Discovering the Higgs with Low Mass Muon Pairs

Mariangela Lisanti

SLAC/Stanford

June 7, 2009

Andy Haas w/DØ Collaboration, arXiv: 0905.3381
Status of Higgs Searches

[as of March 2009]

Mariangela Lisanti

June 7, 2009
LEP Direct Bounds

Mass limit of 114 GeV pertains specifically to Standard Model decay modes

\[ e^+ \rightarrow Z^0 \rightarrow e^+ + e^- \]

\[ e^- \rightarrow Z^{0*} \rightarrow b, \bar{b}, \tau^+, \bar{\tau}^- \]
LEP Direct Bounds

Mass limit of 114 GeV pertains specifically to Standard Model decay modes

Nonstandard Decays

Model-independent: $m_{h^0} \gtrsim 82$ GeV
LEP Direct Bounds

Mass limit of 114 GeV pertains specifically to Standard Model decay modes

Nonstandard Decays

Model-independent: $m_{h^0} \gtrsim 82$ GeV

Cascade-decaying Higgs: $m_{h^0} \gtrsim 86$ GeV
Cascading Higgs

Let Higgs decay dominantly to two new scalars

\[ h^0 \rightarrow \phi \phi \rightarrow (\tau^+ \tau^-)(\tau^+ \tau^-) \]

Unexplored light Higgs region


Mariangela Lisanti

June 7, 2009
Pseudoscalars

Approximate symmetry in Higgs potential explicitly broken

pseudo-Goldstone bosons

pseudoscalars have $O(1)$ coupling to Higgs

Higgs has substantial branching fraction to pseudoscalars
Outline

I. Light pseudoscalar phenomenology

II. Cascade-decaying higgses at colliders

III. Preliminary results from DØ experiment
Two Higgs doublet model with additional singlet

\[ H_u = \left( \frac{1}{\sqrt{2}} (v \sin \beta + h_u) \right) e^{ia_u/v \sin \beta} \quad H_d = \left( \frac{1}{\sqrt{2}} (v \cos \beta + h_d) \right) e^{ia_d/v \cos \beta} \]

\[ S = \frac{1}{\sqrt{2}} (\langle S \rangle + s^0) e^{ia_s/\langle S \rangle} \]

The interactions between the three pseudoscalars \( a_u, a_d, a_s \) arise from

(i) derivative couplings in kinetic terms
(ii) symmetry breaking terms in the potential
Symmetry Breaking

\[ \mathcal{L} = \mathcal{L}_{\text{kin}} - \lambda_1 S^2 H_u^\dagger H_d^\dagger - \lambda_2 S^2 H_u H_d + \text{h.c.} \]

(Pseudo-) Goldstones

\[ \omega_{Z^0} = -a_u \sin \beta + a_d \cos \beta \]

Gives mass to the $Z^0$
Symmetry Breaking

\[ \mathcal{L} = \mathcal{L}_{\text{kin}} - \lambda_1 S^2 H_u^\dagger H_d^\dagger - \lambda_2 S^2 H_u H_d + \text{h.c.} \]

(Pseudo-) Goldstones

1. \[ \omega_{Z^0} = -a_u \sin \beta + a_d \cos \beta \] Gives mass to the \( Z^0 \)

2. \[ A^0 = \cos \theta_a (a_u \cos \beta + a_d \sin \beta) - a_s \sin \theta_a \] Heavy pseudo-Goldstone
Symmetry Breaking

\[ \mathcal{L} = \mathcal{L}_{\text{kin}} - \lambda_1 S^2 H_u^\dagger H_d^\dagger - \lambda_2 S^2 H_u H_d + \text{h.c.} \]

1. \[ \omega_{Z^0} = -a_u \sin \beta + a_d \cos \beta \] Gives mass to the $Z^0$

2. \[ A^0 = \cos \theta_a (a_u \cos \beta + a_d \sin \beta) - a_s \sin \theta_a \] Heavy pseudo-Goldstone

3. \[ a^0 = \sin \theta_a (a_u \cos \beta + a_d \sin \beta) + a_s \cos \theta_a \] Light pseudo-Goldstone

(Pseudo-) Goldstones
Coupling to Higgs

\[ \mathcal{L}_{\text{int}} = \tilde{c}_h \frac{v}{\langle S \rangle^2} h^0 \partial_{\mu} a^0 \partial_{\mu} a^0 - \tilde{d}_h \frac{m_{a^0}^2}{v} h^0 a^0 a^0 \]

- Kinetic terms in Lagrangian give
  \[ \tilde{c}_h \frac{v}{\langle S \rangle^2} \sim \frac{1}{1 + \left( \frac{\langle S \rangle}{\sin 2\beta} \right)^2} \]

- Value of \( \tilde{d}_h \) depends on symmetry breaking potential

\[ \langle S \rangle / \sin 2\beta \ (\text{GeV}) \]

\[ \text{Br}(h^0 \rightarrow a^0 a^0) \]

symmetry-preserving interaction dominates below 1000 GeV
LEP Limits

LEP sets limits on branching fraction of Higgs into Standard Model

\[ \xi_{h \rightarrow X}^2 \equiv \frac{\sigma(e^+e^- \rightarrow Zh)}{\sigma(e^+e^- \rightarrow Zh)_{SM}} \text{Br}(h \rightarrow X) \]

This translates into a bound on coupling strength of Higgs to a\(^0\)

Mariangela Lisanti
June 7, 2009
Coupling to Fermions

\[ \mathcal{L}_{\text{int}} = ig_f \frac{m_f}{v} \bar{f} \gamma_5 f a^0 \]

\[ g_f = \sin \theta_a \begin{cases} \cot \beta & \text{(up-type quarks)} \\ \tan \beta & \text{(down-type quarks/leptons)} \end{cases} \rightarrow \text{suppressed by 2 powers of } \tan \beta \]

Below the b-quark threshold, pseudoscalar decays primarily to taus rather than charm quarks
CLEO limits

CLEO sets limits on the coupling of $a^0$ to fermions

$$\frac{\text{Br}(\Upsilon \to a^0 \gamma)}{\text{Br}(\Upsilon \to \mu^+\mu^-)} \propto g_d^2 \left( 1 - \frac{m_{a^0}^2}{m_{\Upsilon}^2} \right)$$

Region allowed by LEP for 87-110 GeV Higgs

\[ \langle S \rangle / \sin 2\beta \sim 250 \text{ GeV} \]

\[ \langle S \rangle / \sin 2\beta \sim 500 \text{ GeV} \]

\[ \langle S \rangle / \sin 2\beta \sim 1000 \text{ GeV} \]
CLEO sets limits on the coupling of $a^0$ to fermions

$$\frac{\text{Br}(\Upsilon \to a^0\gamma)}{\text{Br}(\Upsilon \to \mu^+\mu^-)} \propto g_d^2 \left(1 - \frac{m_{a^0}^2}{m_{\Upsilon}^2}\right)$$

**Tension**

LEP results prefer strong coupling of pseudoscalar to Higgs... but CLEO results tightly bound this region.
Outline

I. Light pseudoscalar phenomenology

II. Cascade-decaying higgses at colliders

III. Preliminary results from DØ experiment
Signal

\[ h^0 \rightarrow 4\tau \rightarrow \text{leptons} + \not{E}_T \]

Challenges

• Tau decays leptonically 33% of time
• Leptons are soft
Branching fraction of $a^0$ to muons is much smaller than that to taus

$$\frac{\Gamma(a^0 \rightarrow \mu^+\mu^-)}{\Gamma(a^0 \rightarrow \tau^+\tau^-)} = \frac{m_{\mu}^2}{m_{\tau}^2 \sqrt{1 - (2m_{\tau}/m_{a^0})^2}}$$

Despite small branching fraction to muons...

For 7 GeV pseudoscalar,

$$\text{Br}(a^0 \rightarrow \mu^+\mu^-) = 0.4\%$$
$$\text{Br}(a^0 \rightarrow \tau^+\tau^-) = 98\%$$

300 events 20 fb$^{-1}$ Tevatron
250 events 0.5 fb$^{-1}$ LHC
Characteristic Signatures

• collinear, high pT muon pair

• 1 or 2 jets opposite to the muons

• Missing energy acoplanar with muons
Main Backgrounds

Drell-Yan

Most important background
Muons recoil against ISR jet
Missing energy from jet energy mismeasurement or neutrinos from heavy semileptonic decays in jet

Summary

<table>
<thead>
<tr>
<th></th>
<th>DY+j</th>
<th>WW</th>
<th>tt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>0.15</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>LHC</td>
<td>0.24</td>
<td>0.08</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Mariangela Lisanti
June 7, 2009
Hadronic Backgrounds

(i) Double semi-leptonic decays

Background:  \( b \rightarrow c \rightarrow s/d \)

Minimal because: hadronic activity surrounding muons
high pT muons are rare
Hadronic Backgrounds

(i) Double semi-leptonic decays

**Background:** \( b \to c \to s/d \)

**Minimal because:** hadronic activity surrounding muons
high pT muons are rare

(ii) Heavy flavor quarkonia

**Background:** \( \Upsilon \to \tau's \to \mu's \)

**Minimal because:** missing energy in direction of muon pair
pT spectrum of \( \Upsilon \) falls off rapidly
Hadronic Backgrounds

(i) Double semi-leptonic decays

*Background:* \( b \rightarrow c \rightarrow s/d \)

*Minimal because:* hadronic activity surrounding muons
high pT muons are rare

(ii) Heavy flavor quarkonia

*Background:* \( \Upsilon \rightarrow \tau's \rightarrow \mu's \)

*Minimal because:* missing energy in direction of muon pair
pT spectrum of \( \Upsilon \) falls off rapidly

(ii) Leptonic decays of light mesons

*Background:* \( J/\Psi \) muon invariant mass distribution

*Minimal because:* Lorentzian tail of decay width
Gaussian mismeasurement tail

Hadronic contribution is \(< 10\%\) Drell-Yan background
Muon Invariant Mass

LHC, 5 fb$^{-1}$

Events

Muon Invariant Mass (GeV)

Signal

D-Y Background
Total Invariant Mass

Events

Total Invariant Mass (GeV)

Mariangela Lisanti

June 7, 2009
Total Invariant Mass

LHC, 5 fb⁻¹

* Project missing energy in direction of hardest jet *
Expected Sensitivity

Combined results of DØ and CDF can set lower limit on Higgs mass regardless of admixture to pseudoscalars

Recover LEP limit with ~1 fb⁻¹

Higgs discovery with sub-fb⁻¹ data set possible
DØ Results


Mariangela Lisanti

June 7, 2009
Conclusions

• Possible to evade LEP bound if Higgs decays primarily to pseudoscalars

• Light pseudoscalars typical when there is an approximate symmetry in Higgs potential that is broken

• Possible to discover cascading Higgs in $2\mu 2\tau$ channel with complete Tevatron data set or early data at LHC
Extras
Light Higgs in Theory

One-loop corrections to Higgs mass in MSSM:

\[ m_{h^0}^2 \simeq m_{Z^0}^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left( \log \frac{m_t^2}{m_{\tilde{t}}^2} + a_t^2 \left(1 - \frac{a_t^2}{12}\right) \right) \]

Mass corrections depend on stop mass \( m_{\tilde{t}} \) and mixing \( a_t \simeq \frac{A_t}{m_{\tilde{t}}} \)

<table>
<thead>
<tr>
<th>Moderate Mixing</th>
<th>Maximal Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_h = 120 \text{ GeV} )</td>
<td>( m_h = 130 \text{ GeV} )</td>
</tr>
<tr>
<td>( m_h = 120 \text{ GeV} )</td>
<td></td>
</tr>
</tbody>
</table>

Mariangela Lisanti       June 7, 2009