Searching for the Higgs at the LHC

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Outline

- Theory & Background of Higgs Mechanism
- Production Modes
- Decay Modes
  - Discovery Channels
- Invisible Higgs
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- Production Modes
  - Decay Modes
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Emphasis on SM
The Higgs Mechanism

- Describes the way in which gauge bosons obtain a mass by interacting with the Higgs Field
  - Mechanism requires Higgs Field to have non-zero vacuum expectation value: spontaneous symmetry breaking of electroweak symmetry

- Successfully explains the mass ratio between $W^\pm / Z$ gauge bosons
  - Correctly predicted to 5 decimal places
  - Leptons and quarks also acquire mass as a result of interaction with the Higgs

- Higgs field has 4 degrees of freedom
  - 3 DOF mix with the $W^\pm / Z$ bosons, giving them mass
  - 4th DOF manifests as the Higgs boson (scalar)
Searching for the Higgs

- Higgs is difficult to search for since couplings to the Higgs are proportional to mass
  - Coupling is small for the light particles that are most copiously available
- Mass of the Higgs is unknown
  - SM + spontaneous symmetry breaking predicts the existence of Higgs boson(s), but not mass
  - $M_H$ depends on coefficient of self-interaction $\lambda$. No other observables depend on $\lambda$ in a measurable way
- Current LEP limits on $M_H$
  - $114.4 \text{ GeV} < M_H < 182 \text{ GeV}$ (indirect)
Higgs Production Modes

- **Gluon Fusion (GF)**
  - Most dominant production mode (cross-section)
  
  \[
  gg \rightarrow H
  \]

- **Vector Boson Fusion (VBF)**
  - $\sigma$ is $\times 10$ below GF but VBF gives *much cleaner* signal in detectors
  
  \[
  qq \rightarrow VV^* \rightarrow Hqq
  \]

- **Associated Production with W,Z**
  - $\sigma$ is $\times 15-30$ below GF, but allows for unique signatures using W/Z as *tag*
  
  \[
  qq \rightarrow WH / ZH
  \]

- **Associated Production with Heavy Quarks**
  - $\sigma$ is $\times 30-60$ below GF. Difficult jet/QCD backgrounds
  
  \[
  qq,gg \rightarrow ttH
  \]
Higgs Production Cross Sections at LHC


The figure illustrates the production cross sections for various Higgsboson production mechanisms at the Large Hadron Collider (LHC) for a center-of-mass energy of $14$ TeV. The cross sections are shown as a function of the Higgs boson mass $M_H$.

- **GF** (Gluonic Fusion)
- **VBF** (Vector Boson Fusion)
- **AP (W,Z)**
- **AP (t)**

The graph shows the cross sections for:
- $gg \rightarrow H$
- $gg \rightarrow Hqg$
- $gq \rightarrow WH$
- $gg \rightarrow ZH$
- $pp \rightarrow t\bar{t}H$

The cross sections are given in [pb] (protons on protons) and are calculated using MRST/NLO with a top quark mass of $m_t = 178$ GeV.
Gluon-Fusion Production

- ~10 orders of magnitude greater production $\sigma$ in low-mass range
- Dominant production factor for $H \rightarrow \gamma \gamma$ based searches
  - As we will see, this is one of the cleanest decay modes in the low-mass (~140 GeV) range
- Lots of QCD background issues at LHC with gluon-fusion production
  - This is why, despite the dominant production cross-section, much effort has been made to calculate/understand the other less dominant production modes
Vector Boson Fusion Production

- Provides distinctive signature via forward tagging jets
  - Good rejection of QCD background via central jet veto!

- Importance in low-mass region
  - Dominant production mode for $H \to \tau\tau$ decays
    (relevant in low-mass region)
Associated Production with $W, Z$

- Sometimes called \textit{Higgs-strahlung}
- Clean signatures from leptonic decays of $W, Z$
  - However, possible high QCD background from hadronic decays of $W, Z$
  - Requires summation of $W, Z$ leptonic decays to increase statistics due to low branching ratio of these decays
Associated Heavy Quark Production

- Complex final states. Dominated by \([ttH \rightarrow bb]\)
  - \(bb\) state dominates BR at: \(100 \text{ GeV} < M_H < 120 \text{ GeV}\)
  - **Problem**: dominant background: \(tt + jets\)
- Successful work with this channel requires
  - Good b-tagging!
  - Very good knowledge of jet background
Higgs Decay Modes

SM Higgs decay branching ratio as a function of $M_H$

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“low mass” range: $110 \text{ GeV} \leq M_H \leq 130 \text{ GeV}
Higgs Decay Modes

SM Higgs decay branching ratio as a function of $M_H$


"low mass" range: $110 \text{ GeV} \leq M_H \leq 130 \text{ GeV}

"intermediate mass" range: $130 \text{ GeV} \leq M_H \leq 180 \text{ GeV}

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Higgs Decay Modes

SM Higgs decay branching ratio as a function of $M_H$


“low mass” range: $110 \text{ GeV} \leq M_H \leq 130 \text{ GeV}$

“intermediate mass” range: $130 \text{ GeV} \leq M_H \leq 180 \text{ GeV}$

“high mass” range: $180 \text{ GeV} \leq M_H \leq 1 \text{ TeV}$
The “low-mass” Range @ the LHC

- In range where: $M_H < 2M_{W,Z}$ fermionic decay modes dominate
- Higgs will decay to heaviest fermions allowed by energy conservation
- However, $qq$ final states have too much QCD background at LHC to be useful as a search channel
  - This is why emphasis is placed on other channels ($H \rightarrow \tau\tau$, $H \rightarrow \gamma\gamma$) despite their lower branching ratios
Primary Search Channels @ LHC

- Four Lepton Decay: $H \rightarrow ZZ^{(*)} \rightarrow 4\ell (4e, 4\mu, 2e2\mu)$
- Two Photon Decay: $H \rightarrow \gamma\gamma$
- Tau Pair Decay: $H \rightarrow \tau^+ \tau^-$
- W-Boson Pair Decays: $H \rightarrow W^+W^- \rightarrow \ell\nu\ell\nu (\ell = e^\pm \text{or} \ell = \mu^\pm)$
\( H \rightarrow ZZ^* \rightarrow 4 \text{ lepton Decays} \)

- Provides clean signature for wide range of \( M_H \) above \( \sim 130 \) GeV
  - Except in range \((2m_W, 2m_Z)\) where branching ratio is dominated by \( H \rightarrow W^+ W^- \)

- Background:
  - Irreducible: Direct \( ZZ^* \) and \( Z\gamma^* \) production
  - Reducible: \( tt, Zbb, ZW \) production

- At least one \( Z \) is expected to be on mass shell
  - Two-lepton invariant mass is used to confirm this and reject false events

- Method relies heavily on:
  - lepton reconstruction
  - invariant-mass resolution
Background Suppression in 4 Lepton Decay

Backgrounds from $ZZ^*$, $tt$, $Zbb$ processes are suppressed via:

- Require leptons to be isolated in the tracker
- Cuts on 2-lepton & 4-lepton invariant mass
  - Require at least one of the 2-lepton invariant mass to be consistent with on-shell $Z$
- Require $p_T$ threshold
  - For CMS typically $p_T > 20$GeV for largest $p_T$ lepton

Four-lepton invariant mass of $H \rightarrow ZZ^* \rightarrow 4\ell$ signal with $M_H = 130, 150, 170$ GeV

S. Abdullin et. al., CMS Note 2003/033
$H \rightarrow ZZ^* \rightarrow 4e$ In “intermediate” $M_H$ Range

Four-electron invariant mass of $H \rightarrow ZZ^* \rightarrow 4e$ signal with $M_H = 130, 150, 170$ GeV

S. Abdullin et. al., CMS Note 2003/033
4 Lepton Decay in “high” $M_H$ Region

$H \rightarrow ZZ^* \rightarrow 4\ell$ signal presents an important discovery channel in “high” mass region as well.

Expected $H \rightarrow ZZ \rightarrow 4\ell$ signal above background for $M_H = 300$ GeV in ATLAS experiment.

Expected $H \rightarrow ZZ \rightarrow 4\ell$ signal for range of $M_H$ in ATLAS experiment.
Very high discovery potential in $H \rightarrow ZZ^* \rightarrow 4\ell$ channel
Decay mode only detectable in region: $80 \text{ GeV} < M_H < 150 \text{ GeV}$

Requires excellent energy and angular resolution!

Method relies on detecting mass peak above:

- Irreducible background from prompt $\gamma\gamma$ continuum
- Reducible background from direct $\gamma$ production + QCD jet production

Simulation studies have brought sources of reducible background to $\sim 20\%$ of irreducible background

Efficiency and purity of this method depend heavily on minimum-bias event model and $p_T$ spectrum of $H$

- high $p_T$ tracks used to distinguish Higgs events from pileup
$H \rightarrow \gamma\gamma$ - Event Selection

<table>
<thead>
<tr>
<th>Signal Process</th>
<th>Cross-section (fb)</th>
<th>Background Process</th>
<th>Cross-section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td>21</td>
<td>$\gamma\gamma$</td>
<td>562</td>
</tr>
<tr>
<td>VBF $H$</td>
<td>2.7</td>
<td>Reducible $\gamma j$</td>
<td>318</td>
</tr>
<tr>
<td>$ttH$</td>
<td>0.35</td>
<td>Reducible $jj$</td>
<td>49</td>
</tr>
<tr>
<td>$VH$</td>
<td>1.3</td>
<td>$Z \rightarrow e^+e^-$</td>
<td>18</td>
</tr>
</tbody>
</table>

Expected cross-sections for different signal ($M_H = 120$ GeV) and background processes within a mass window of $m_{\gamma\gamma} = \pm 1.4\sigma$

Diphoton mass spectrum with fiducial and $p_T$ cuts applied.

Diphoton mass spectrum based on event selection requiring the presence of two tagging jets

*Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020*
$H \rightarrow \gamma\gamma$ - Inclusive vs VBF

Di-photon invariant mass distribution for inclusive $H \rightarrow \gamma\gamma$ signal. Yellow represents irreducible prompt $\gamma\gamma$ production and $j\gamma$ QCD processes.

$\sim 83\%$ of $\sigma_H$

Di-photon invariant mass distribution for VBF, $H \rightarrow \gamma\gamma$. Yellow represents irreducible $jj\gamma\gamma$ background.

$\sim 10\%$ of $\sigma_H$

S. Abdullin et al., CMS Note 2003/033
$H \rightarrow \gamma\gamma$ - Discovery Potential

Expected signal significance for a Higgs boson using the $H \rightarrow \gamma\gamma$ decay for 10fb$^{-1}$ of integrated luminosity as a function of the mass using a variety of analysis/fit methods.

*Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020*
H → τ⁺τ⁻ Decays

- Provides one of the best sensitivities in “low” M_H range
- Searches based on
  - double leptonic decay: \(qqH → qqττ → qqlν\bar{ν}l\bar{ν}\)
  - lepton-hadron decay: \(qqH → qqττ → qqlν\bar{ν} + \text{had} + ν\)
- ττ invariant mass reconstruction based on collinear approximation
  - Assume τ directions are collinear to measured decay products
- Primary background from Z+jets with Z → τ⁺ τ⁻
  - Other backgrounds: W+jets, tt, di-jets
- Analysis methods rely on VBF
  - Lack of color flow between interacting partons results in diminished hardonic activity in barrel region
  - Forward tagging jets used to reject SM background
$H \rightarrow \tau^+ \tau^-$ - Signal vs Background

Reconstructed $\tau\tau$ invariant mass for $M_H$ of 120 GeV in the $e\mu$ channel after application of all cuts (except mass window)

Reconstructed $\tau\tau$ invariant mass for $M_H$ of 135 GeV in the $l+\text{hadron}$ channel after application of all cuts (except mass window)
Discovery Potential of $H \rightarrow \tau^+\tau^-$ Channel

Discovery in “low” $M_H$ region possible with 30 fb$^{-1}$

*Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020*
W Boson Pair Decay

\[ H \rightarrow W^+ W^- \rightarrow l\nu l\nu \]

- Provides most sensitive search in range: \(2m_W < M_H < 2m_Z\)
  - Due to dominating \(H \rightarrow WW\) branching ratio in this mass range (~95%)
- Primary source of background from direct \(W^+ W^-\) production (and \(tt\) production)
  - Strongly reduced by cuts based on angular correlation of the \(W\) decay products due to spin correlation of the two \(W\) bosons in \(H\) frame (Lepton Opening Angle)
  - \(tt\) background reduced via veto on central jets
  - Can also extend search to utilize VBF production (tagging jets in final state)
- Problem: Cannot reconstruct Higgs mass peak due to neutrinos in final state!
Presence of high $p_T$ neutrinos makes reconstruction of Higgs mass peak unfeasible.

Excess of events above expected backgrounds used to establish presence of Higgs

Transverse mass based on lepton $p_T$ and missing $E_T$ is used to discriminate between signal and background

- In the inclusive channel:

$$m_T = \sqrt{2P_{ll}^T \cancel{E}_T (1 - \cos \Delta \varphi)}$$

Transverse mass distribution for summed $H \rightarrow WW \rightarrow l\nu l\nu$ signal with $M_H$ of 150 GeV
W Boson Decay - VBF Event Selection

- Further signal enhancement obtained via VBF production mode
  - Presence of tagging jets and veto on central jet activity allow additional suppression of background
  - Result: Signal sensitivity less affected by prediction of background rates

Here, transverse mass defined as:

\[ m_T = \sqrt{(E_T^{ll} + E_T^{\gamma\gamma})^2 + (\mathbf{p}_T^{ll} + \mathbf{p}_T^\gamma)^2} \]

Distribution of transverse mass for \( M_H \) of 160 GeV and backgrounds in the \( e\mu \) channel.
Right plot shows same distribution after relaxing kinematic cuts.
Presence of $H \rightarrow WW$ signal can also be determined via the difference of the azimuthal angle between the two leptons in the final state.

- Expect to see structure at small $\Delta \Phi$ characteristic of spin-0 resonance.
W Boson Decay - Discovery Potential

Significance as a function of different Higgs masses with a luminosity of 5 fb$^{-1}$, solid line for kinematic cuts optimized at $M_H = 165$ GeV, dashed line for kinematic cuts optimized as a function of the Higgs mass.

Discovery potential in $2m_W < M_H < 2m_Z$ range with 5 fb$^{-1}$

V. Drollinger et. al., CMS Note 2006/055
Invisible Higgs Decays

- Several extensions to SM allow for the Higgs boson (or the lightest scalar which plays its role if several are present) to have substantial branching ratios to invisible decay products

- In such models, the light Higgs will decay to Goldstone bosons, Majorons, or a pair of the lightest SUSY particles (LSP)
  - None of these interact with the detector

- Occurs in a variety of SUSY extensions to SM:
  - light neutralinos, spontaneously broken lepton number, radiatively generated neutrino masses, additional singlet scalars, right handed neutrinos in the extra dimensions of TeV scale

- Ex SUSY: Current limits on $M_H$ in general SUSY model kinematically allow for a decay into two LSPs with a BR as high as 0.7

- Ex Models with 4th gen. leptons allow for $H \rightarrow \nu \nu'$ decays
Invisible Higgs - Impact on SM Physics

- Only invisible Higgs decay in SM via: \( H \rightarrow ZZ^* \rightarrow 4\nu \)
  - BR ~ 1% for \( M_H > 180\) GeV and smaller for lower \( M_H \)

- In BSM scenarios invisible Higgs decays can have substantial BR in “intermediate” mass range: 115 GeV < \( M_H < 180\) GeV

- Detection of Higgs in “intermediate” range relies heavily on
  - \( WW \rightarrow (\ell\nu) (\ell\nu) \)
  - \( ZZ^* \rightarrow 4\ell \)

- Reduction of these BRs due to substantial invisible decays could impede/prevent detection of the Higgs

- Presence of invisible Higgs decay modes would require development of new search strategies in the “intermediate” mass range (or beyond)
Invisible Higgs - Search Strategies

- Invisible Higgs detection in dominant GF production not feasible
  - Would have to consider $gg \rightarrow H + \text{jet}$ signatures containing a monojet with large $E_T$ and substantial missing $E_T$ for the event.
  - Such signals overwhelmed by QCD background

- VBF channel combined with tagging jets to reduce QCD background presents viable option
  - Recently shown to be able to probe down to BR $\sim$ 25% with 30 fb$^{-1}$
    [CMS AN -2008/083]
  - Can serve to complement AP channel with high statistics

- Associated production with $W/Z$ provides clean signature by exploiting leptonic decays of $W/Z$
Invisible Higgs - WH vs ZH Channel

- Two options for invisible Higgs decays in associated VB production
  - $qq' \rightarrow W^* \rightarrow W + H \rightarrow (\ell \nu) + \text{invisible}$
    - Signature: single lepton + missing $E_T$
  - $qq' \rightarrow Z^* \rightarrow Z + H \rightarrow (\ell^+\ell^-) + \text{invisible}$
    - Signature: di-lepton + missing $E_T$

- Production rate of WH ~5-6 greater than ZH in “intermediate” mass range

- However, background in WH due to off-shell $W^*$ production overwhelms signal
  - Not a problem for ZH channel since mass-cuts can be made based on di-lepton invariant mass

- ZH channel favored for search despite relatively lower production rate
Invisible Higgs - Background in WH Signal

\[
qq' \rightarrow W^* \rightarrow W + H \quad \Rightarrow \quad l\bar{\nu} \quad \Rightarrow \text{invisible}
\]

- Charged Drell-Yan (DY) production via: \(qq' \rightarrow W^{(*)} \rightarrow l\bar{\nu}\)
- Neutrino decay of Z: \(qq' \rightarrow WZ \rightarrow (l\nu)(\nu\nu)\)
  - Irreducible, yet low BR in SM
- Lepton ID failure: \(qq' \rightarrow WW' \rightarrow (l\nu)(l'\nu')\)
  - If one of the leptons is outside the fiducial volume, it will misrepresent missing \(E_T\)
- Jet ID failure: \(qq' \rightarrow W \rightarrow l\nu + \text{jet}\)
  - Failure to identify the jet results in misidentification as missing \(E_T\)
- Jet misidentification: \(qq' \rightarrow Z + \text{jets} \rightarrow (\nu\nu') + \text{jets}\)
  - Jet misidentified as lepton gives false signal
Invisible Higgs - Background in ZH Signal

\[ qq' \rightarrow Z^* \rightarrow Z + H \]

- DY production: \( qq' \rightarrow Z^* \rightarrow (\ell^+ \ell^-) + \text{jets} \)
  - Failure to ID jets results in false missing \( E_T \) signature

- Irreducible neutrino decay of Z: \( qq' \rightarrow ZZ' \rightarrow (\ell^+ \ell^-)(\nu \nu') \)

- Lepton ID failure: \( qq' \rightarrow WZ \rightarrow (\ell \nu)(\ell^+ \ell^-) \)
  - Failure to identify one lepton results in false signal

- WW production: \( qq' \rightarrow WW \rightarrow (\ell \nu)(\ell \nu) \)
Invisible Higgs - Cuts in ZH Channel

- Select events with exactly two leptons, same flavor and opposite sign
  - Kinematic requirement: \(|M_{\ell\ell} - M_Z| < 10 \text{ GeV}\)
  - Transverse energy threshold: \(E_T^{\ell} > 10 \text{ GeV}\)
  - Fiducial cut: \(|\eta^{\ell}| < 3\)

- Hadronic veto on jets in the barrel region
  - Reject jets with \(E_T^{j} > 30 \text{ GeV}\) or \(|\eta^j| < 4\)

- Enforce missing transverse momentum threshold
  - Requite: missing \(p_T > 30 \text{ GeV}\)
Invisible Higgs - ZH BR Limits

P. Gagnon - ATLAS Physics Workshop - May 2003
Invisible Higgs - WH vs ZH

**WH**

$E_T^\ell$ distribution for signal (dashed) and background (solid) in WH channel for 100 fb$^{-1}$

**ZH**

Missing $p_T$ distribution for signal (dashed) and background (solid) in ZH channel for 100 fb$^{-1}$

Signal for ZH channel comparable to background (due to ZZ and WZ cross sections). Better signal ratio expected once LHC measures these cross sections.

Invisible Higgs - Discovery Potential

ATLAS sensitivity at 95% CL for 30 fb\(^{-1}\) of integrated luminosity

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

\(\xi^2 < 1\): Observation of invisible Higgs possible with SM \(\sigma\)

\(\xi^2 > 1\): Observation of invisible Higgs requires enhanced \(\sigma\)

Conclusions

- The Search for Higgs boson(s) is a complex problem requiring multifaceted approach
  - All search channels needed to probe entire mass range
  - No single channel alone will suffice, since discovery of a Higgs boson in one mass region does not exclude existence in other regions
- Background considerations strongly affect signal significance at LHC
  - Signals with diminished production rates can play substantial roles
- Invisible Higgs searches are important tools for:
  - Verifying SM predictions
  - Providing early indication for new physics