ATLAS trigger is based on a 3-level design:

- **Level 1** is in hardware.
- **Level 2 & Event Filter** are called “High-Level Trigger” implemented in software.

**Level 2** constrained to “Regions of Interest”, Event Filter has access to entire event.

Output rate $\sim 200$ Hz. Event Size $\sim 2$MB.
The Analyses
- Excellent EM Calorimetry needed for $\Delta M_H / M_H \approx 1\%$

- Excellent $\gamma$/jet separation needed

- Convincing signal with sideband subtraction

- Often associated with a hard jet (or 2 à la VBF), which can be used to improve S/B & reduce sensitivity to systematics
Example Analyses: $H \rightarrow ZZ \rightarrow 4l$

Considered the “golden channel”

- Powerful if $m_H > 130$ GeV
- Recent analyses use MC@NLO for Signal & Background
- Provides precise mass determination

Event Display for $H \rightarrow ZZ \rightarrow 2e2\mu$

ATLAS + CMS
\[ \int L \, dt = 300 \, fb^{-1} \]
Example Analyses: $H \to ZZ \to 4l$

Considered the “golden channel”

- Powerful if $m_H > 130$ GeV
- Provides spin and CP measurement

Event Display for $H \to ZZ \to 2e2\mu$

Figure 9: The overall significance for the exclusion of the non-standard spin and CP eigenvalue. The significance from the polar angle measurement and the decay plane correlation are plotted separately.
Recent Progress

Additional Channels:
- ATLAS & CMS included VBF $H \rightarrow WW$ and VBF $H \rightarrow \tau\tau$ channels
- Corresponding updates to SUSY scans & coupling measurements
- Many new channels under investigation: $ttH(H \rightarrow WW, \tau\tau)$; $ZH(H \rightarrow \gamma\gamma)$; etc.

Improved Monte Carlo:
- NLO & NNLO x-sec. generators (MCFM, PHOX, etc.) and event generators (MC@NLO)
- Higher-order tree-level generators (MadEvent, Alpgen, etc.)
- Matrix Element - Parton Shower matching (CKKW, MLM, Sherpa, etc.)
- New Underlying Event & Min-Bias tunings (Pythia, Jimmy)

Improved Realism in Simulation:
- Most channels studied with Geant3 or Geant4 and use real reconstruction algorithms
- Studies with Pile-up, underlying event, electronic noise, cavern background, etc.
- Determine background control samples from data, estimation of systematics, etc.
Higgs Discovery Potential 1999 → 2003

![Signal significance vs. m_H (GeV)](image)

**Higgs Potential in ATLAS TDR (1999)**

![Signal significance vs. m_H (GeV)](image)

Addition of Vector Boson Fusion Channels at Low mass SN-ATLAS-2003-024

Both ATLAS and CMS cover entire SM Higgs mass range early in LHC running

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Higgs Searches at the LHC:
Challenges, Prospects, and Developments (page 22)

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**VBF H → WW → llνν: Scientific Note Results**

<table>
<thead>
<tr>
<th></th>
<th>signal (fb)</th>
<th>background (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VV</td>
<td>gg</td>
</tr>
<tr>
<td>Lepton acceptance</td>
<td>5.20</td>
<td>17.30</td>
</tr>
<tr>
<td>+ Forward Tagging</td>
<td>1.85</td>
<td>0.27</td>
</tr>
<tr>
<td>+ Lepton angular cuts</td>
<td>1.36</td>
<td>0.18</td>
</tr>
<tr>
<td>+ $\tau$ rejection</td>
<td>1.27</td>
<td>0.18</td>
</tr>
<tr>
<td>+ Jet mass</td>
<td>0.88</td>
<td>0.08</td>
</tr>
<tr>
<td>+ $p_T^{jet}$</td>
<td>0.68</td>
<td>0.05</td>
</tr>
<tr>
<td>+ Jet veto</td>
<td>0.59</td>
<td>0.05</td>
</tr>
<tr>
<td>+ $m_T(\ell\ell\nu)$-cut</td>
<td>0.52</td>
<td>0.05</td>
</tr>
</tbody>
</table>

$H → WW^{(*)} → e\mu + X$ | 0.52 | 0.05 | 0.58 | 0.27 | 0.03 | 0.02 | 0.05 | 0.95 |

$H → WW^{(*)} → ee/\mu\mu + X$ | 0.50 | 0.04 | 0.58 | 0.30 | 0.03 | 0.03 | 0.39 | 1.33 |

- Based on work of Rainwater, Zeppenfeld in 1999-2000 (hep-ph/9906218)
- Used fast simulation (90% lepton efficiency) & LO $t\bar{t}$ M.C.
- Can’t reconstruct $m_H$, only “transverse mass” $m_T$
- Dominated by irreducible $t\bar{t}$ + jets and $WW$ + jets background
- Possible discovery channel for $M_H > 125$ GeV with 30 fb$^{-1}$
To evaluate VBF channels, need $Zjj$, $WWjj$, & $t\bar{t}j$ matrix element for high-$p_T$ forward jets.

Parton-Shower severely under-estimates high-$p_T$ tail.

For ATLAS scientific note, we worked with Zeppenfeld to interface background Matrix Element code to Showering & Hadronization generators like PYTHIA and HERWIG (MadCUP).

Now we mainly rely on general purpose tools like MadEvent, Alpgen, & Sherpa.
Uses of Multivariate Methods

Complex final state of VBF $H \rightarrow WW \rightarrow llE_T^{miss}$ well-suited for multivariate methods

Used 7 variables:
$\Delta\eta_{ll}, \Delta\phi_{ll}, M_{ll}, \Delta\eta_{jj}, \Delta\phi_{jj}, M_{jj}, M_T$

Compared Neural Networks, Genetic Programming, and Support Vector Regression

<table>
<thead>
<tr>
<th>Ref. Cuts</th>
<th>low-$m_H$ Cuts</th>
<th>NN</th>
<th>GP</th>
<th>SVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 ee</td>
<td>0.87</td>
<td>1.72</td>
<td>1.66</td>
<td>1.44</td>
</tr>
<tr>
<td>120 e(\mu)</td>
<td>2.30</td>
<td>3.92</td>
<td>3.60</td>
<td>3.33</td>
</tr>
<tr>
<td>120 (\mu)(\mu)</td>
<td>1.16</td>
<td>2.28</td>
<td>2.26</td>
<td>2.08</td>
</tr>
<tr>
<td>Combined</td>
<td>2.97</td>
<td>4.98</td>
<td>4.57</td>
<td>4.26</td>
</tr>
<tr>
<td>130 e(\mu)</td>
<td>4.94</td>
<td>7.55</td>
<td>7.22</td>
<td>6.59</td>
</tr>
</tbody>
</table>

Table 1: Expected significance in sigma after 30 fb$^{-1}$ for two cut analyses and three multivariate analyses for different Higgs masses and final state topologies.
The VBF $H \rightarrow \tau\tau$ channel and Why It’s Important

Standard Model (Atlas Scientific Note)
Most powerful channel near LEP limit and very important for MSSM.

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Challenges, Prospects, and Developments (page 26)

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**VBF $H \rightarrow \tau\tau$: Scientific Note Results**

Based on work of Rainwater, Zeppenfeld, Hagiwara, Plehn in 1999-2000

- Used fast simulation: 90% lepton efficiency, parametrized $\tau$-id, etc.
- Possible discovery channel for $M_H = 115$-140 GeV with 30 fb$^{-1}$
- Dominated by irreducible $Z \rightarrow \tau\tau$ background
Simulating The ATLAS Detector

**ATLFAST**

- Parametrized Resolutions & Particle Identification Efficiency

**GEANT**

- Detailed Showering Model, Simulation of Detector Electronics

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MissingET is the dominant experimental issue

Unexpected complications from finely segmented calorimeter and noise suppression

Several GeV of bias in MissingET if one simply cuts all cells with $E < 2\sigma_{\text{noise}}$

Translates into bias on $m_{\tau\tau}$
Mass Reconstruction:

- Observe missing transverse momentum and visible Tau–decay products
- Assume Tau decay products collinear with original Tau
- Solve 2 linear equations for the neutrinos
- Taus can be reconstructed
- Higgs can be reconstructed

Some Comments:

- After jet cuts, $M_{\tau\tau}$ is the only discrimination we use between $Z \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$
- Collinear approximation doesn’t take into account MissingET resolution
- Define $x_{\tau}$: fraction of τ’s momentum in visible decay product

$$x_{\tau h} = \frac{h_x l_y - h_y l_x}{h_x l_y + p_x l_y - h_y l_x - p_y l_x}$$

$$x_{\tau l} = \frac{h_x l_y - h_y l_x}{h_x l_y - p_x h_y - h_y l_x + p_y h_x}$$

$$M_{\tau\tau} = \sqrt{2(E_h + E_{\nu h})(E_l + E_{\nu l})(1 - \cos \theta_{\tau\tau})}$$ is equivalent to

$$M_{\tau\tau} = \frac{M_{ll}}{\sqrt{x_{\tau l}x_{\tau h}}}$$ only when $0 < x_{\tau} < 1$
We Observe MissingET and visible $\tau$ decay products. From $\sum |E_T|$ we know $1\sigma$ MissingET contour.

Assuming $\nu$’s collinear with $\tau$’s the MissingET can be
- Constrained to Hypothesized Higgs Mass
- Constrained to Z Mass
- $x_{\tau\ell} = (M_{ll}^2/M_0^2) / x_{\tau h}$

Kinematic fits can be used to find hypothetical MissingET most consistent with observed MissingET and mass constraint. Each has it’s own $\chi^2$.

Finally, $\Delta \chi^2$ quantifies if event is more consistent with $H \rightarrow \tau\tau$ or $Z \rightarrow \tau\tau$.

Leads to a low- and high-purity sample. Preliminary results very promising.
Progress on Systematics
**ttH(H → bb)**


Combinatorial background is challenging with 4b-jets and ≥ 6 jets total

Signal efficiency goes like $\epsilon_b^A$

Signal & bkgnd. have similar shape

Estimating $ttjj$ and $ttbb$ background from data difficult, large systematics

- This is (was) one of the few powerful channels near the LEP limit

- Do ATLAS and CMS results agree?

It’s not clear if this channel will ever reach 5σ
A note on systematic errors

Background determination from sidebands carries two sources of error:

- Class I: statistical error from sideband measurement
- Class II: systematic on extrapolation from sideband to signal-like area (shape systematic)

The shape systematic does not (necessarily) reduce with increased luminosity

Normal significance measure $s/\sqrt{b}$ is replaced by $s/\sqrt{b(1 + b\Delta^2)}$

If $s/b$ is fixed as we increase luminosity, the expected significance saturates:

$$\sigma_\infty = \frac{s/b}{\Delta_{shape}}$$

With its low $S/B$ and 10% shape systematic, $ttH(\rightarrow bb)$ can't get to 5$\sigma$ even with $L \rightarrow \infty$
The $H \to \gamma\gamma$ Example

Systematic Error on background for $H \to \gamma\gamma$ usually considered negligible. S. Paganis & I Tested background prediction from side-band with ToyMC.

$$\frac{d\sigma}{dM_{\gamma\gamma}} = N \ e^{-aM_{\gamma\gamma}}$$

$$\tau = \frac{\sigma_{SB}}{\sigma_{sig}}$$

$\sigma_{SB}$, $\sigma_{sig}$

Systematic Error is small, but not negligible:

$$N\sigma \approx \frac{S}{\sqrt{b + (\delta b)^2}} \rightarrow \frac{S}{\sqrt{b}\sqrt{1 + 1/\tau}}$$
At PhyStat2003, Sinervo provided a classification of systematic errors.

The background uncertainty discussed on previous slide is another statistical error (Class I).

In the $H \rightarrow \gamma \gamma$ example, there is also uncertainty on the shape of the continuum $M_{\gamma\gamma}$ spectrum.

These shape uncertainties impact the background prediction from the sideband, and do not scale like statistical errors (Class II).

Class II systematics under investigation for $H \rightarrow \gamma \gamma$.
At PhyStat2005, I compared the most common statistical methods to incorporate background uncertainty in significance calculation.

Simple example where:
- sideband is same size as signal-like region
- truth = 100 background events

$x = \text{events in signal like region}$

$y = \text{sideband measurement} = \text{background estimate}$

$\text{lines = discovery criterion}$

Clearly the background uncertainty needs to be incorporated

Large variation in discovery criterion ($\pm 15$ events), and most give too many discoveries when signal is absent

(ovals indicate contours of true pdf)
Coupling Measurements
Assume CP-even, spin-0, only one Higgs

Ratios of partial widths to within 20% with 30 fb$^{-1}$

Weak assumptions:
$g(H, V) < 105\% g(H, V, SM)$ allow for unobserved decays & new loops

Absolute couplings measured to within 10% with 2×300 fb$^{-1}$
**Table 2:** Theoretical QCD and PDF uncertainties on the various Higgs boson production channels. The channel $gg \rightarrow Hgg$ was added to all WBF analyses at 10\% of the WBF rate with an uncertainty of a factor 2.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF</td>
<td>20%</td>
</tr>
<tr>
<td>$ttH$</td>
<td>15%</td>
</tr>
<tr>
<td>$WH$</td>
<td>7%</td>
</tr>
<tr>
<td>$ZH$</td>
<td>7%</td>
</tr>
<tr>
<td>WBF</td>
<td>4%</td>
</tr>
<tr>
<td>$gg \rightarrow Hgg$</td>
<td>100%</td>
</tr>
</tbody>
</table>

$\Delta \phi_{jj}$ can be used to fit relative contribution from $gg \rightarrow Hgg$

Should reduce systematic error considerably.
The Near Future:

The Timeline for Startup
Even including our (naive?) estimates of systematics, the standard model Higgs can be discovered with 1-15 fb\(^{-1}\) of data.

Of course, that’s well understood data. How long will that take?
Examples from Atlas Cosmic Ray Commissioning

TileCal:

Cosmic Ray Commissioning: First with Individual Subdetectors

Muon chambers underground

First muons in TRT on surface
Timeline for the LHC Commissioning

- Physics running: 140 days/year
- ATLAS/CMS running: ~100 days/year
- Typical efficiency for physics: 40%
- Effective ATLAS/CMS running time/year: ~1000 hours \(\sim 4 \times 10^6 \text{s} \sim 4 \times 10^{38} \text{cm}^{-2} \sim 4 \times 10^{14} \text{b}^{-1} = 400 \text{pb}^{-1} @ 10^{32}\text{cm}^{-2}\text{s}^{-1}
- Note that the schedule below [R. Bailey, LHCAC, 6/5/05] is “all goes well” scenario

<table>
<thead>
<tr>
<th>Year</th>
<th>Pilot Run</th>
<th>2008, 75/25ns</th>
<th>2009, 25ns</th>
<th>2010, 25ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>L~5\times10^{30} \text{cm}^{-2}\text{s}^{-1} \text{Ldt} ~20 \text{pb}^{-1}</td>
<td>L~3\times10^{32} \text{cm}^{-2}\text{s}^{-1} \text{Ldt} ~1.2 \text{fb}^{-1}</td>
<td>L~1\times10^{33} \text{cm}^{-2}\text{s}^{-1} \text{Ldt} ~4 \text{fb}^{-1}</td>
<td>L~1\times10^{34} \text{cm}^{-2}\text{s}^{-1} \text{Ldt} ~40 \text{fb}^{-1}</td>
</tr>
</tbody>
</table>

Aspen 2005 Workshop
Greg Landsberg, The First Three Years: Before the Champagne?
The Distant Future:

An LHC Upgrade
What the LHC Will & Won’t Do

Will Do

**Discovery of SM Higgs:**
- SM Higgs could be discovered over full mass range with 30 fb$^{-1}$
- Several Channels Available, VBF a big improvement

**Measurements of Higgs Parameters:**
- Masses 0.1 - 1%
- Ratios of Widths 10-60%
- Couplings 15-50%

**MSSM Higgs:**
- Cover most of $M_A - \tan \beta$ plane in ~ 1 year
- Many prospects to distinguish SM from MSSM Higgs sectors (eg. charged Higgs)

Won’t Do

**At All:**
- Measurements of Higgs Self-Coupling
- Observe/Discover $H \rightarrow \mu \mu$?

**In Some Cases:**
- Distinguish SM from MSSM Higgs Sector (small $\tan \beta$)

**As Well as SLHC:**
- Coupling Measurements
- Rare Decays $H \rightarrow \mu \mu$
Super-LHC

$H \rightarrow ZZ \rightarrow e\mu e\mu$

10$^{33}$ cm$^{-2}$s$^{-1}$

10$^{34}$ cm$^{-2}$s$^{-1}$

10$^{35}$ cm$^{-2}$s$^{-1}$

See Wesley Smith’s talk:
http://cmsdoc.cern.ch/cms/TRIDAS/tr/0508/SmitHLHC_SLHC_Aug05.pdf

(1) **LHC IR quads life expectancy** estimated <10 years from radiation dose
(2) the **statistical error halving time** will exceed 5 years by 2011-2012
(3) therefore, it is reasonable to plan a **machine luminosity upgrade based on new low-β IR magnets before ~2014**

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SLHC will significantly improve coupling measurements.

By the end of the LHC, we should understand forward jets and central jet veto much better!

Many new channels since this study, should be revisited.
Use of $H/A \rightarrow$ SUSY particles is model dependent.

$H/A \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l$ contributes in the region where only $h$ is seen decaying to SM particles

$\downarrow$ SLHC can extend discovery potential for $H/A \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l$

example:
MSSM parameters: $M_a = 120 \text{ GeV}$, $M_1 = 60 \text{ GeV}$, $\mu = -500 \text{ GeV}$,
m(sleptons) = 250 GeV, m(squarks, gluinos) = 1 TeV

$\uparrow$ SLHC extends discovery potential for Heavy Higgs.
Interference between diagrams important
Variation in trilinear self-coupling dominates
No hope of measuring quartic self-coupling at SLHC or VLHC
Summary

If the standard model Higgs is there, we should discover it relatively early at the LHC.

Several channels are available: opportunity to measure Higgs couplings to 15-50%.

Recent effort is a mix of theoretical developments, improved realism in detector simulation, and more sophisticated analysis techniques.

Most of the SUSY Higgs plane is covered by the LHC under most well-motivated scenarios.

LHC will not observe Higgs self-coupling. Many measurements and discovery reach are statistics-limited. ⇒ motivation for a luminosity upgrade: “SuperLHC”

We have lots to do before turn-on!
Backup
Staged commissioning plan for protons

I. Pilot physics run
   - First collisions
   - 43 bunches, no crossing angle, no squeeze, moderate intensities
   - Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
   - Performance limit $10^{32}$ cm$^2$ s$^{-1}$ (event pileup)

II. 75ns operation
   - Establish multi-bunch operation, moderate intensities
   - Relaxed machine parameters (squeeze and crossing angle)
   - Push squeeze and crossing angle
   - Performance limit $10^{33}$ cm$^2$ s$^{-1}$ (event pileup)

III. 25ns operation I
   - Nominal crossing angle
   - Push squeeze
   - Increase intensity to 50% nominal
   - Performance limit $2 \times 10^{33}$ cm$^2$ s$^{-1}$

IV. 25ns operation II
   - Push towards nominal performance
### Stage I physics run

- Start as simple as possible
- Change 1 parameter \((k_b, N, \beta^* 1, 5)\) at a time
- All values for
  - nominal emittance
  - 7TeV
  - 10m \(\beta^*\) in point 2 (luminosity looks fine)

### Table: Parameters and Beam Levels

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k_b)</td>
<td>(</td>
<td>N</td>
<td>)</td>
</tr>
<tr>
<td>1</td>
<td>(10^{10})</td>
<td>18</td>
<td>(1 \times 10^{10})</td>
</tr>
<tr>
<td>43</td>
<td>(10^{10})</td>
<td>18</td>
<td>(4.3 \times 10^{11})</td>
</tr>
<tr>
<td>43</td>
<td>(4 \times 10^{10})</td>
<td>18</td>
<td>(1.7 \times 10^{12})</td>
</tr>
<tr>
<td>43</td>
<td>(4 \times 10^{10})</td>
<td>2</td>
<td>(1.7 \times 10^{12})</td>
</tr>
<tr>
<td>156</td>
<td>(4 \times 10^{10})</td>
<td>2</td>
<td>(6.2 \times 10^{12})</td>
</tr>
<tr>
<td>156</td>
<td>(9 \times 10^{10})</td>
<td>2</td>
<td>(1.4 \times 10^{13})</td>
</tr>
</tbody>
</table>

### Notes:
- Protons/beam \(\leq 10^{13}\) (LEP beam currents)
- Stored energy/beam \(\leq 10\text{MJ}\) (SPS fixed target beam)
Stage II physics run

- Relaxed crossing angle (250 μrad)
- Start un-squeezed
- Then go to where we were in stage I
- All values for
  - nominal emittance
  - 7TeV
  - 10m $\beta^*$ in points 2 and 8

Protons/beam $\approx$ few $10^{13}$

Stored energy/beam $\leq$ 100MJ

---

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2 and 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_b$</td>
<td>$N$</td>
<td>$\beta^* 1,5$ (m)</td>
<td>$I_{beam}$ (proton)</td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>18</td>
<td>$3.7 \times 10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>2</td>
<td>$3.7 \times 10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>1</td>
<td>$3.7 \times 10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$9 \times 10^{10}$</td>
<td>1</td>
<td>$8.4 \times 10^{13}$</td>
</tr>
</tbody>
</table>
### Stage III physics run

- Nominal crossing angle (285 μrad)
- Start un-squeezed
- Then go to where we were in stage II
- All values for
  - nominal emittance
  - 7TeV
  - 10m $\beta^*$ in points 2 and 8

$$L = \frac{N^2 k_0 f \gamma}{4 \pi e^2 \beta} F$$

$$F = 1 / \sqrt{1 + \left(\frac{\epsilon_1 \Delta_z}{2 \sigma^2}\right)^2}$$

**Eventrate / Cross** = \( \frac{L \sigma_{tot}}{k_1 f} \)

### Parameters & Beam levels

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2 and 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_0$</td>
<td>$N$</td>
<td>$\beta^*$ 1,5 (m)</td>
<td>$l_{beam}$ proton</td>
</tr>
<tr>
<td>2808</td>
<td>$4 \times 10^{10}$</td>
<td>18</td>
<td>$1.1 \times 10^{14}$</td>
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<tr>
<td>2808</td>
<td>$4 \times 10^{10}$</td>
<td>2</td>
<td>$1.1 \times 10^{14}$</td>
</tr>
<tr>
<td>2808</td>
<td>$5 \times 10^{10}$</td>
<td>2</td>
<td>$1.4 \times 10^{14}$</td>
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<td>0.55</td>
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</tr>
<tr>
<td>Nominal</td>
<td></td>
<td></td>
<td>$3.2 \times 10^{14}$</td>
</tr>
</tbody>
</table>

Protons/beam ≈ $10^{14}$

Stored energy/beam ≈ 100MJ
**Multivariate Analysis vs. Event Weighting**

In addition to multivariate techniques, the most powerful search considers:

\[
\text{Likelihood of experiment} = \prod \text{likelihood of each event}
\]

This was done by LEP Higgs WG and follows from the Neyman-Pearson Lemma.

Essentially, weight each event by \( \log(1 + s/b) \)
Migrating LEP Statistics to the LHC

LEP Higgs Working group developed formalism to combine channels and take advantage of discriminating variables in the likelihood ratio.

\[
Q = \frac{L(x|H_1)}{L(x|H_0)} = \frac{\prod_{i}^{N_{chan}} \text{Pois}(n_i|s_i+b_i) \prod_{j}^{n_i} \frac{s_i f_s(x_{ij}) + b_i f_b(x_{ij})}{s_i+b_i}}{\prod_{i}^{N_{chan}} \text{Pois}(n_i|b_i) \prod_{j}^{n_i} f_b(x_{ij})}
\]

\[
q = \ln Q = -s_{tot} \sum_{i}^{N_{chan}} \sum_{j}^{n_i} \ln \left(1 + \frac{s_i f_s(x_{ij})}{b_i f_b(x_{ij})}\right)
\]

Hu and Nielsen’s CLFFT used Fourier Transform and exponentiation trick to transform the log-likelihood ratio distribution for one event to the distribution for an experiment.

Cousins-Highland was used for systematic error on background rate.

Getting this to work at the LHC is tricky numerically because we have channels with \(n_i\) from 10-10000 events (physics/0312050)
Complementarity of VBF $h \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ covers almost all the plane not excluded by LEP

Also shown:
- VBF $h \rightarrow WW$
- VBF $H \rightarrow WW$

There are more recent ATLAS results from M. Schumacher (with systematic errors), but they are still preliminary.