$h \rightarrow 2a \rightarrow 4\tau$ at ALEPH

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New York University

arXiv:1003.0705
The Higgs was not observed at LEP

Direct searches placed a lower bound on the Higgs mass of $114 \text{ GeV/c}^2$

- Narrow range of $114 \text{ (LEP)} < M_H < 157 \text{ (Tevatron)}$ not yet excluded

However, EW fits prefer a light Higgs mass

Additionally, suggestive excess at $\sim 98 \text{ GeV/c}^2$, consistent with NMSSM (R. Dermisek and J. F. Gunion, Phys.Rev.D73:111701, 2006)
How could we have missed the Higgs?

If the Higgs exists and is light, how could we have missed it at LEP?

- One way: If the production cross-section were smaller than expected
  - Has direct implications on how the Higgs couples to the Z and its role in electroweak symmetry breaking
- Another way: If it decayed into something exotic that the standard analyses missed
  - Small $Hb\bar{b}$ coupling $\Rightarrow$ new decay modes can dominate the $b\bar{b}$ mode

A prominent example is the next-to-minimal supersymmetric extension of the standard model (NMSSM), where $a$ is naturally light

- allows for $h \rightarrow aa$, where $a$ is pseudoscalar (mixture of A from MSSM)
- if $m_a < 2m_b$, evades 4$b$ searches and expect $a \rightarrow \tau^+ \tau^-$


**OPAL low A-mass search**

OPAL also carried out a search in the region $2m_\tau < m_a < 11\text{ GeV}/c^2$

Search for a low mass CP-odd Higgs boson in $e^+e^-$ collisions with the OPAL detector at LEP2

### 6.2 MSSM no-mixing scenario interpretation

We scan the region with $2 \leq m_A \leq 11\text{ GeV}/c^2$ and $45\text{ GeV}/c^2 \leq m_h \leq 85\text{ GeV}/c^2$ in the $m_A$ versus $m_h$ plane for the MSSM benchmark parameter scenario. The maximum theoretically allowed value for $m_h$ in this scenario is $85\text{ GeV}/c^2$ [6]. The scan procedure...
Going back to LEP data

LEP operated from 1989-2000

<table>
<thead>
<tr>
<th>$E_{CM}$ (GeV)</th>
<th>183</th>
<th>189</th>
<th>192</th>
<th>196</th>
<th>200</th>
<th>202</th>
<th>205</th>
<th>207</th>
</tr>
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<tr>
<td>$\int L,dt$ (pb$^{-1}$)</td>
<td>56.82</td>
<td>174.21</td>
<td>28.93</td>
<td>79.83</td>
<td>86.30</td>
<td>41.90</td>
<td>81.41</td>
<td>133.21</td>
</tr>
</tbody>
</table>

= 683 pb$^{-1}$

Resurrecting the ALEPH analysis framework and accessing the data required some archeology

The ALEPH Detector
Simulated signal event \[ e^+e^- \rightarrow ZH \rightarrow 2e4\tau \]

2 back-to-back electrons clearly distinguished from 2 back-to-back jets. Not much else in the event; about 50 GeV of missing energy (from the taus).
Reconstructing $a \rightarrow \tau^+ \tau^-$

The $h$ is produced nearly at rest, thus the $h \rightarrow aa$ are nearly back-to-back

On each side, $a \rightarrow \tau^+ \tau^-$ leads to a well collimated jet from the decay products of two taus, with mass $< m_a$, which were clustered with the JADE algorithm (requiring $m_j < 15 \text{ GeV}/c^2$)

Standard tau algorithms will not be efficient for highly collinear $a \rightarrow \tau^+ \tau^-$

- but the jet has a characteristic multiplicity corresponding to 1-prong (85%) and 3-prong (15%) branching ratios of the taus
  - expect 2, 4, or 6 tracks in each jet
  - conversions lead to some spillage
  - require jets to be well-contained so tracking efficiency is stable and high

In the end, only use jets with 2 or 4 tracks
$Zh \rightarrow e^+ e^- 4\tau$ & $Zh \rightarrow \mu^+ \mu^- 4\tau$

Clean channel (because of the Z peak), but the signal rate is very low
- use standard ALEPH lepton ID
- no tau reconstruction; we remove leptons and photons from the event, and run our JADE jet algorithm on remainder

Loose selection:
- 2 oppositely charged, isolated leptons
- 2 jets, well-contained within tracking volume
- jets and leptons sufficiently isolated from each other

Final selection:
- invariant mass of lepton pair near Z mass
- some missing energy (from neutrinos from tau decays)
- jets separated
- signal-like track multiplicity

\[ \cos \theta_j < 0.9 \]
\[ |\cos \theta^{\text{min}}_{jl}| < 0.95 \]
\[ 80 < M_{l^+ l^- (\gamma)} < 102 \text{ GeV} / c^2 \]
\[ E > 20 \text{ GeV} \]
\[ \cos \theta_{jj} < 0 \]
\[ n^{trk}_{1,2} = 2 \text{ or } 4 \]

<table>
<thead>
<tr>
<th>@ loose selection</th>
<th>data</th>
<th>background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z &gt; e^+ e^-$</td>
<td>299</td>
<td>332</td>
</tr>
<tr>
<td>$Z &gt; \mu^+ \mu^-$</td>
<td>83</td>
<td>75</td>
</tr>
</tbody>
</table>
Zh → ν̅ν 4τ

Drives analysis due to larger Z branching ratio

- more difficult, because of the lack of a clean Z → ll

Loose selection:

- missing energy and mass
  \[ E > 30 \text{ GeV} \]
  \[ |\cos \theta_j| < 0.85 \]
  \[ m_{jj} > 10 \text{ GeV/c}^2 \]

- exactly 2 jets, well-contained
  \[ |\cos \theta_{\text{miss}}| < 0.9 \]
  \[ E_{\text{vis}} > 0.05 E_{\text{CM}} \]
  \[ E_{j_1} > 25 \text{ GeV} \]
  \[ n^{\text{trk}}_1 = 2 \text{ or } 4 \]

<table>
<thead>
<tr>
<th>@ loose selection</th>
<th>data</th>
<th>background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z &gt; νν</td>
<td>206</td>
<td>200</td>
</tr>
</tbody>
</table>

Final selection:

- less than 5 GeV within 30° of beam axis
- consistency with Z → ν̅ν: \[ \bar{E} > 60 \text{ GeV} \text{ and } \eta \bar{H} > 90 \text{ GeV/c}^2. \]
- small aplanarity (<0.05) consistent with 2 back-to-back, highly collimated jets
  - signal has higher aplanarity for high \( m_a \) and low \( m_h \): cut chosen to maintain efficiency
  - signal-like track multiplicity \( n^{\text{trk}}_{1,2} = 2 \text{ or } 4 \)
Our signal efficiency is good, but very few events in lepton channels:

- but we also have < 0.1 expected background in $Z \rightarrow ll$ channels
- expect 6 background events in $Z \rightarrow \nu\bar{\nu}$ channel
**Results at loose selection**

Good agreement between data and MC

- Estimate systematics from tracking, jet energy scale, energy deposits in forward region (beam halo), etc.
  - 5% uncertainty on signal efficiency; 10% for background in lepton channels; 30% for neutrino channel
  - data/MC consistent well within this range; statistical errors dominate

![Graph 1](zh-mumu4tau.png)

![Graph 2](zh-elee4tau.png)
Observations after all selection criteria

Here, for signal with $m_h = 100 \text{ GeV}/c^2$

$Zh \rightarrow \nu \bar{\nu} \ 4\tau$

$Zh \rightarrow e^+ e^- 4\tau$

$Zh \rightarrow \mu^+ \mu^- 4\tau$

0 events observed after all cuts

Data
Limits

Based on event counts in (3 track multiplicity bins) X (3 Z decay channels)

- very weak dependence on $m_a$

$$\xi^2 = \frac{\sigma \text{BR}(h \rightarrow aa) \text{BR}(a \rightarrow \tau\tau)}{\sigma_{SM}}$$

![Graph showing observed and expected upper limits for $\sigma_{SM}$ with $m_a = 10 \text{ GeV/c}^2$](image.png)
Limits

Based on event counts in (3 track multiplicity bins) X (3 Z decay channels)

- very weak dependence on m_a

\[ \xi^2 = \frac{\sigma \text{BR}(h \rightarrow aa) \text{BR}(a \rightarrow \tau\tau)^2}{\sigma_{SM}} \]

\( m_a = 10 \text{ GeV/c}^2 \)
Limits

Based on event counts in (3 track multiplicity bins) X (3 Z decay channels)

- very weak dependence on $m_a$

$$\xi^2 = \frac{\sigma \text{BR}(h \rightarrow aa) \text{BR}(a \rightarrow \tau\tau)^2}{\sigma_{SM}}$$

Figure 7: Upper limits at 95% CL for $s_2$ in the $m_A$ versus $m_h$ plane, assuming 100% decays of $h_0$ into $A_0 A_0$ and 100% decays of $A_0 A_0$ into (a) $c\bar{c} c\bar{c}$ (b) $gggg$ (c) $\tau^+ \tau^- \tau^+ \tau^-$ (d) $\tau^+ \tau^- gg$ (e) $c\bar{c} \tau^+ \tau^-$ and (f) $c\bar{c} gg$. The iso-contour lines are for values of $s_2 \leq 1, 0.8, 0.6, 0.5, 0.4$ and 0.2. These limits are derived using the combined results from $Z_0 \rightarrow \nu \bar{\nu}$, $Z_0 \rightarrow \mu^+ \mu^-$ and $Z_0 \rightarrow e^+ e^-$ channels and for centre-of-mass energies between 189 and 209 GeV.
Limits

Based on event counts in (3 track multiplicity bins) X (3 Z decay channels)

- very weak dependence on $m_a$

$$\xi^2 = \frac{\sigma \text{BR}(h \rightarrow aa) \text{BR}(a \rightarrow \tau\tau)}{\sigma_{SM}}$$

![Graph showing limits on $m_a$ and $m_h$](image)

James Beacham (NYU)  Moriond QCD, 17 March 2010
Conclusions

We revisited the ALEPH data, looking for $h \rightarrow aa \rightarrow 4\tau$
in the range $70 < m_h < 114$ GeV/$c^2$ and $4 < m_a < 12$ GeV/$c^2$, 
- allowed us to close one of the few remaining holes in LEP Higgs searches

First analysis: $e^+e^- \rightarrow Zh \rightarrow (ee, \mu\mu, \nu\nu) 4\tau$. No excess observed.

New Limits:
- for $m_h < 107$ GeV/$c^2$ and $4 < m_a < 10$ GeV/$c^2$, 
  $\xi^2 > 1$ is excluded at 95% CL
- extend the limits from the OPAL analysis
- exclude some NMSSM Higgs scenarios, except for those at low $\tan\beta \approx 2$, where there is a larger BR($a \rightarrow c\bar{c}, gg$)

These new results available at arXiv:1003.0705 (since 3 March); submitted to JHEP
- we may follow up with other analyses to close remaining holes

Advisor: Kyle Cranmer (NYU)
Collaborators: Itay Yavin (NYU), Paolo Spagnolo (INFN Pisa), for the ALEPH Collaboration
Acknowledgments: Neal Weiner, Riccardo Barbieri
Backups
Event Counts

Numbers of events in different track multiplicity bins

Table 3: Number of events passing loose and final selections in each channel, in data, simulated background, and simulated signal \((m_h = 100, m_a = 4 \text{ GeV}/c^2)\). The numbers of events passing the final selection are categorised by track multiplicity.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Selection ((n_1^{\text{track}}, n_2^{\text{track}}))</th>
<th>data</th>
<th>total background</th>
<th>background category</th>
<th>signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z \to e^+e^-)</td>
<td>Loose ((2,2))</td>
<td>299</td>
<td>332</td>
<td>183 137 12.31 0.65</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td>((2,4)+(4,2))</td>
<td></td>
<td></td>
<td>0.034 0.000 0.000 0.000</td>
<td>0.689</td>
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<tr>
<td></td>
<td>((4,4))</td>
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<td></td>
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<td>(Z \to \mu^+\mu^-)</td>
<td>Loose ((2,2))</td>
<td>83</td>
<td>74.50</td>
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<tr>
<td></td>
<td>((2,4)+(4,2))</td>
<td></td>
<td></td>
<td>0.058 0.053 0.000 0.000</td>
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<tr>
<td></td>
<td>((2,2))</td>
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<td>0.005 0.005 0.000 0.000</td>
<td>0.676</td>
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<td>0.006 0.006 0.000 0.000</td>
<td>0.127</td>
</tr>
<tr>
<td>(Z \to \nu\bar{\nu})</td>
<td>Loose ((2,2))</td>
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<td>200</td>
<td>135 47.97 13.50 3.74</td>
<td>12.63</td>
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<tr>
<td></td>
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<td>1.948 0.575 0.845 0.000</td>
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<td></td>
<td>2.569 0.820 1.288 0.000</td>
<td>1.089</td>
</tr>
</tbody>
</table>

\[
P(N_{m,f}|\xi^2, b_{m,f}) = \prod_{m \in \mathcal{M}} \prod_{f \in \{ee, \mu\mu, \nu\nu\}} \text{Pois}(N_{m,f}|\xi^2 s_{m,f} + b_{m,f}) \cdot N(b_{m,f}^{MC}|b_{m,f}, \Delta_f).
\]
Monte Carlo

Two particularly important processes for these searches are 4 fermion and 2 photon processes

4f Four fermion events compatible with $WW$ final states are generated using KoralW 1.51 [69], with quarks fragmented into parton showers and hadronized using either PYTHIA 6.1 [38]. Events with final states incompatible with $WW$ production but compatible with $ZZ$ production are generated with KoralZ

2ph Two-photon interaction processes, $e^{+}e^{-} \rightarrow e^{+}e^{-}X$, are generated with the PHOT02 generator [70]. When $X$ is a pair of leptons, a QED calculation is used with preselection cuts to preferentially generate events that mimic $WW$ production. When $X$ is a multi-hadronic state, a modified version of PYTHIA is used to generate events with the incident beam electron and positron scattered at $\theta < 12^\circ$ and $168^\circ < \theta$, respectively. Events in which the beam electron or positron is scattered through an angle of more than $12^\circ$ are generated using HERWIG 6.2 [39].
Monte Carlo Simulation

After decades of running in a very clean environment, and tuning Monte Carlo to data the description of standard model processes in ALEPH is excellent.

$q\bar{q}$  The process $e^+e^- \rightarrow Z/\gamma^* \rightarrow q\bar{q}(\gamma)$ is modeled using KK 4.14 [67], with initial state radiation from KK and final state radiation from PYTHIA.

$e^+e^-$  Bhabha scattering and $e^+e^- \rightarrow Z/\gamma^* \rightarrow e^+e^- (\gamma)$ is modeled using BH\textsc{wide} 1.01 [68].

$\mu^+\mu^-$  Pair production of muons, $e^+e^- \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^- (\gamma)$, is calculated using KK 4.14 [67], including initial and final state radiative corrections and their interference.

$\tau^+\tau^-$  Pair production of taus, $e^+e^- \rightarrow Z/\gamma^* \rightarrow \tau^+\tau^- (\gamma)$, is calculated using KK 4.14 [67], including initial and final state radiative corrections and their interference.

$Iph$  Single photon production, $e^+e^- \rightarrow Z/\gamma^* \rightarrow \nu\bar{\nu} (\gamma)$, is included in the background estimate.

$Nph$  Multiphoton production, $e^+e^- \rightarrow n\gamma$, with $n \geq 2$, is included in the background estimate.
**Expected significance**

For what it’s worth: Our goal was not to just set a limit... certainly not a mediocre one. We saw we had discovery sensitivity early on, so we really went for a discovery.

- Since the analysis was blind, we really didn’t know

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**Expected discovery significance for \( m_a = 4 \text{ GeV} \)**
Blind analysis

Because the LEP data is old and it is not possible to confirm anything with “next year’s data”, we had to be quite careful

- remember, we’re shooting for a discovery!
- no one would believe a signal if we adjusted our cuts looking at data
- Also, we don’t want to spoil the other analyses that we might be interested in: $a \rightarrow \text{jets, } \mu, ..$

But we do need to verify that our Monte Carlo is describing the data well.

- So we did a blind blind analysis and defined 5 control samples
  1. exclude $m_{ll}$ around $M_Z$, that kills our signal, but otherwise similar
  2. Select events if #tracks<2 for each jet (kills $\tau\tau, \mu\mu, q\bar{q}, gg$ )
  3. in $Z \rightarrow ll$ exclude events with $M(j_1, j_2, \text{invisible}) > 60 \text{GeV}$
  4. in $Z \rightarrow \nu\nu$ exclude events with missing mass > 80 GeV
  5. exclude events with #track>6 in both jets (to remove taus) AND if di-jet mass > 60 (to avoid seeing $h \rightarrow aa \rightarrow q\bar{q}, gg$ if it exists)
**Blind analysis**

Because the LEP data is old and it is not possible to confirm anything with “next year’s data”, we had to be quite careful:

- remember, we’re shooting for a discovery!
- no one would believe a signal if we adjusted our cuts looking at data
- Also, we don’t want to spoil the other analyses that we might be interested in: \( a \rightarrow \text{jets, } \mu, .. \)

But we do need to verify that our Monte Carlo is describing the data well.

- So we did a blind blind analysis and defined 5 control samples
  1. exclude \( m_{ll} \) around \( M_Z \), that kills our signal, but otherwise similar
  2. Select events if \#tracks<2 for each jet (kills \( \tau\tau, \mu\mu, q\bar{q}, gg \))
  3. in \( Z \rightarrow ll \) exclude events with \( M(j_1, j_2, \text{invisible}) > 60 \text{GeV} \)

James Beacham (NYU)  
Moriond QCD, 17 March 2010
“Unboxing” celebration

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- since the analysis was blind, we really didn’t know

Champagne
(to be consumed regardless of result)

Thanks, Neal!

Oct. 9, 2009
The ALEPH detector

Tracking: silicon + large time projection chamber (~31 hits)

\[
\frac{\Delta 1/p_T}{1/p_T} = (6 \cdot 10^{-4} \oplus 5 \cdot 10^{-3}/p_T)
\]

ECAL: lead + proportional wire chambers, 22X₀

\[
\frac{\Delta E}{E} = 0.18/\sqrt{E}
\]

HCAL: 23 layers of iron yolk + streamer tubes

\[
\frac{\Delta E}{E} = 0.85/\sqrt{E}
\]

muons identified via HCAL + 2 muon chambers

Detector simulation based on Geant 3, analysis based on 10 year old fortran framework
Choice of jet algorithms

At LEP, the dominant jet algorithms were DURHAM and JADE.

- both are iterative recombination type algorithms: merge if $m_{ij}^2 / E_{\text{tot}}^2 < y_{\text{cut}}$
  - $y_{\text{cut}}$ is an adjustable parameter and $E_{\text{tot}}$ was often chosen to be the visible energy in the event
  - Often (as in the case of the OPAL analysis), events were “forced into N jets”, eg. the algorithm scanned $y_{\text{cut}}$ until the event had exactly N jets.
    - Then that value of $y_{\text{cut}}$ would be used as a discriminating variable together with the jet’s mass.
- DURHAM defines $m_{ij}^2$ in a way that is more robust to soft radiation, which is good if you are interested in bona fide hadronic showers.
  - But we are looking for a purely electroweak decay, so the straight invariant mass combination of JADE is more natural.
  - Furthermore, we know that we are interested in $m_a < 15 \text{ GeV}$ which leads to an obvious choice for $y_{\text{cut}}$ if we use a fixed $E_{\text{tot}}$.

By choosing this approach our s/b was significantly higher than forcing to two jets with DURHAM and cutting on the jet mass
  - Additionally we have track multiplicity in jets as a handle
**Figure 3:** Sections motivated by the Higgsstrahlung cascade process plot. In plot (a) the Higgs bosons produced via Higgsstrahlung decaying to $4b$ are highly constrained. Here we see that Higgs bosons produced via Higgsstrahlung decaying to $4b$ are highly constrained.

- $4\tau$ are less constrained with a notable hole for $m_h > 85$ GeV, $2m_\tau < m_\alpha < 10$ GeV.
**Higgs production at LEP**

Higgs primarily produced via higgsstrahlung process

- kinematic threshold for production $\sim 115$ GeV
- in that mass range, standard model Higgs decays dominated by $H \rightarrow bb, \tau\tau$

Many (most) MSSM Higgs searches were recycled versions of SM searches

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**Diagram**:

- **Left Panel**: Diagram showing Higgs production processes, including $bb$, $WW$, $ZZ$, $gg$, $\gamma\gamma$, $Z\ell\ell$, $t\bar{t}$, plotted against $M_H$ (in GeV) on a logarithmic scale.

- **Right Panel**: Graph showing $\sigma(p\text{b})$ versus $\sqrt{s}$ (in GeV) for different Higgs masses ($M_H=60, 70, 80, 90, 100$ GeV$^2$), with a focus on the process $e^+e^- \rightarrow HZ$.

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**Figure 10**

- **Left**: Diagram illustrating Higgs production via vector boson fusion (VBF), shown with $e^+e^- \rightarrow HZ$.

- **Right**: Graph depicting the Higgs boson's coupling to vector bosons ($Z$, $W$, $\gamma$).
Some results from LEP Higgs searches

Searches for the Standard Model Higgs put a limit at $M_H > 114.4$ GeV

- SM searches dominated by $H \rightarrow bb, \tau\tau$

Searches for neutral Higgs bosons in the MSSM also quite stringent

- $m_h, m_A < 93$ for $0.5 < \tan \beta < 2.5$ in “$m_h$-max” scenario

Decay independent based on Z recoil place a lower limit at 82 GeV

- other decay topologies, flavor independent analyses, etc. were considered.
The other LEP Higgs excess

Plots take time to interpret, main features:

- Excess at 115 GeV is SM like
- Larger excess at 98 GeV is not SM like: \( \sim 10\% \) SM BR(H->bb)

New decays would compete with h->bb decay

1-CLb

LEP

1

-1

10

-2

10

-3

80 85 90 95 100 105 110 115 120

mH(GeV/c^2)

 Expected for signal plus background
 Expected for background

Observed

m_a<2m_b

solid: observed limit
dashed: expected limit

C_{2h}^2 vs. m_h

F<10

10\leq F<25

m_a<2m_b

0.05

0.10

0.20

0.50

1.00

0.01

0.02

0.05

0.10

0.20

0.50

1.00

0.01

20

40

60

80

100

120

m_h (GeV)
### Summary of similar LEP searches

<table>
<thead>
<tr>
<th>Process</th>
<th>$m_{H_2}$</th>
<th>$m_{H_1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow H_2Z \rightarrow (H_1H_1)Z \rightarrow (\ldots)(\ldots)$</td>
<td>91</td>
<td>16.2</td>
</tr>
<tr>
<td>$(\text{any})(qq)$</td>
<td>91</td>
<td>9.7</td>
</tr>
<tr>
<td>$V^0\bar{V}^0(\text{any but } \tau^+\tau^-)$</td>
<td>91</td>
<td>12.5</td>
</tr>
<tr>
<td>$(\gamma\gamma)(\text{any})$</td>
<td>91</td>
<td>12.9</td>
</tr>
<tr>
<td>$(4 \text{ prongs})(\text{any})$</td>
<td>91</td>
<td>12.9</td>
</tr>
<tr>
<td>$(\text{hadrons})(\nu\bar{\nu})$</td>
<td>91</td>
<td>15.1</td>
</tr>
<tr>
<td>$(\tau^+\tau^-\tau^+\tau^-)(\nu\bar{\nu})$</td>
<td>161,172</td>
<td>20.0</td>
</tr>
<tr>
<td>$(\text{any})(\nu\bar{\nu})$</td>
<td>183</td>
<td>54.0</td>
</tr>
<tr>
<td>$(\text{b}b\text{b}b)(qq)$</td>
<td>183</td>
<td>54.0</td>
</tr>
<tr>
<td>$(\text{b}b\text{b}b, b\text{b}c\text{c}, c\text{c}c\text{c})(qq)$</td>
<td>192-208</td>
<td>452.4</td>
</tr>
<tr>
<td>$(\text{c}c\text{c}c)(qq)$</td>
<td>192-208</td>
<td>452.4</td>
</tr>
<tr>
<td>$(\text{H}_1 \rightarrow bb, cc, gg)(qq)$</td>
<td>189 - 209</td>
<td>626.9</td>
</tr>
<tr>
<td>$(qqq\bar{q})(\nu\bar{\nu})$</td>
<td>183</td>
<td>54.1</td>
</tr>
<tr>
<td>$(b\bar{b}b)(qq)$</td>
<td>189</td>
<td>172.1</td>
</tr>
<tr>
<td>$(b\bar{b}b)(qq)$</td>
<td>192-209</td>
<td>421.2</td>
</tr>
<tr>
<td>$(b\bar{b}b)(\nu\bar{\nu})$</td>
<td>183</td>
<td>53.9</td>
</tr>
<tr>
<td>$(qq\bar{q})(\nu\bar{\nu})$</td>
<td>189</td>
<td>171.4</td>
</tr>
<tr>
<td>$(b\bar{b}b)(\tau^+\tau^-)$</td>
<td>189</td>
<td>53.7</td>
</tr>
<tr>
<td>$(b\bar{b}b)(\tau^+\tau^-)$</td>
<td>189</td>
<td>168.7</td>
</tr>
<tr>
<td>$(b\bar{b}b, b\bar{b}\tau^+\tau^-, \tau^+\tau^-\tau^+\tau^-)(\nu\bar{\nu}, e^+e^-, \mu^+\mu^-)$</td>
<td>189-209</td>
<td>598.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ref.</th>
</tr>
</thead>
</table>
Similar Searches at the LHC

Searches for similar Higgs scenarios have been considered

- Hadronic taus have significant QCD background, focus is on events with 2 or more muons (from tau decays)
- Lots of backgrounds; challenging search for the LHC

Event Topology

- 2 high pt forward jets ($O(W,Z \text{ mass})$) → apply Pt > 20GeV cut
- No activity in the central region, only Higgs decay products are detected.
  → QCD BG suppressed
- By focusing on $4\tau \rightarrow \mu\mu\mu\mu$, we find signals where taujet-μ are very near to each other.
- Intensive study on reconstructed taujet is required
  → New TauID Algorithm
- Isolation of Muon need to be redefined.
  → New Muon Isolation Definition

K. S. Khaw, J. Tanaka, S. Asai, T. Kobayashi
University of Tokyo, ICEPP
2010
**Search for NMSSM Higgs bosons in the h→aa→μμ μμ, μμ ττ channels using pp collisions at \( \sqrt{s} = 1.96 \) TeV**

![Graph showing observed and expected limits for H → aa → 2μ2τ](image)

**FIG. 3:** The expected and observed limits and ±1 s.d. and ±2 s.d. expected limit bands for \( \sigma(pp \rightarrow h + X) \times \text{BR}(h \rightarrow aa) \), for (a) \( M_h=100 \) GeV and (b) \( M_a=4 \) GeV. The signal for \( \text{BR}(h \rightarrow aa)=1 \) is shown by the solid line. The region \( M_h<86 \) GeV is excluded by LEP.

<table>
<thead>
<tr>
<th>( M_a ) (GeV)</th>
<th>( \sigma \times \text{BR} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(exp)</td>
<td>obs (fb)</td>
</tr>
<tr>
<td>0.2143</td>
<td>10.0</td>
</tr>
<tr>
<td>0.3</td>
<td>9.5</td>
</tr>
<tr>
<td>0.5</td>
<td>7.3</td>
</tr>
<tr>
<td>1</td>
<td>6.1</td>
</tr>
<tr>
<td>3</td>
<td>5.6</td>
</tr>
</tbody>
</table>

**TABLE I:** The third muon identified, compared to about 50% of the signal muon track) distribution, and the number of events with \( \Delta \phi \approx 0 \) for (a) \( E \rightarrow \mu \mu \) and (b) \( E \rightarrow \mu \mu \).

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \sigma \times 2 \times \text{BR} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td></td>
</tr>
<tr>
<td>( M_a=3.6 ) GeV</td>
<td>[23.8] 19.1 fb</td>
</tr>
<tr>
<td>( M_a=4 ) GeV</td>
<td>[23.9] 45.9 fb</td>
</tr>
<tr>
<td>( M_a=7 ) GeV</td>
<td>[25.0] 24.6 fb</td>
</tr>
<tr>
<td>( M_a=10 ) GeV</td>
<td>[24.7] 27.3 fb</td>
</tr>
<tr>
<td>( M_a=19 ) GeV</td>
<td>[30.0] 33.7 fb</td>
</tr>
</tbody>
</table>

Andy Haas and company collaborated with Wacker and Lisanti to look for these signatures at the Tevatron

**Discovering the Higgs with Low Mass Muon Pairs**

Mariangela Lisanti and Jay G. Wacker

\( ^{\dagger} \) SLAC, Stanford University, Menlo Park, CA 94025

Physics Department, Stanford University, Stanford, CA 94305

(Dated: March 8, 2009)

These searches are probing ~1% of the expected production cross-section.

- there are not enough signal events at LEP to compete

However, the \( 4\tau \) signature is significantly more difficult at hadron colliders than at LEP, due to QCD backgrounds.
Constraints from CLEO/BaBar

\[ L_{\alpha f \bar{f}} \equiv i C_{\alpha f \bar{f}} \frac{ig_2 m_f}{2m_W} \bar{f} \gamma_5 f a, \]

What limits on the \( a \) can be obtained from existing data?

- Define a generic coupling to fermions by
  \[ L_{\alpha f f} \equiv \frac{iC_{\alpha f f}}{\tan \beta}, \]

At large \( \tan \beta \), SUSY corrections \( C_{ab b} = C_{\text{tree}} \frac{1}{(1 + \Delta_{\text{SUSY}} b)} \) can be large and either suppress or enhance \( C_{ab b} \) relative to \( C_{a \tau^- \tau^+} \). Will ignore.

- To extract limits from the data on \( C_{ab b} \), we need to make some assumptions. Here, we presume a 2HDMvIIw model as appropriate to the NMSSM and SUSY in general. Then, we can predict the branching ratios of the \( a \).

\[ \text{CLEO, D. Kreinick, arXiv:0710.5929 [hep-ex]} \]
Other motivations for a light $a$

The searches above were done with a 2 higgs doublet model in mind

- the same search is also sensitive to a wide range of theories with extended Higgs sectors

- probably the most useful prototype is the next-to-minimal SSM, in which the MSSM is extended with an additional singlet $\hat{S}$ [Gunion, et al]

  - the scalar part naturally acquires a vev and can provide a dynamical explanation for the size of the $\mu$ term.

  - this gives rise to a (mostly singlet) CP-odd scalar boson $a$

  - approximate accidental symmetries (à la Peccei-Quinn or when trilinear couplings vanish) can give a mechanism to make the $a$ light

Here we are taking a model independent attitude, and just look for a signal like

$h \rightarrow aa \rightarrow 2\tau 2\tau$ where the $a$ is light, without interpreting it in the context of any particular model

- eg. place limit on:

$$\xi^2 = \frac{\sigma \text{BR}(h \rightarrow aa) \text{BR}(a \rightarrow \tau\tau)^2}{\sigma_{SM}}$$
Low $\tan\beta$ have reduced $\text{BR}(a \to \tau^+ \tau^-)$
New constraints on a light CP-odd Higgs boson and related NMSSM Ideal Higgs Scenarios.

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and Theory Group, CERN, CH-1211, Geneva 23, Switzerland

Abstract: Recent BaBar limits on $BR(\Upsilon(3S) \to \gamma a \to \gamma \tau^+ \tau^-)$ and $BR(\Upsilon(3S) \to \gamma a \to \gamma \mu^+ \mu^-)$ provide increased constraints on the $ab\bar{b}$ coupling of a CP-odd Higgs boson, $a$, with $m_a < M_{\Upsilon(3S)}$. We extract these limits from the BaBar data and compare to the limits previously obtained using other data sets, especially the CLEO-III $BR(\Upsilon(1S) \to \gamma \rightarrow \tau^+ \tau^-)$ limits. Comparisons are made to predictions in the context of “ideal”-Higgs NMSSM scenarios, in which the lightest CP-even Higgs boson, $h_1$, can have mass below 105 GeV (as preferred by precision electroweak data) and yet can escape old LEP limits by virtue of decays to a pair of the lightest CP-odd Higgs bosons, $h_1 \to a_1a_1$, with $m_{a_1} < 2m_B$. Most such scenarios with $m_{a_1} < 2m_\tau$ are eliminated, but the bulk of the $m_{a_1} > 7.5$ GeV scenarios, which are theoretically the most favored, survive. We also outline the impact of preliminary ALEPH LEP results in the $e^+e^- \to Z + 4\tau$ channel. For $\tan\beta \geq 3$, only NMSSM ideal Higgs scenarios with $m_{a_1} \sim 105$ GeV (the upper limit of “ideal”) and $m_{a_1}$ close to $2m_B$ satisfy the preliminary ALEPH limits. For $\tan\beta \leq 2$, the ALEPH results pick out the most theoretically preferred NMSSM scenarios which are those with $m_{a_1}$ close to $2m_B$ and $m_{h_1} \sim 90$ GeV − 100 GeV.

Keywords: Higgs, NMSSM, BaBar, ALEPH.

This analysis may be sensitive to other physics processes we have not considered.