Could the Higgs boson be invisible?

Pauline Gagnon
Indiana University

- Why do we need the Higgs boson?
- Current status on Higgs searches
- Could it be invisible?
- Could we see it if it’s invisible?
The Standard Model

- Theoretical model describing constituents of matter and their interactions
- All experimental observations corroborate the SM predictions to great precision

Two central ideas:
1. All matter is made of quarks and leptons
2. Forces between quarks and leptons are mediated by exchange particles: bosons $W^\pm$, $Z^0$, photon, gluon
# FERMIONS

## Leptons

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ electron neutrino</td>
<td>$&lt;1\times10^{-8}$</td>
<td>0</td>
</tr>
<tr>
<td>e electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\mu$ muon neutrino</td>
<td>$&lt;0.0002$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\tau$ tau neutrino</td>
<td>$&lt;0.02$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.7771</td>
<td>-1</td>
</tr>
</tbody>
</table>

Spin = 1/2

## Quarks

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>d down</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>c charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>s strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>t top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>b bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Spin = 1/2

Matter constituents

Spin = 1/2, 3/2, 5/2, ...
# 2. Fundamental Interactions

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational</th>
<th>Weak (Electroweak)</th>
<th>Electromagnetic</th>
<th>Strong Fundamental</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td>Quarks, Gluons</td>
<td>Hadrons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td>W⁺ W⁻ Z⁰</td>
<td>γ</td>
<td>Gluons</td>
<td>Mesons</td>
</tr>
<tr>
<td>Strength relative to electromag</td>
<td>10⁻¹⁸ m</td>
<td>0.8</td>
<td>1</td>
<td>25</td>
<td>Not applicable to quarks</td>
</tr>
<tr>
<td>for two u quarks at:</td>
<td>10⁻⁴¹</td>
<td>10⁻⁴</td>
<td>1</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>for two protons in nucleus</td>
<td>10⁻¹⁷</td>
<td>10⁻⁷</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Bosons

**Unified Electroweak**  \( \text{spin} = 1 \)

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass ( \text{GeV/c}^2 )</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W⁻</td>
<td>80.4</td>
<td>-1</td>
</tr>
<tr>
<td>W⁺</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>Z⁰</td>
<td>91.187</td>
<td>0</td>
</tr>
</tbody>
</table>

**Strong (color)**  \( \text{spin} = 1 \)

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass ( \text{GeV/c}^2 )</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>g gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Where does the Higgs boson come into play?

Electroweak theory predicts 4 massless bosons

Peter Higgs invented a mechanism called “electroweak symmetry breaking” which turns the 4 massless bosons into

- 3 massive bosons: $W^+$, $W^-$, $Z^0$
- 1 massless boson: $\gamma^0$

All fermions acquire mass by interacting with the Higgs field: analogous to “drag” force
Where have we looked for the Higgs so far?

- **CERN**: the European Laboratory for Particle physics near Geneva, Switzerland with LEP (Large Electron Positron Collider)
  - Aleph, OPAL, L3 and Delphi
- **Fermilab**, since 2000 with the Tevatron
  - D0
  - CDF
Higgs searches at CERN

- **LEP I: 1989-1994** \( e^+e^- \rightarrow Z \rightarrow Z^*H^0 \)
  
  17 million Z decays analyzed
  
  *SM Higgs mass limit: \( m_H > 65 \text{ GeV} \) (95% CL)
  
  *MSSM Higgs \( h^0 \) and \( A^0 \): \( m_{h,A} > 45 \text{ GeV} \) (95% CL)

- **LEP II: 1995-2000** \( e^+e^- \rightarrow Z^* \rightarrow Z H^0 \)

  \( E_{CM} = 135, 161, 171, 183, 189-209 \text{ GeV} \)
  
  *Integrated luminosity: 2.46 fb\(^{-1}\) @ \( E_{CM} > 189 \)
  
  *0.55 fb\(^{-1}\) @ \( E_{CM} > 206 \)
  
  *SM limit: \( m_H > 114.1 \text{ GeV} \) (95% CL)
  
  *MSSM limit: \( m_H > 91.1 \text{ GeV} \) (95% CL)
SM constraints on $m_H$

One sided limit:

(LEP + SLD + Tevatron): $m_H < 186$ GeV @95% CL.

Renormalising to $m_H > 114$ GeV:

(LEP + SLD + Tevatron): $m_H < 219$ GeV @95% CL
Searches for alternative Higgs at LEP

Fermiophobic Higgs: $m_h > 114.4 \text{ GeV}/c^2$

Charged Higgs: $m_{H^+} > 78.6 \text{ GeV}/c^2$

Invisible Higgs: $m_{H^0} > 99.3 \text{ GeV}/c^2$

Decay-mode independent

Doubly charged Higgs

Quark- and lepton-couplings

2HDM limits

Anomalous Higgs

C flipping Higgs

Low NA Higgs

NMSSM
Tevatron Higgs Searches Combined (Spring 2006)

95% CL Limits/SM

$\ln \sigma$ vs $m_H$ (GeV)

- $ZH \rightarrow \tau\tau b\bar{b}$
  - D0: 261 pb$^{-1}$
  - CDF: 319 pb$^{-1}$

- $WH \rightarrow l\nu b\bar{b}$
  - D0: 382 pb$^{-1}$

- $WH \rightarrow WW$ (combined)
  - D0: 363-384 pb$^{-1}$
  - CDF: 194 pb$^{-1}$

- $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$
  - D0: 300-325 pb$^{-1}$
  - CDF: 360 pb$^{-1}$
Higgs prospects for discovery/exclusion:
1998-1999 Higgs SUSY study / 2003 update
Tevatron Higgs prospects for discovery/exclusion: Prospects in time

Higgs Sensitivity Study ('03)
statistical power only (no systematics)

SUSY/Higgs Workshop ('98-'99)

End 2006
End 2007
Mid 2009

LHC: the Large Hadron Collider at CERN

ATLAS: one of 4 new detectors built for LHC

<table>
<thead>
<tr>
<th></th>
<th>Beams</th>
<th>Energy</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LEP</strong></td>
<td>e⁺ e⁻</td>
<td>200 GeV</td>
<td>(10^{32}) cm(^{-2})s(^{-1})</td>
</tr>
<tr>
<td><strong>LHC</strong></td>
<td>p p</td>
<td>14 TeV</td>
<td>(10^{34}) cm(^{-2})s(^{-1})</td>
</tr>
<tr>
<td>Tevatron</td>
<td>p⁺ p⁻</td>
<td>2 TeV</td>
<td>(10^{32}) cm(^{-2})s(^{-1})</td>
</tr>
</tbody>
</table>
ATLAS detector

3000 scientists
150 institutes
34 countries
144 ft long
72 ft diameter
~ 2007-2017
Upcoming milestones:

- 500-piece jigsaw puzzle available end of April 2006
- TRT will be lowered into place this summer
- Full detector completed by summer 2007
IU contributions to ATLAS

TRT: Transition Radiation Tracker

- Half the TRT barrel modules were constructed here at IU from 1998-2004
- Studies on $e/\pi$ separation using the TRT
- Modules Quality Control done at CERN
- Modules assembly on the detector
- Software development for track reconstruction and monitoring of the TRT detector
- Tier-2 GRID center
- Data analysis on invisible Higgs
Quality control lab at CERN
Full TRT Barrel after assembly
Standard Model Higgs decay channels

Higgs decays to heaviest available fermions until $m_H > 2m_W$ or $2m_Z$

For low $m_H$:
$H \rightarrow \tau^+\tau^-$ or $H \rightarrow bb$

For $m_H > 160$ GeV:
$H \rightarrow WW$ or $H \rightarrow ZZ$

$m_H < 219$ GeV @95% CL.
Invisible Higgs decays

- No invisible Higgs decays in Standard Model
- But many other models predict invisible Higgs branching fraction with strong suppression of the main SM decay channels
- Many such models: MSSM, extra dimensions, NMSSM, spontaneously breaking R-parity models etc.
Minimal Super Symmetric Model

$BR (H \rightarrow \tilde{\chi}^0 \tilde{\chi}^0)$ in the $M_2 - \mu$ plane

$\tilde{\chi}^0$: neutralino (lightest SUSY particle)

$M_2$: gaugino mass

$\mu$: Higgs doublet mixing

Boudjema, Bélanger, Godbole hep-ph/0206311

$BR (H \rightarrow \chi^0 \chi^0) = 60\%$

$BR (H \rightarrow \chi^0 \chi^0) = 20\%$

Excluded by dark matter searches

Excluded by chargino searches at LEP
Models with extra dimensions


\[ H \rightarrow \nu \tilde{G} \]

\[ \tilde{G}: \text{Goldstino} \]

\[ M = \text{auxiliary mass parameter} \]

Lepton number is conserved
Spontaneously Broken R-Parity

$H \rightarrow JJ$

$J =$ Goldstone boson (Majoron)

$R_{Jb} = \frac{BR(H \rightarrow JJ)}{BR(H \rightarrow bb)}$

$\eta =$ reduced coupling to $Z$

$h =$ Yukawa coupling

Lepton number is not conserved and neutrinos get masses
**SM Higgs production mechanisms**

- dominated by **gluon fusion**
- $q\bar{q} \rightarrow q\bar{q}H$ increases at large $m_H$
- $t\bar{t}H$ and $WH, ZH$: less background
## Cross-sections and trigger for invisible Higgs

<table>
<thead>
<tr>
<th>Production $\sigma$ mH = 120 GeV</th>
<th>trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluon fusion $gg \rightarrow H$</td>
<td>$\sim 30$ pb$^{-1}$</td>
</tr>
<tr>
<td>Vector Boson Fusion $qq \rightarrow qqH$</td>
<td>$\sim 4$ pb$^{-1}$</td>
</tr>
<tr>
<td>$qq \rightarrow WH$</td>
<td>$\sim 3$ pb$^{-1}$</td>
</tr>
<tr>
<td>$qq \rightarrow ZH$</td>
<td>$\sim 1$ pb$^{-1}$</td>
</tr>
<tr>
<td>$gg \rightarrow ttH$</td>
<td>$\sim 0.5$ pb$^{-1}$</td>
</tr>
</tbody>
</table>

*with ttH $\rightarrow blv$ bqq inv*
Rapidity $\eta$

A convenient way to determine where a track goes is to use rapidity

$$\eta = -\ln \tan (\theta/2)$$

\[\begin{array}{c}
\eta = 0 \\
\eta = \infty
\end{array}\]
Missing transverse momentum

momentum is not balanced in the Z-direction

But momentum has to be balanced in the transverse plane

\[ \vec{p}_T \text{ missing} = - \sum \vec{p}_T \text{ visible} \]
Vector boson fusion

Decay characteristics:
- two forward jets
- large $p_T^{\text{miss}}$ in central rapidity region

Main backgrounds:
- QCD + 2 jets
- 2 jets + $Z$, $Z \rightarrow \nu\nu$
- 2 jets + $W$, $W \rightarrow l\nu$

<table>
<thead>
<tr>
<th>process</th>
<th>$\sigma$ (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$qqH$</td>
<td>~ 4</td>
</tr>
<tr>
<td>QCD+jj</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>$qqZ$</td>
<td>2731</td>
</tr>
<tr>
<td>$qqW$</td>
<td>6700</td>
</tr>
</tbody>
</table>
Main selection cuts efficiency

<table>
<thead>
<tr>
<th>cut</th>
<th>$qqW$</th>
<th>$qqZ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{miss}$</td>
<td>1.8</td>
<td>520</td>
</tr>
<tr>
<td>jets</td>
<td>0.4</td>
<td>7.6</td>
</tr>
<tr>
<td>$M_{jj}$</td>
<td>0.2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

for 10 fb$^{-1}$: $S/\sqrt{B} \sim 10$

No trigger for this channel yet
The ATLAS 3-level trigger system

Interaction rate
\~ 1 GHz
Bunch crossing rate 40 MHz

LEVEL 1 TRIGGER
\< 75 \text{ kHz}

2.5 \text{ } \mu\text{s}

Levels of Interest

LEVEL 2 TRIGGER
\(\mathcal{O}(1) \text{ kHz}\)

\~ 10 \text{ ms}

Event builder

EVENT FILTER
\~ 200 \text{ Hz}

\~ \text{ sec}

Data recording

Full-event buffers and processor sub-farms

Readout buffers (ROBs)

Readout drivers (RODs)

Pipeline memories

hardware

software

IU Physics seminar - April 3, 2006
Pauline Gagnon - Indiana University
Trigger efficiency for VBF, $H \rightarrow \text{invisible}$

Currently, in trigger menu, we only trigger on central jets

- **Level 1:** $E_T^{\text{miss}} > 60 \text{ GeV}, \ p_T^{\text{jet}} > 60 \text{ GeV}, \ \eta_{\text{jet}} < 3.2$
- **Level 3:** $E_T^{\text{miss}} > 70 \text{ GeV}, \ p_T^{\text{jet}} > 70 \text{ GeV}, \ \eta_{\text{jet}} < 3.2$

Trigger extension needed for VBF $H \rightarrow \text{invisible}$ with $\eta_{\text{jet}}$ up to 4.9

<table>
<thead>
<tr>
<th>acceptance</th>
<th>$\eta_{\text{jet}} &lt; 3.2$</th>
<th>$\eta_{\text{jet}} &lt; 4.9$</th>
<th>$\eta_{\text{jet}} &lt; 3.2$</th>
<th>$\eta_{\text{jet}} &lt; 4.9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>50%</td>
<td>64%</td>
<td>55%</td>
<td>95%</td>
</tr>
<tr>
<td>Level 3</td>
<td>39%</td>
<td>50%</td>
<td>58%</td>
<td>89%</td>
</tr>
</tbody>
</table>

Ongoing work
2nd production mode: $ttH$ channel

**selection: (rejection)**

- only 1 lepton ($bb Z/\gamma^*$)
- 2 b-jets ($Z_{incl.}$ and $W_{incl.}$)
- $t \rightarrow jjb$, $m_{jj}=m_W$, $m_{jjb}=m_t$
- large $m_T$ and $E_T^{miss}$ ($tt$)

**signal**

$t \rightarrow bl\nu$, $t \rightarrow bqq$, $H \rightarrow$ inv.

**main backgrounds**

- $tt$: largest background
- $ttZ$, $Z \rightarrow \nu\nu$
- $ttW$, $W \rightarrow l\nu$
- $bb Z/\gamma^*$ with $Z/\gamma^* \rightarrow ll$
- $bbW$, $W \rightarrow l\nu$
- QCD: $Z_{incl.}$, $W_{incl.}$
Transverse mass

Use only quantities measured in the transverse plane to get transverse mass

\[ m_T^2 = (\Sigma E_T^i)^2 - (\Sigma p_T^i)^2 \]
Effect of \( m_T \) cut on \( tt \) background

**ttH signal:** \( \sigma = 0.5 \text{ pb}^{-1} \)

**tt bgnd:** \( \sigma = 490 \text{ pb}^{-1} \)

fake missing pt from
\[ tt \rightarrow bl\nu b\tau\nu \]
tt background composition

b<sub>gnd</sub> tt events:
70% tt → blν bτν

signal ttH:
88% ttH → blν bqq H

must remove bτν events
Use inter-jet separation $R_{jj}$
Selected events for $ttH$ for 10 fb$^{-1}$ data

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ttH$ ($m_H = 120$ GeV)</td>
<td>15</td>
</tr>
<tr>
<td>$ttZ$</td>
<td>7</td>
</tr>
<tr>
<td>$ttW$</td>
<td>7</td>
</tr>
<tr>
<td>$tt$ (all)</td>
<td>39 (Pythia), 64 (Herwig)</td>
</tr>
<tr>
<td>$tt$ (blv, bqq only)</td>
<td>5 (Pythia), 10 (Herwig)</td>
</tr>
<tr>
<td>$bbW$</td>
<td>2</td>
</tr>
<tr>
<td>$bbZ/\gamma^*$</td>
<td>2</td>
</tr>
</tbody>
</table>

$S/\sqrt{B} = 2.0 \ (1.6)$
Last mode: Associated production. Two possible channels: HZ and WZ

\[ q \rightarrow W^* \text{ or } Z^* \rightarrow W \text{ or } Z \rightarrow H \]
Event selection for associate production

**WH channel**
- large missing $p_T$
- one prompt lepton
- large transverse mass

**Main backgrounds:**
- $WZ \rightarrow l\nu \nu\nu$
- $W$ incl., $W \rightarrow l\nu$
- $t\bar{t}$ → $b\bar{b}$, $b$ → $c\nu$

\[ WH: \quad H \rightarrow \tilde{\chi}^0 \chi^0 \]
\[ W \rightarrow l\nu \]
**Associated vector boson: WH**

**WH selection:**
- 1 lepton + $p_T^{\text{miss}} > 100$ GeV
- + large transverse mass $m_T$

**main backgrounds:**
- WZ: $W \rightarrow l\nu$, $Z \rightarrow \nu\nu$
- W inclusive
- $tt$, $t \rightarrow bl\nu$

\[
m_T = \sqrt{2p_T^l p_T(1 - \cos \phi)}
\]

large $p_T^{\text{miss}} \Rightarrow \text{off-shell } W_{\text{incl}}.$
**Z^0 H^0 → (l^+ l^- + invisible) analysis strategy**

**Trigger:** 1 or 2 prompt leptons

**Preselection:**
- large missing $p_T$
- 2 leptons of opposite sign and same flavour
- loose cut on $Z$ mass

**Final selection:**
Use 10+ discriminative variables in a multivariate analysis to extract signal
Very large background is rejected after the simple pre-selection cuts

<table>
<thead>
<tr>
<th>channel</th>
<th>$Z^0 H^0 \rightarrow l^+ l^- \text{ invisible}$</th>
<th>$Z^0 Z^0 \rightarrow l^+ l^- \nu\nu$</th>
<th>$Z^0 \text{ incl.} \rightarrow l^+ l^-$</th>
<th>$tt \rightarrow b l^+ \nu \ b l^- \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma \times \text{BR (pb)}$</td>
<td>0.043</td>
<td>0.300</td>
<td>2804</td>
<td>125.1</td>
</tr>
<tr>
<td># events @10 fb$^{-1}$</td>
<td>426</td>
<td>3000</td>
<td>28.04 M</td>
<td>1.251 M</td>
</tr>
<tr>
<td>preselection</td>
<td>62.0</td>
<td>183.3</td>
<td>14.6</td>
<td>170.4</td>
</tr>
<tr>
<td>$\mathcal{L}$ selection</td>
<td>54.6</td>
<td>151.8</td>
<td>3.3</td>
<td>6.2</td>
</tr>
</tbody>
</table>
ATLAS reconstruction chain

- MC generation
- Simulation
- Digitization
- Reconstruction
- Create Analysis Object Data (AOD)
- Analysis

15 min CPU time per event

Fast reconstruction

~ 300 ms CPU time per event
Solution: add a filter

Filter goal: emulate preselection cuts after MC generation

MC generation → Filter → Simulation → Digitization → Reconstruction → Create Analysis Object Data → Analysis

Real data

Fast reconstruction
Two handles in filter:

1. \textbf{missing} p_T = \sum (\text{invisible} p_T)
   - Sum over invisible particles: Higgs, neutrinos and particles falling outside the detector acceptance region, i.e. |\eta| > 5.0

2. Leptons from a Z:
   - Two leptons in the tracker acceptance region
   - One or both leptons must pass the trigger requirements
   - Two leptons of same flavor but opposite sign
   - The reconstructed mass must be close to m_Z
## Filter has looser cuts

<table>
<thead>
<tr>
<th>Filter cuts</th>
<th>Preselection cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 leptons with $\eta &lt; 2.7$</td>
<td>2 leptons with $\eta &lt; 2.5$</td>
</tr>
<tr>
<td>Trigger requirements:</td>
<td>Trigger requirements:</td>
</tr>
<tr>
<td>- 1 $e$ with $p_T &gt; 18$ GeV</td>
<td>- 1 $e$ with $p_T &gt; 20$ GeV</td>
</tr>
<tr>
<td>- 2 $e$ with $p_T &gt; 23$ GeV</td>
<td>- 2 $e$ with $p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td>- 1 $\mu$ with $p_T &gt; 8$ GeV</td>
<td>- 1 $\mu$ with $p_T &gt; 10$ GeV</td>
</tr>
<tr>
<td>- 2 $\mu$ with $p_T &gt; 13$ GeV</td>
<td>- 2 $\mu$ with $p_T &gt; 15$ GeV</td>
</tr>
<tr>
<td>missing $p_T &gt; 50$ GeV</td>
<td>missing $p_T &gt; 90$ GeV</td>
</tr>
<tr>
<td>$m_Z = 25$ GeV</td>
<td>$m_Z = 20$ GeV</td>
</tr>
</tbody>
</table>
**Filter requirement #1: no event loss**

<table>
<thead>
<tr>
<th></th>
<th>$H^0Z^0 \rightarrow \ell^+\ell^-$</th>
<th>$Z^0Z^0 \rightarrow \ell^+\ell^-$</th>
<th>$Z$ incl.</th>
<th>$t\bar{t}$bar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight = 0.0043</td>
<td>Weight = 0.0300</td>
<td>Weight = 280.4</td>
<td>Weight = 0.0126</td>
</tr>
<tr>
<td>Filter</td>
<td>Filter</td>
<td>Filter</td>
<td>Filter</td>
<td>Filter</td>
</tr>
<tr>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td><strong>Generated</strong></td>
<td>99034</td>
<td>100 K</td>
<td>100 K</td>
<td>475 K</td>
</tr>
<tr>
<td><strong>Selected</strong></td>
<td>56424</td>
<td>35720</td>
<td>10506</td>
<td>103218</td>
</tr>
<tr>
<td><strong>Unmatched</strong></td>
<td>32969</td>
<td>25214</td>
<td>2</td>
<td>100202</td>
</tr>
</tbody>
</table>
Filter requirement #2: large sample reduction

<table>
<thead>
<tr>
<th>for 100 fb$^{-1}$</th>
<th>$Z^0 H^0 \rightarrow \chi \chi , l^+ l^-$</th>
<th>$Z^0 Z^0 \rightarrow l^+ l^- \nu \nu$</th>
<th>$Z^0$ incl. $\rightarrow l^+ l^-$</th>
<th>$t t \rightarrow b l^+ \nu , bl^- \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unfiltered</strong></td>
<td>4260</td>
<td>30000</td>
<td>280.4 M</td>
<td>12.5 M</td>
</tr>
<tr>
<td><strong>Filter retention</strong></td>
<td>50.5%</td>
<td>60.3%</td>
<td>99.996%</td>
<td>99.6%</td>
</tr>
<tr>
<td><strong>To be fully reconstructed</strong></td>
<td>2130</td>
<td>8910</td>
<td>12200</td>
<td><strong>217500</strong></td>
</tr>
</tbody>
</table>

From 8360 CPU years down to 7 CPU years...
### Cut flow on fast simulation after filter

<table>
<thead>
<tr>
<th></th>
<th>HZ</th>
<th>ZZ -&gt; llnunu</th>
<th>Z incl.</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td># of generated events</td>
<td>100 K</td>
<td>100 K</td>
<td>40.726 M</td>
<td>47270</td>
</tr>
<tr>
<td>event weight</td>
<td>0.0043</td>
<td>0.03</td>
<td>0.689</td>
<td>26.47</td>
</tr>
<tr>
<td>Events at 10 fb⁻¹</td>
<td>430</td>
<td>3000</td>
<td>28.04 M</td>
<td>1.251 M</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Events after filter</td>
<td>213</td>
<td>890</td>
<td>1224</td>
<td>21767</td>
</tr>
<tr>
<td></td>
<td>49.6%</td>
<td>29.7%</td>
<td>0.0044%</td>
<td>1.74%</td>
</tr>
<tr>
<td>Events after ptmiss cut @ 90 GeV</td>
<td>117</td>
<td>362</td>
<td>146</td>
<td>9758</td>
</tr>
<tr>
<td></td>
<td>27.3%</td>
<td>12.1%</td>
<td>0.0005%</td>
<td>0.78%</td>
</tr>
<tr>
<td>Events after # lepton cut</td>
<td>103</td>
<td>298</td>
<td>116</td>
<td>5254</td>
</tr>
<tr>
<td></td>
<td>24.0%</td>
<td>9.9%</td>
<td>0.0004%</td>
<td>0.42%</td>
</tr>
<tr>
<td>Events after full trigger</td>
<td>103</td>
<td>298</td>
<td>116</td>
<td>5254</td>
</tr>
<tr>
<td></td>
<td>24.0%</td>
<td>9.9%</td>
<td>0.0004%</td>
<td>0.42%</td>
</tr>
<tr>
<td>Events after mZ cut @ +/- 20 GeV</td>
<td>103</td>
<td>297</td>
<td>116</td>
<td>4128</td>
</tr>
<tr>
<td></td>
<td>24.0%</td>
<td>9.9%</td>
<td>0.0004%</td>
<td>0.33%</td>
</tr>
<tr>
<td>Events after btag</td>
<td>100</td>
<td>288</td>
<td>59</td>
<td>876</td>
</tr>
<tr>
<td></td>
<td>23.2%</td>
<td>9.6%</td>
<td>0.0002%</td>
<td>0.07%</td>
</tr>
<tr>
<td>Initial fast reconstruction analysis</td>
<td>62</td>
<td>183.3</td>
<td>14.6</td>
<td>178.4</td>
</tr>
<tr>
<td></td>
<td>14.4%</td>
<td>6.1%</td>
<td>0.0001%</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

#jet and b-tag values not yet reliable in fast simulation.
## Cut flow on full reconstruction

<table>
<thead>
<tr>
<th></th>
<th>HZ</th>
<th>ZZ → llνν</th>
</tr>
</thead>
<tbody>
<tr>
<td># of generated events</td>
<td>FAST</td>
<td>FULL</td>
</tr>
<tr>
<td></td>
<td>100 K</td>
<td>1 K</td>
</tr>
<tr>
<td>Events after filter</td>
<td>52.7%</td>
<td>33.6%</td>
</tr>
<tr>
<td>Events after missing p_T cut</td>
<td>29.1%</td>
<td>13.7%</td>
</tr>
<tr>
<td>Events after # leptons cut</td>
<td>28.5%</td>
<td>11.1%</td>
</tr>
<tr>
<td>Events after trigger</td>
<td>28.5%</td>
<td>11.1%</td>
</tr>
<tr>
<td>Events after lepton id cut</td>
<td>28.5%</td>
<td>11.1%</td>
</tr>
<tr>
<td>Events after m_Z cut</td>
<td>28.1%</td>
<td>10.5%</td>
</tr>
<tr>
<td>Events after b-tagging</td>
<td>27.4%</td>
<td>10.1%</td>
</tr>
</tbody>
</table>

**Fast simulation reconstruction problems**
We need large MC sample to go further

- In ATLAS, all MC samples used for analyses must be approved
- MC samples produced centrally on the grid
- Our filter has been approved and our signal & background samples will soon be centrally produced
- Next step: multivariate analysis with fully reconstructed events (maximum likelihood, neural network or decision tree)
Discriminating variables after preselection (based on fast simulation)
missing pT

transverse mass

\[ Cos \ \text{pTmiss-pT} \]

lepton #1

Discriminating variables

after preselection (based on fast simulation)
Interpreting results w.r.t SM predictions

\[ \xi^2 = \frac{\sigma \times BR(H\rightarrow\text{invisible})}{\sigma_{SM} \times BR_{SM}(H\rightarrow bb)} \]

\( \xi^2 \) is a scaling factor, the ratio of the production cross-section times the branching fraction for Higgs to invisible of a certain model to the prediction of the Standard Model.
Analysis potential @ 10 fb$^{-1}$: $S/\sqrt{B} \sim 4.0$ (2.6 with syst.)

**LHC luminosity**

10 fb$^{-1}$ expected in 2007

100 fb$^{-1}$ per year the following years

**Discovery potential:**

Not much in 2007

$\chi^2 \sim 0.5$ in 2008

$\chi^2 \sim 0.3$ in 2010
Summary

- LHC is due to start in 2007
  - Last chance for exclusion or evidence at the Tevatron for \( m_H < 130 \text{ GeV} \)
- LHC reach and luminosity should cover any possible Higgs decay mode
- Even being invisible won’t be an excuse for the Higgs not to be seen!