Higgs Searches with the ATLAS Experiment at the LHC

Bruce Mellado
University of Wisconsin-Madison

Finding the Light, Hidden Higgs, UCD
03/08/08
Outline

Introduction

Most relevant observation channels (SM)
- $H \rightarrow \gamma \gamma$
- $H \rightarrow \tau \tau$
- $H \rightarrow Z Z(\*) \rightarrow 4l$
- $H \rightarrow W W(\*) \rightarrow l l \nu \nu$

MSSM Higgs
- What can the Tevatron tell us?
- Feasibility of searches

Focus on what we can do with 10 fb$^{-1}$ of data at the LHC
A Higgs boson in predicted and required to give mass to particles.
What is the origin of the particle masses?

Why some particles are heavier than others?

The discovery of the Higgs boson should answer these questions.
The Quest for the Higgs

Experimentalists have been looking for the Higgs since the 70’s and 80’s in decays of nuclei, $\pi$, $K$, $B$, $Y$, etc... yielding mass limit <5 GeV

One of the goals of the LEP experiments ($e^+e^-$ collisions 1989-2000) was to search for a Higgs boson. The most stringent limit to date comes from the LEP experiments
LEP Higgs Searches ($M_H=115$)

- $b \bar{b}$, $q \bar{q}$, $e^+e^- \rightarrow HZ$, $q\bar{q}$, $b\bar{b}$, $\approx 54\%$ of Total
- $\nu \bar{\nu}$, $q \bar{q}$, $e^+e^- \rightarrow HZ$, $\nu\bar{\nu}$, $q\bar{q}$, $\approx 15\%$
- $\ell \ell$, $q \bar{q}$, $e^+e^- \rightarrow HZ$, $\ell^+\ell^-$, $q\bar{q}, \tau^+\tau^-$, $\approx 5\%$ ($\ell^\pm = e^\pm \mu^\pm$)
- $e^+e^- \rightarrow HZ$, $\tau^+\tau^-$, $q\bar{q}$, $\approx 2.6\%$
- $e^+e^- \rightarrow HZ$, $\tau^+\tau^-$, $q\bar{q}$, $\theta^+\theta^-$, $\approx 5\%$
First Possible Hint for a Higgs boson (2000)

ALEPH observed three golden candidates in the four-jet channel

Input $M_H = 115 \text{GeV}/c^2$
The LEP Limit

ALEPH observed an excess over background-only prediction with significance of $2.8\sigma$ at 115 GeV/$c^2$

Overall significance of LEP experiments $\sim 1.8\sigma$ → limit setting $M_H > 114.4$
Electro-Weak Fits

Experimental constraints so far:

- Indirect measurements from fitting the EW data using new world average for $M_{\text{top}}=170.9\pm1.8$ GeV and $M_w=80.398\pm0.025$ GeV:
  - $m_H = 76^{+33}_{-24}$ GeV
  - $m_H < 144$ GeV @ 95%CL (including LEP exclusion $m_H < 182$ GeV)

Data prefers low mass Higgs
Present Tevatron Exclusion Limit

Note: the combined result is essentially equivalent to one experiment with 1.3 fb\(^{-1}\), since both experiments have "complementary" statistics at low and high mass.
The LHC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of mass $E$</td>
<td>14 TeV</td>
</tr>
<tr>
<td>Design Luminosity</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Luminosity Lifetime</td>
<td>10 h</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns</td>
</tr>
</tbody>
</table>
LHC Discovery Reach

Approximate discovery reach for one Experiment

Bruce Mellado, UCD 03/08/08
Higgs Production at LHC

**Leading Process (gg fusion)**

**Sub-leading Process (VBF)**

![Diagram showing gg fusion and VBF processes]

- **Leading Process** (gg fusion): $gg \rightarrow H$
- **Sub-leading Process** (VBF): $q\bar{q} \rightarrow Hq\bar{q}$
  - $q\bar{q} \rightarrow HW$
  - $gg, q\bar{q} \rightarrow H\gamma$
  - $gg, q\bar{q} \rightarrow H\gamma$

**Graphical Representation**

- **Graph Title**: $\sigma(pp \rightarrow H+X)$
- **Graph Parameters**:
  - $\sqrt{s} = 14$ TeV
  - $m_t = 175$ GeV
  - CTEQ4M

- **Graph Axes**:
  - $M_H$ (GeV)
  - $\sigma$ (pb)
  - Events for $10^5$ pb$^{-1}$

**Legend**

- $gg \rightarrow H$
- $q\bar{q} \rightarrow Hq\bar{q}$
- $q\bar{q} \rightarrow HW$
- $gg, q\bar{q} \rightarrow H\gamma$
- $gg, q\bar{q} \rightarrow H\gamma$

**Acknowledgments**

M. Spira et al.

NLO QCD

Bruce Mellado, UCD 03/08/08
Main Decay Modes

Close to LEP limit: \( H \rightarrow \gamma\gamma, \tau\tau, bb \)

For \( M_H > 140 \text{ GeV} \):
\( H \rightarrow WW^{(*)}, ZZ^{(*)} \)

Djouadi, Kalinowski, Spira
Cross-sections at LHC

- Search for Higgs and new physics hindered by huge background rates
  - Known SM particles produced much more copiously
- This makes low mass Higgs especially challenging
  - Narrow resonances
  - Complex signatures
    - Higgs in association with tops and jets.
Low Mass Higgs Associated with Jets

Slicing phase space in regions with different S/B seems more optimal when inclusive analysis has little S/B

Inclusive

H+1jet

H+2jet

Analyses in TDR were mostly inclusive

Applied to $H \rightarrow \gamma\gamma, \tau\tau, WW^{(*)}$

- Central jet veto initially suggested in V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)
SM Higgs + ≥1jet at the LHC

1. Large invariant mass of leading jet and Higgs candidate
2. Large $P_T$ of Higgs candidate
3. Leading jet is more forward than in QCD background

Higgs Decay Products

- Loose Central Jet Veto ("top killer")
- Quasi-central Tagging Jet

$\eta$

S. Abdullin et al, PL B431 (1998) for $H \rightarrow \gamma \gamma$
B. Mellado, W. Quayle and Sau Lan Wu, Phys. Lett. B611:60-65, 2005 for $H \rightarrow \tau \tau$
Weight: 7000 t

22 m

44 m
Low Mass SM
Higgs: $H \rightarrow \gamma \gamma$
$H \rightarrow \gamma \gamma$ ($m_H = 100$ GeV, $L = 10^{34}$)
Higgs decay to $\gamma\gamma$

$\gamma\gamma$ Backgrounds

Reducible $\gamma j$ and $jj$ Backgrounds

$q \rightarrow \pi^0$
CMS and ATLAS analyses for 100 fb$^{-1}$
Higgs Mass Reconstruction

In ATLAS Expect about 50% of events to have at least one converted photon, but can achieve $<1.2\%$ mass resolution

Events with at least one conversion

Low Lumi

High Lumi

$\sigma=1.36$ GeV

$\sigma=1.59$ GeV
Photon Identification

To separate jets from photons is crucial for Higgs discovery

- Need rejection of > 1000 against quark-initiated jets for $\varepsilon_\gamma = 80\%$ to keep fake background about 20% of total background
- Expect rejection against gluon-jets to be 4-5 times greater

Jet rejection will be evaluated with data

- Look into sub-leading jets in multi-jet final states with different $P_T$ thresholds
  - Avoid trigger bias
  - Apply trigger pre-scaling if needed
  - Correct for contribution from prompt photons

ATLAS TDR (1999)
Inclusive $H \rightarrow \gamma\gamma$

ATLAS

\[ \int L = 30 \text{ fb}^{-1} \left( 2 \times 10^{33} \text{ s}^{-1} \text{ cm}^{-2} \right) \]

\[ \int L = 100 \text{ fb}^{-1} \left( 10^{34} \text{ s}^{-1} \text{ cm}^{-2} \right) \]
\[ h, A \rightarrow \tau^+ \tau^-; \ H^\pm \rightarrow \tau^\pm \nu \]
Low Mass SM $H\rightarrow\tau\tau + \text{jets}$

Because of the poor Higgs mass resolution obtained with $H\rightarrow\tau\tau$, inclusive analysis not possible. Need to reduce QCD backgrounds by using distinct topology of jets produced in association with Higgs

$H\rightarrow\tau\tau + \geq 2 \text{ jets}$

$H\rightarrow\tau\tau + \geq 1 \text{ jets}$

Central Jet Veto

Higgs Decay Products

Quasi-central Tagging Jet

Loose Central Jet Veto ("top killer")

Higgs Decay Products

Tagging Jets
In order to reconstruct the Z mass need to use the collinear approximation

Tau decay products are collinear to tau direction

Fraction of τ momentum carried by visible τ decay

\[ x_{\tau_1} = \frac{p_{Tlep_1,x} \cdot p_{Tlep_2,y} - p_{Tlep_1,y} \cdot p_{Tlep_2,x}}{p_{THiggs,x} \cdot p_{Tlep_2,y} - p_{THiggs,y} \cdot p_{Tlep_2,x}} \]

\[ x_{\tau_2} = \frac{p_{Tlep_1,x} \cdot p_{Tlep_2,y} - p_{Tlep_1,y} \cdot p_{Tlep_2,x}}{p_{THiggs,y} \cdot p_{Tlep_1,x} - p_{THiggs,x} \cdot p_{Tlep_1,y}} \]

\( x_{\tau_1} \) and \( x_{\tau_2} \) can be calculated if the missing \( E_T \) is known

Good missing \( E_T \) reconstruction is essential

Bruce Mellado, UCD 03/08/08
Low Mass SM $H \rightarrow \tau\tau + \text{jets}$

Reconstruct Higgs mass with collinear approxim

$H(\rightarrow \tau\tau \rightarrow l\bar{l}) + \geq 2\text{jets}$

$H(\rightarrow \tau\tau \rightarrow l\bar{l}) + \geq 1\text{jet}$

Bruce Mellado, UCD 03/08/08
Two independent ways of extracting $Z \rightarrow \tau \tau$ shape

- Data driven and MC driven
- Similar procedure has been defined for $H \rightarrow WW(*)$

**Control Sample 1**
$Z \rightarrow ee, \mu\mu$
Loose cuts on Jets

**Control Sample 2**
$Z \rightarrow \tau\tau$
Loose cuts on Jets

**Control Sample 3**
$Z \rightarrow ee, \mu\mu$
Tight cuts on Jets

Replace $Z \rightarrow ee, \mu\mu$ by $Z \rightarrow \tau\tau$

**Signal Region**
$Z \rightarrow \tau\tau$
Tight cuts on Jets

$M_{HJ}, \Delta \eta_{JJ}$

$85 < M_{ll} < 95$ GeV

Determine shape and normalization of $Z \rightarrow \tau\tau$ background

$M_{ll} < 75$ GeV

Bruce Mellado, UCD 03/08/08
Normalization of $Z \rightarrow \tau \tau$ using $Z \rightarrow ee, \mu\mu$

- $Z \rightarrow ee, \mu\mu$ offers about 35 times more statistics w.r.t to $Z \rightarrow \tau \tau \rightarrow ll$

- Ratio of efficiencies depends weakly with $M_{HJ}$ and can be easily determined with MC after validation with data
SM Higgs: $H \rightarrow ZZ^(*) \rightarrow 4l$
Higgs decay to $Z^0Z^0$

Irreducible $Z^0Z^0$ backgrounds

Reducible 4l backgrounds
Backgrounds

Higgs → ZZ(\(\ast\)) → 4l
(l=eμ)

Continuum Irreducible

Non-Resonant reducible

Resonant reducible
SM Higgs$\rightarrow$ZZ(*)$\rightarrow$4l

- Able to reconstruct a narrow resonance, with mass resolution close to 1%. Can achieve excellent signal-to-background $> 1$
- Major issue: Lepton ID and rejection of semi-leptonic decays of B decays. Suppress reducible background $Z_{bb}, t\bar{t} \rightarrow 4l$
\[ \int L \, dt = 10 \text{ fb}^{-1} \]
(no K-factors)
SM Higgs: $H \rightarrow WW(*) \rightarrow 2l2\nu$
Higgs decay to $W^+W^-$

$W^+W^-$ backgrounds

+ Single top
& non-resonant $WWbb$
SM Higgs $H \rightarrow WW(\ast) \rightarrow 2l2\nu$

Strong potential due to large signal yield, but no narrow resonance. Left basically with event counting experiment.

Bruce Mellado, UCD 03/08/08
SM $H \rightarrow WW$ +0,1,2 jets

Defined three independent analysis, depending on the number of tagged jets

- Systematic errors added in significance calculation

Bruce Mellado, UCD 03/08/08
Background Suppression and Extraction

- Not able to use side-bands to subtract background. This makes signal extraction more challenging. Need to rely on data rather than on theoretical predictions.
- Definition & understanding of control samples is crucial.

**ttbar suppression**
- Jet veto (understand low $P_T$ jets)
- Semi-inclusive b-tagging or “top killing” algorithm
- Combined rejection of >10 times

**Non-resonant WW suppression**
- $\Delta \phi_{ll}$ and $M_{ll}$, very important variables
- Transverse momentum of WW system
  - Higgs production is harder
  - Missing $E_T$ reconstruction plays a role
Main control sample is defined with two cuts

\[ \Delta \phi_{ll} > 1.5 \text{ rad.} \] and \[ M_{ll} > 80 \text{ GeV} \]

Because of \( t\bar{t} \) contamination in main control sample, need b-tagged sample (\( M_{ll} \) cut is removed)
MSSM Higgs

- Minimal super-symmetric extension of Higgs sector
- Five Higgs: $h$ (light), $H$, $A$, $H^\pm$ (heavy)
- Parameter space reduced to two: $M_A, \tan \beta$
- Theoretical limit on light MSSM Higgs: $h < 135$ GeV
Large number of discovery modes:

- **SUSY particles heavy:**
  - **SM-like:** \( h \rightarrow \gamma\gamma, bb, \tau\tau, WW; H \rightarrow 4l \)
  - **MSSM-specific:** \( A/H \rightarrow \mu\mu, \tau\tau, tt \);
    \( H \rightarrow hh, A \rightarrow Zh; H^\pm \rightarrow \tau^\pm \nu \)

- **SUSY accessible:**
  - \( H/A \rightarrow \chi^0_2 \chi^0_2, \chi^0_2 \rightarrow h \chi^0_1 \)
  - Small impact on Higgs branching ratio to SM particles
Does the data favor a MSSM Higgs?

M_t = 171.4 GeV
M_W = 80.398 GeV

Slepton/squark one loop corrections

Contributions from MSSM Higgs bosons

Caution: This is not the only way of achieving agreement with data
MSSM Higgs Cross-sections (large tan\(\beta\))

**Tevatron**

\[
\begin{align*}
\Phi \text{ production cross section [fb]} \\
M_\Phi \text{ [GeV]} \\
\begin{array}{c}
gg\Phi \\
W/Z\Phi \\
qq\Phi \\
tt\Phi \\
\end{array}
\end{align*}
\]

**LHC**

\[
\begin{align*}
\Phi \text{ production cross section [fb]} \\
M_\Phi \text{ [GeV]} \\
\begin{array}{c}
gg\Phi \\
W/Z\Phi \\
qq\Phi \\
tt\Phi \\
(\bar{q}q)\Phi \\
\end{array}
\end{align*}
\]
Heavy CP-odd Higgs boson (A) branching ratios

\[ \text{BR}(A) \]

\[
\begin{align*}
tan \beta &= 3 \\
tan \beta &= 30
\end{align*}
\]
MSSM Higgs Search at the Tevatron

CDF Run II 1.8 fb⁻¹
MSSM φ→ττ Search
Preliminary

DØ Preliminary, 1.0 fb⁻¹

Visible Mass (GeV)
MSSM Higgs $\rightarrow \tau \tau$ Search, 95% CL Exclusion

CDF Run II Preliminary, 1.8 fb$^{-1}$

$\tan \beta$

$m_A$ (GeV/c$^2$)

$\tan \beta$

$m_A$ (GeV)

Bruce Mellado, UCD 03/08/08
D0 3b-jet Analysis

Bruce Mellado, UCD 03/08/08
D0 3b-jet Analysis

DØ Run II Preliminary

Cross section (pb)

10^2

10

100 110 120 130 140 150 160 170

mH (GeV)

Observed
Expected

DØ Run II Preliminary

160

140

120

100

80

60

40

20

100 110 120 130 140 150 160 170

mA (GeV)

Observed
Expected

Bruce Mellado, UCD 03/08/08
LHC Discovery Potential

CMS, 30 fb⁻¹

pp → bbφ, φ = h, H, A

m⁻¹ max scenario

M_{SUSY} = 1 TeV/c²

M₂ = 200 GeV/c²

μ = 200 GeV/c²

m{guino} = 800 GeV/c²

Stop mix: X₁ = 2 M_{SUSY}

ATLAS

30 fb⁻¹
Outlook and Conclusions

The search for a Higgs boson is a priority of CMS and ATLAS. One experiment should be able to observe a SM Higgs with $O(10) \text{ fb}^{-1}$ and also cover most of the MSSM plane.

Higgs searches at the LHC comprise a large number of final states involving all the signatures that the CMS and ATLAS detectors can reconstruct:

- Electrons, muons, photons, $\tau$, jets, $b$-jets
- Need to understand $V, VV$, $(V=Z, W)$, $tt$, $\gamma\gamma$, $j\gamma$ and their production in association with jets

Higgs searches at the LHC promise is a rich program that promises to turn the LHC era into fascinating times for High Energy Physics.