MSSM Higgs Searches at LEP

Aaron Dominguez (UCSD/L3)

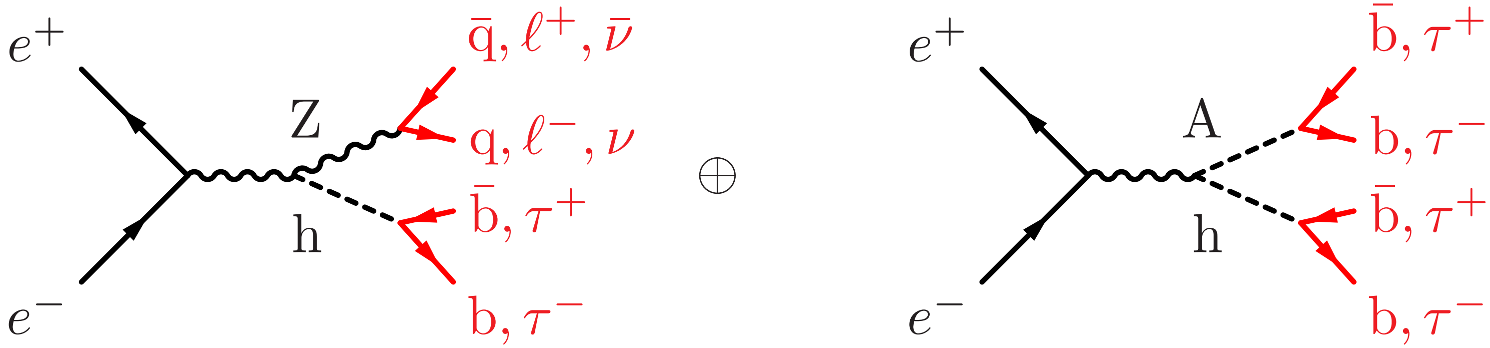
June 18, 1999

SUSY 99, Fermilab, USA

- Experimental program
- Flavor of MSSM Higgs search using L3 as an example
- Summary of results from ALEPH, DELPHI and OPAL

LEP Neutral Higgs Search

Signal



- All 4 exps. consider same production and ∼same decay modes
- Relative production rates depend on $\tan\beta$ which is a free parameter of the MSSM
- Must devise search sensitive to both hZ and hA!

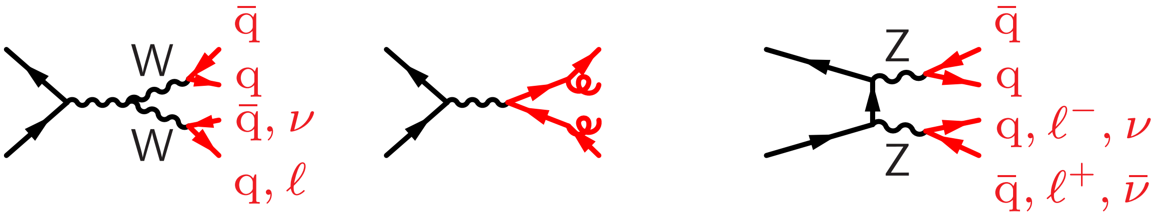
Benchmarks

- All 4 consider "restricted version" of MSSM (6 free parameters other than SM parameters).
- Benchmark parameter values agreed upon for comparisons during LEP 2 workshop in '95 (caveat: new partial 2-loop calculations?)
  - Minimal Mixing: $A = 0$, $\mu = -1$ TeV, $M_2 = m_0 = 1$ TeV.
  - Maximal Mixing: $A = \sqrt{6}$ TeV, $\mu = -0.1$ TeV, $M_2 = m_0 = 1$ TeV. Also $m_{\mathrm{t}} = 175$ GeV.
- We scan over $\tan\beta$ and m_{A} or $\sin^2(\beta-\alpha)$ and m_{h}.
- OPAL considers a semi-general scan over all 6 parameters as well for the $\sqrt{s} = 189$ GeV data.
- All restrict possibility of decays into SUSY particles.

$\Rightarrow$ This sets the experimental program.

Overview

Lots a Background



- W^+W^- is the dominant background. It's especially important at large $\tan\beta$.

- ZZ is important for low $\tan\beta$ and will become more important as we gain sensitivity to higher equal mass hA.

- Must have powerful and well understood B-tags.

- Everybody uses final discriminants now $\Rightarrow$ no more counting experiments!

- Calculation of CL and conclusions about signal use spectra of final discriminants.

- With large BG, need lots of $\int\mathcal{L}$ $\Rightarrow$ 680 pb^{-1} LEP combined at $\sqrt{s} = 189$ GeV!

L3: Analysis Procedures

Up to 4×60 hZ events for $m_{\mathrm{h}} = 90$ GeV

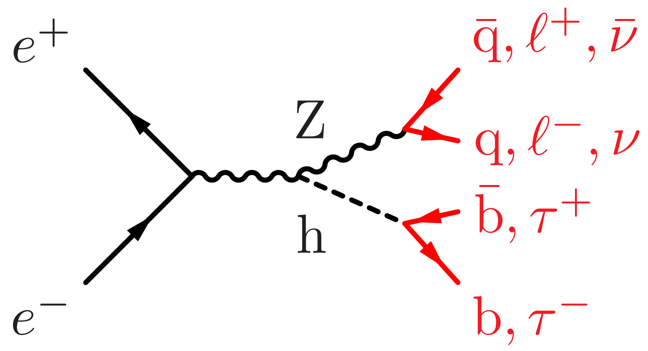
Up to 4×20 hA events for $m_{\mathrm{h}} = m_{\mathrm{A}} = 75$ GeV

3 stage procedure for all analyses:

- Hadronic preselection (b/c of $\mathrm{q\bar{q}}$ in all final states)
- Tighter set of cuts specific to topology in question
- Final discriminant (including mass information: L3 only): purity, likelihood, weighted prob., neural network output, reconstructed $(m_{\mathrm{h}}, m_{\mathrm{A}})$

L3: $\mathrm{e^+e^- \rightarrow Z^* \rightarrow hZ}$

Signal



- Analyses Performed for
  - $\mathrm{hZ \rightarrow b\bar{b}q\bar{q}}$
  - $\mathrm{hZ \rightarrow b\bar{b}}\nu\bar{\nu}$
  - $\mathrm{hZ \rightarrow b\bar{b}}\ell^+\ell^-$ $(\ell = \mathrm{e}, \mu)$
  - $\mathrm{hZ \rightarrow b\bar{b}}\tau^+\tau^-$, $\mathrm{hZ} \rightarrow \tau^+\tau^-\mathrm{q\bar{q}}$

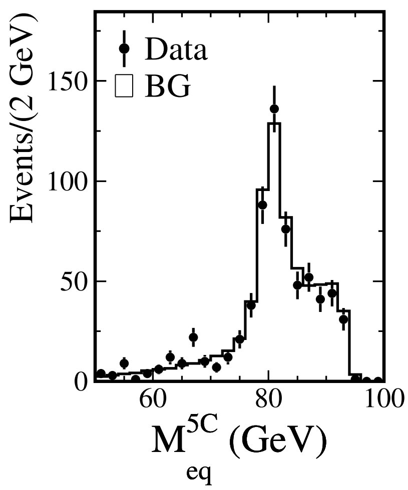
- Includes charm, gluonic decays $\Rightarrow \sim 98\%$ Br.

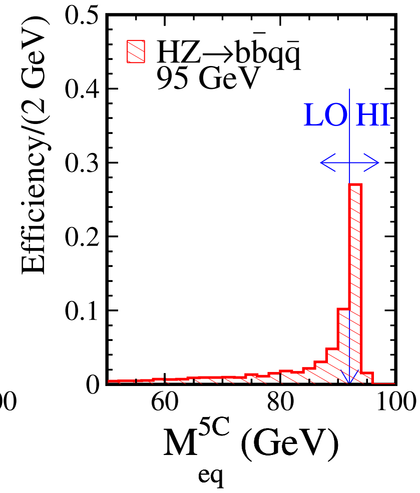
- Data collected: 176.4 $\mathrm{pb^{-1}}$ at $\sqrt{s} = 188.6$ GeV.

L3: $\mathrm{hZ} \rightarrow \mathrm{b\bar{b}q\bar{q}}$

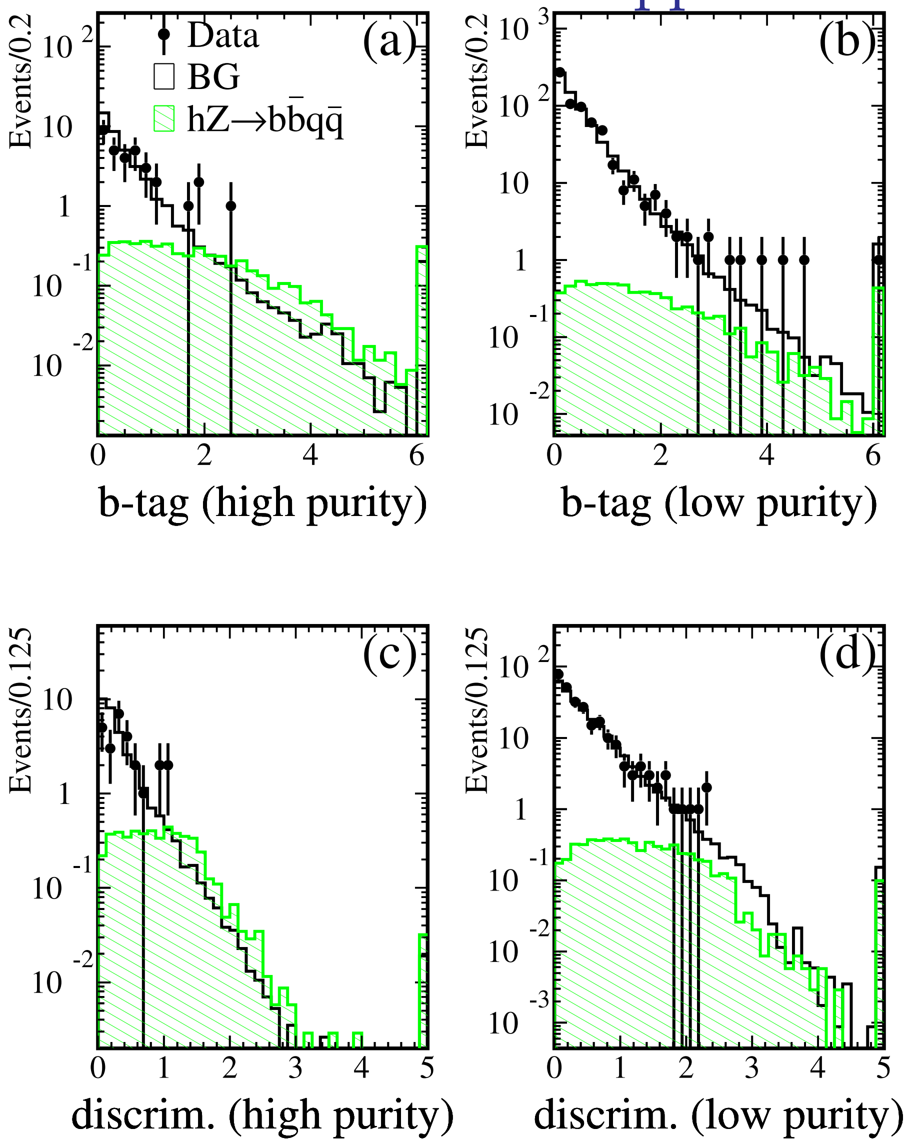
Signal: 4 jets, b quarks, $M_{\mathrm{q\bar{q}}} \approx m_{\mathrm{Z}}$
Background: 4 jet QCD, hadronic $\mathrm{W^+W^-}$ & ZZ

- *Preselection:* High multiplicity hadronic events
- *Optimized cuts:* Maximize $< CL >$ by automatically (MINUIT) adjusting kinematic cuts. Kills mostly $\mathrm{q\bar{q}}$+gluons.
- After optimized cuts: 682 data, 703 BG with 85% $\mathrm{W^+W^-}$
- Hadronic $\mathrm{W^+W^-}$ events have
  - low b-tags
  - dijet masses $\approx m_{\mathrm{W}}$
- Split sample into Low/High purity samples using sliding cut on M^{5C}_{eq}:





L3: $hZ \rightarrow b\bar{b}q\bar{q}$



Final var. is weighted combo of $B_{\rm tag} \times {\rm Mass}$

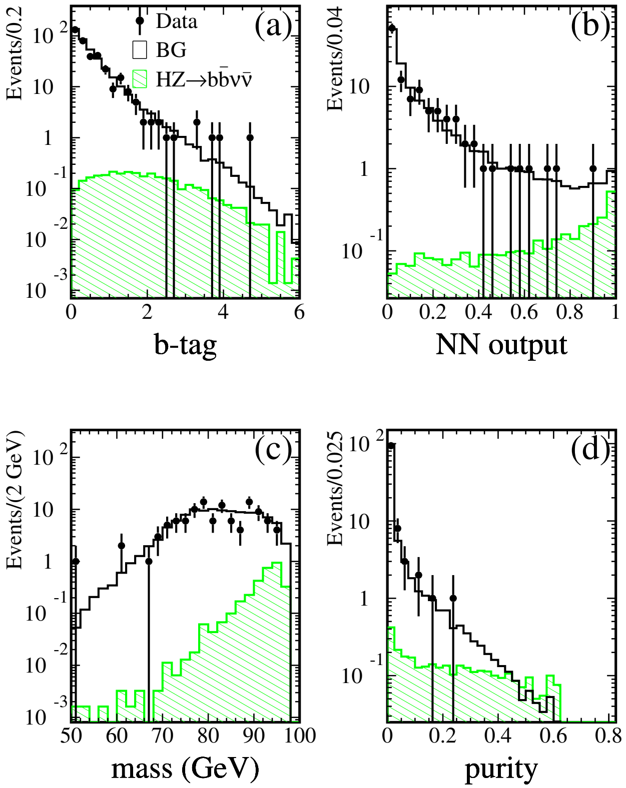
- HI: $B_{\rm tag} > 0.09 \Rightarrow$ 26 data, 31 BG, 28% eff. for 95 GeV
- LO: $B_{\rm tag} > 0.41 \Rightarrow$ 263 data, 239 BG, 34% eff. for 95 GeV

L3: $hZ \to b\bar{b}\nu\bar{\nu}$

Signal: 2 jets, b quarks, $M_{miss} \approx m_Z$

Background: 2 jet QCD, semileptonic W^+W^-, $ZZ \to q\bar{q}\nu\bar{\nu}$

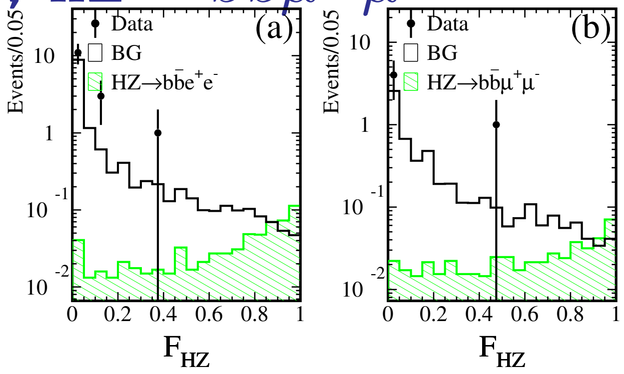
- *Preselection:* Hadronic events with missing energy
- *Selection:* High eff. on signal to train neural network
  - Train mass-independent neural network to identify $hZ \to b\bar{b}\nu\bar{\nu}$
  - Use a cocktail of various signal masses (ALEPH does likewise)
  - Can't train NNet on very tricky ZZ background!
- Final var. is purity from M_H^{5C} and NNet for given mass hypothesis.



109 Data, 116 BG and 62% eff. for 95 GeV

L3: $\mathrm{hZ} \to \mathrm{b\bar{b}e^+e^-}$, $\mathrm{hZ} \to \mathrm{b\bar{b}}\mu^+\mu^-$

Signal: 2 high energy $\mathrm{e}^\pm$ or $\mu^\pm$, 2 b jets, $M_{\mathrm{lep}} \approx m_{\mathrm{Z}}$



- *Preselection:* Hadronic events + leptons
- *Selection:* High eff. to build likelihood as final variable
- This is a low rate channel, but very clean, efficient and would be nice for m_{h} measurement!

- 3 input variables: $i = (B_{\mathrm{jet1}}, B_{\mathrm{jet2}}, M_{\mathrm{H}}^{5\mathrm{C}})$
- 5 event classes: $j = (\mathrm{ZZ}, \mathrm{W^+W^-}, \mathrm{q\bar{q}}, \mathrm{Ze^+e^-}, \mathrm{hZ})$
- f_j^i prob. density of var. i for event class j
- $p_j^i = f_j^i / \sum_k f_k^i$ prob. to belong to j based on i

Likelihood for event to be hZ

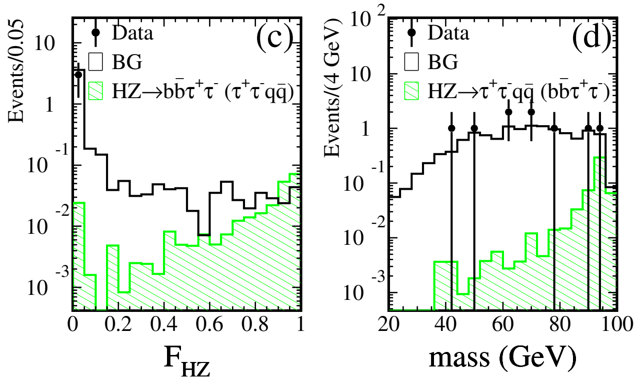
$$F_{\mathrm{hZ}} = \prod_i p_{\mathrm{hZ}}^i / \sum_k \prod_i p_k^i$$

$\mathrm{e^+e^-}$: 15 data, 13.2 BG, 77% eff $\quad$ $\mu^+\mu^-$: 5 data, 5.5 BG, 57% eff

L3: $\mathrm{hZ} \to \mathrm{b\bar{b}}\tau^+\tau^-$, $\mathrm{hZ} \to \tau^+\tau^-\mathrm{q\bar{q}}$

Signal: Taus + jets. Very similar final states!

- *Preselection:* Hadronic events, $E_{\mathrm{e},\mu} \leq 40$ GeV to reject semileptonic $\mathrm{W^+W^-}$
- *τ-id:* particle-based *OR* jet-based
  - Challenging channel!
  - particle-based: decay into e or μ or isolated jet with 1,3 tracks and $Q = 1$.
  - jet-based: Force event into 4-jets. Must have 2 jets with < 4 tracks.

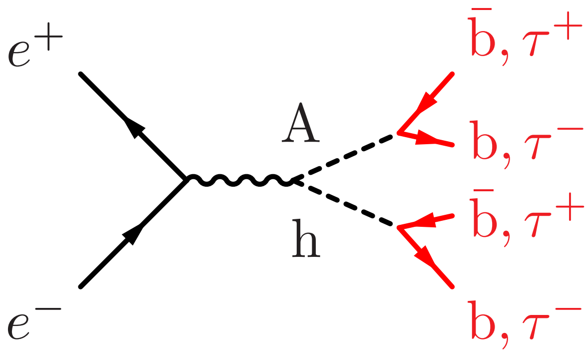


- $\mathrm{hZ} \to \mathrm{b\bar{b}}\tau^+\tau^-$: $M_{\tau\tau}$ consistent with m_{Z}
- $\mathrm{hZ} \to \tau^+\tau^-\mathrm{q\bar{q}}$: $M_{\mathrm{jet-jet}}$ consistent with m_{Z}
- Significant cross-efficiency ($\sim 30\%$).
- Events passing both selections assigned to channel with largest F_{hZ}.

12 data, 17.1 BG, 30% eff for both $\mathrm{b\bar{b}}\tau^+\tau^-$ and $\tau^+\tau^-\mathrm{q\bar{q}}$

$e^+e^- \rightarrow Z^* \rightarrow hA$

Signal



- Analyses Performed for
  - $hA \rightarrow b\bar{b}b\bar{b}$
  - $hA \rightarrow b\bar{b}\tau^+\tau^-(\tau^+\tau^-b\bar{b})$

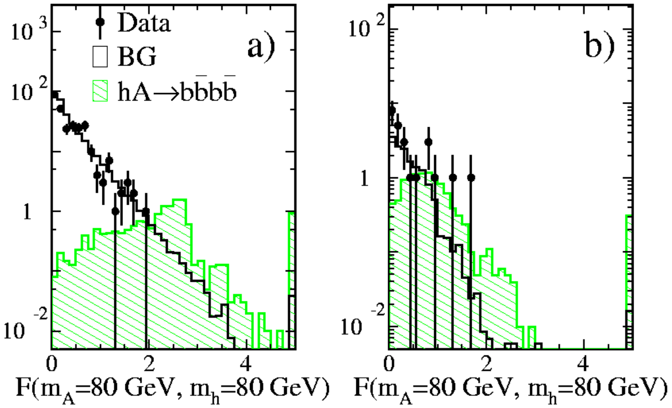
- Covers $\sim$ 97% Br. for benchmark scans above $\tan\beta > 1$

- Same analyses as similar hZ channels, but new set of optimized cuts, generally looser.

L3: $\mathrm{hA} \to \mathrm{b\bar{b}b\bar{b}}$

- With new set of cuts, now have 3 classes of 4-jet events:
  1. hA
  2. hZ
  3. hA and hZ
- ALEPH has similar situation. Must uniquely assign events to either hA or hZ for (3).
  - L3 solves this by choosing best hypothesis based on mass $\chi^2(m_{\mathrm{A}}, m_{\mathrm{h}})$, $\chi^2(m_{\mathrm{Z}}, m_{\mathrm{h}})$, and $\sigma(\mathrm{hZ})/\sigma(\mathrm{hA})$

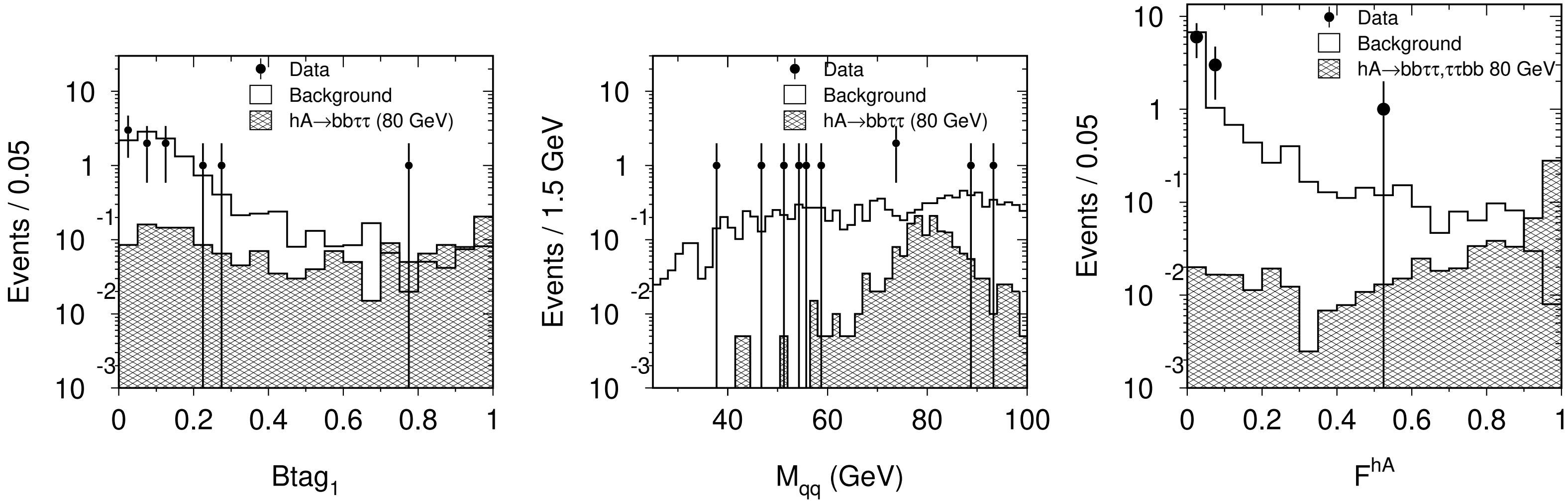
The Final Variable



a) $189\ \mathrm{GeV}$ data, background and hA signal eff$\times 50$ for $\mathrm{hA}'_{\mathrm{b\bar{b}b\bar{b}}}$ analysis at high $\tan\beta$.

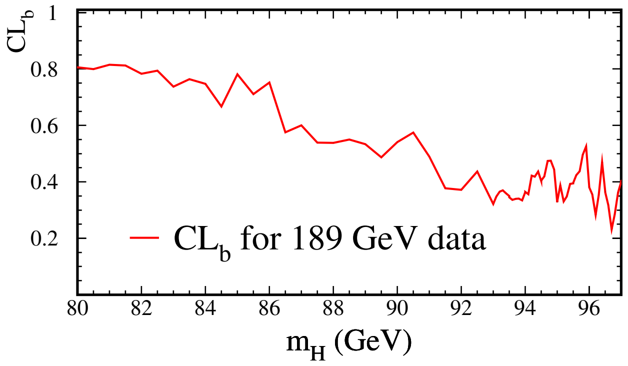
b) $\mathrm{hA}_{\mathrm{b\bar{b}b\bar{b}}}$ analysis.

L3: $\mathrm{hA} \rightarrow \mathrm{b\bar{b}}\tau^+\tau^-$



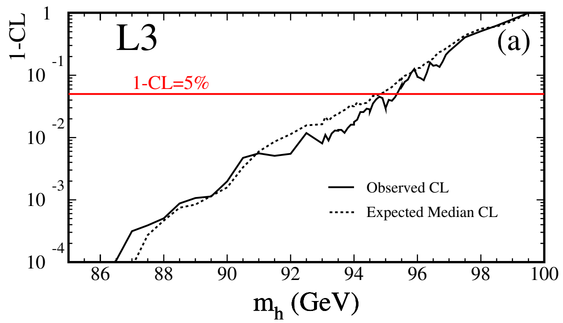
- Common preselection with the hZ τ-channels
- New $\mathrm{hA} \rightarrow \mathrm{b\bar{b}}\tau^+\tau^-$ selection
- Final variable is a likelihood combination of b-tag and $\mathrm{M}_{\tau\tau}$ or $\mathrm{M_{jj}}$.
- Events selected by both the hA and hZ search are assigned to one based on the relative-cross-section-weighted comparison of F_{hA}, F_{hZ}

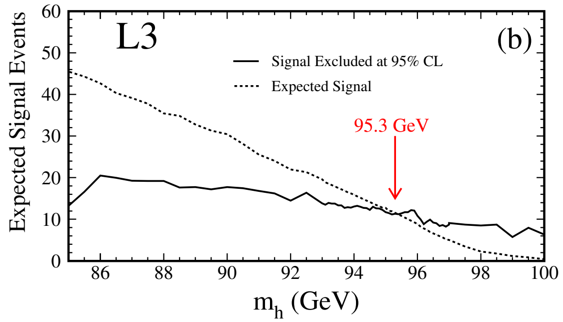
CL and Final Variables



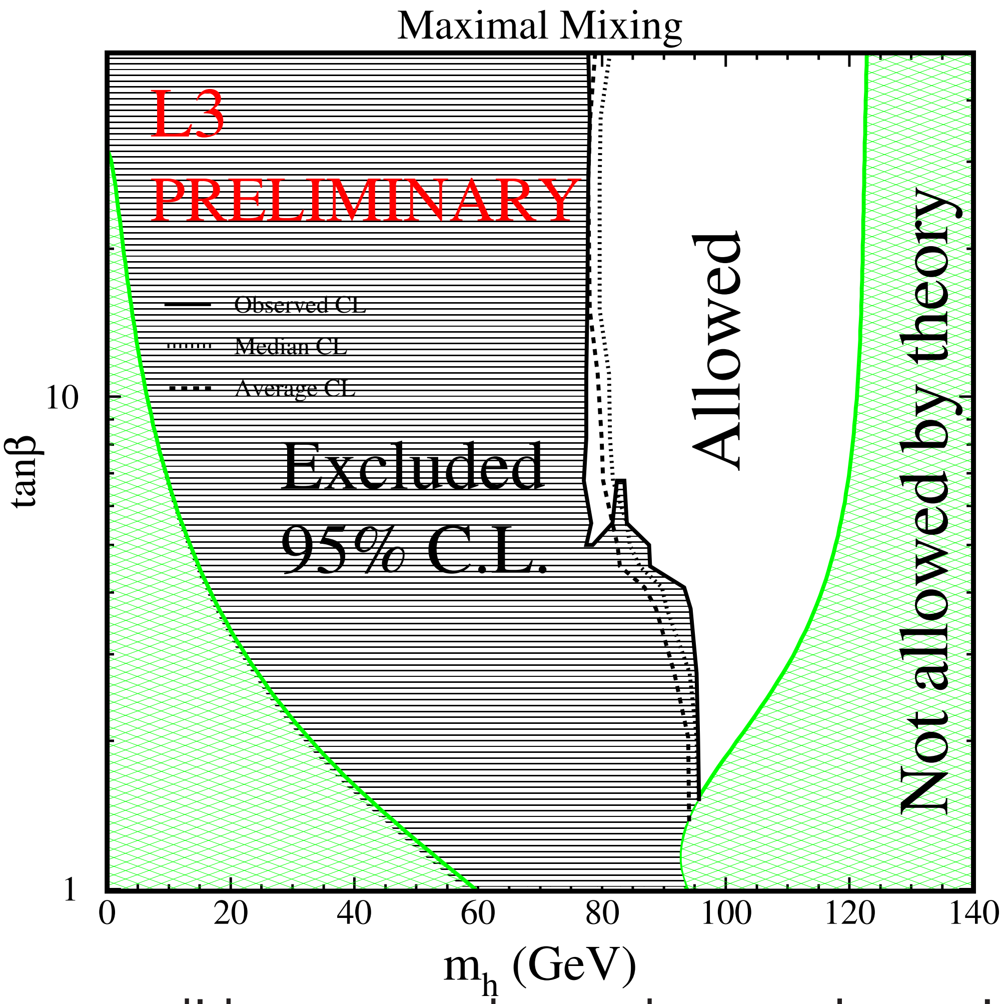
- Example: Calculate CL_b, CL from final variable spectra of hZ analyses
- No large values of $CL_b \Rightarrow$ no clear excess anywhere

- Now at any given scan point $(\tan\beta, m_{\mathrm{A}})$, we have spectra of final variables in all channels for given mass hypothesis.





L3: Mass Limits



- Some candidates around m_{W}, but no clear evidence of signal.

- $m_{\mathrm{h}} > 77$ GeV, $m_{\mathrm{A}} > 78$ GeV at 95% CL.

- $\tan\beta$ excluded between 1.0 and 1.5 at the 95% CL, but this depends on m_{t} and the accuracy of the theoretical upper bounds on m_{h}.

ALEPH

Data: 175.5 pb^{-1} at $\sqrt{s} = 188.6$ GeV

- Cover nearly all the final states of hZ and hA

- $\mathrm{hZ} \rightarrow \mathrm{b\bar{b}}\nu\bar{\nu}$: Triple coverage!
  1. cut-based selection
  2. neural network based selection A
  3. neural network based selection B

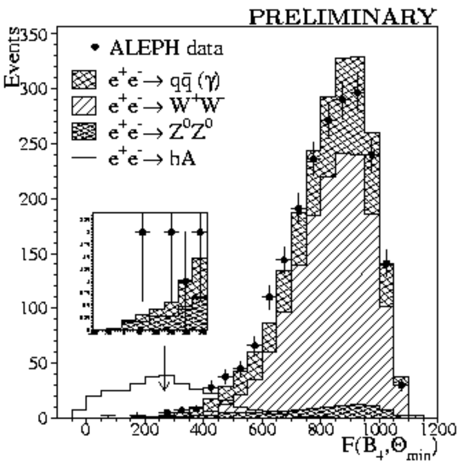
- 4-jets: Double coverage!
  1. cut-based selection
  2. neural network selection

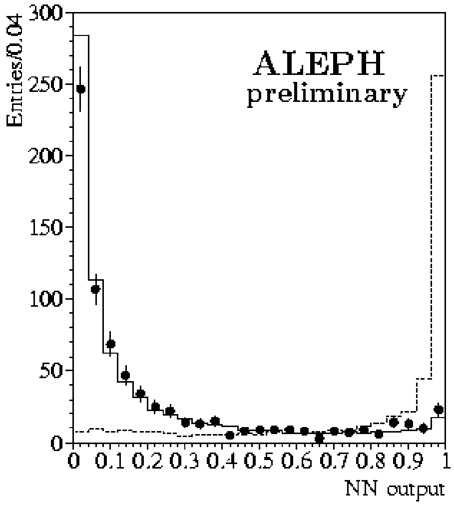
- Dedicated $\mathrm{b\bar{b}b\bar{b}}$ selection relying mainly on b-tagging (which they are very good at!)

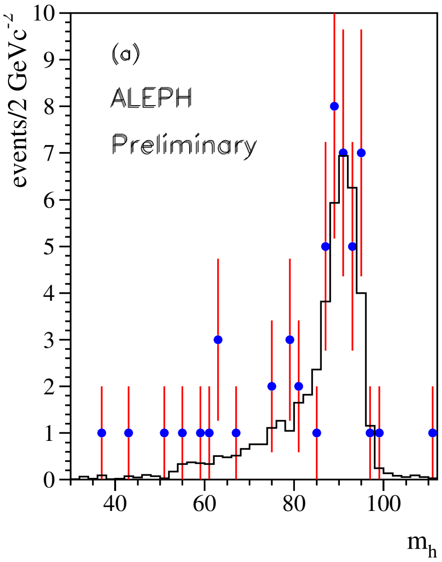
- tau-analyses: similar situation to L3 in that they must make an assignment to $\mathrm{hA} \rightarrow \mathrm{b\bar{b}}\tau^+\tau^-$, $\mathrm{hZ} \rightarrow \mathrm{b\bar{b}}\tau^+\tau^-$, or $\mathrm{hZ} \rightarrow \tau^+\tau^-\mathrm{q\bar{q}}$

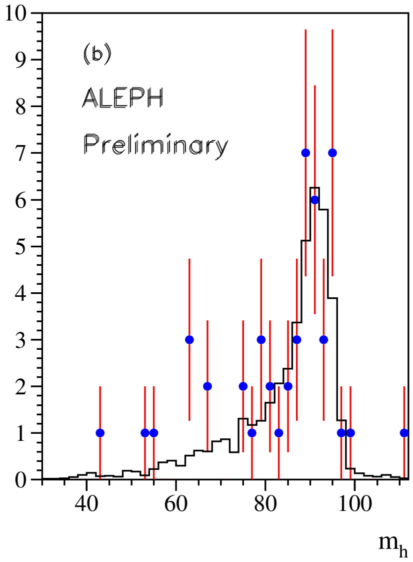
- Choose which final var to use based on best $<CL>$ in mass scan

ALEPH

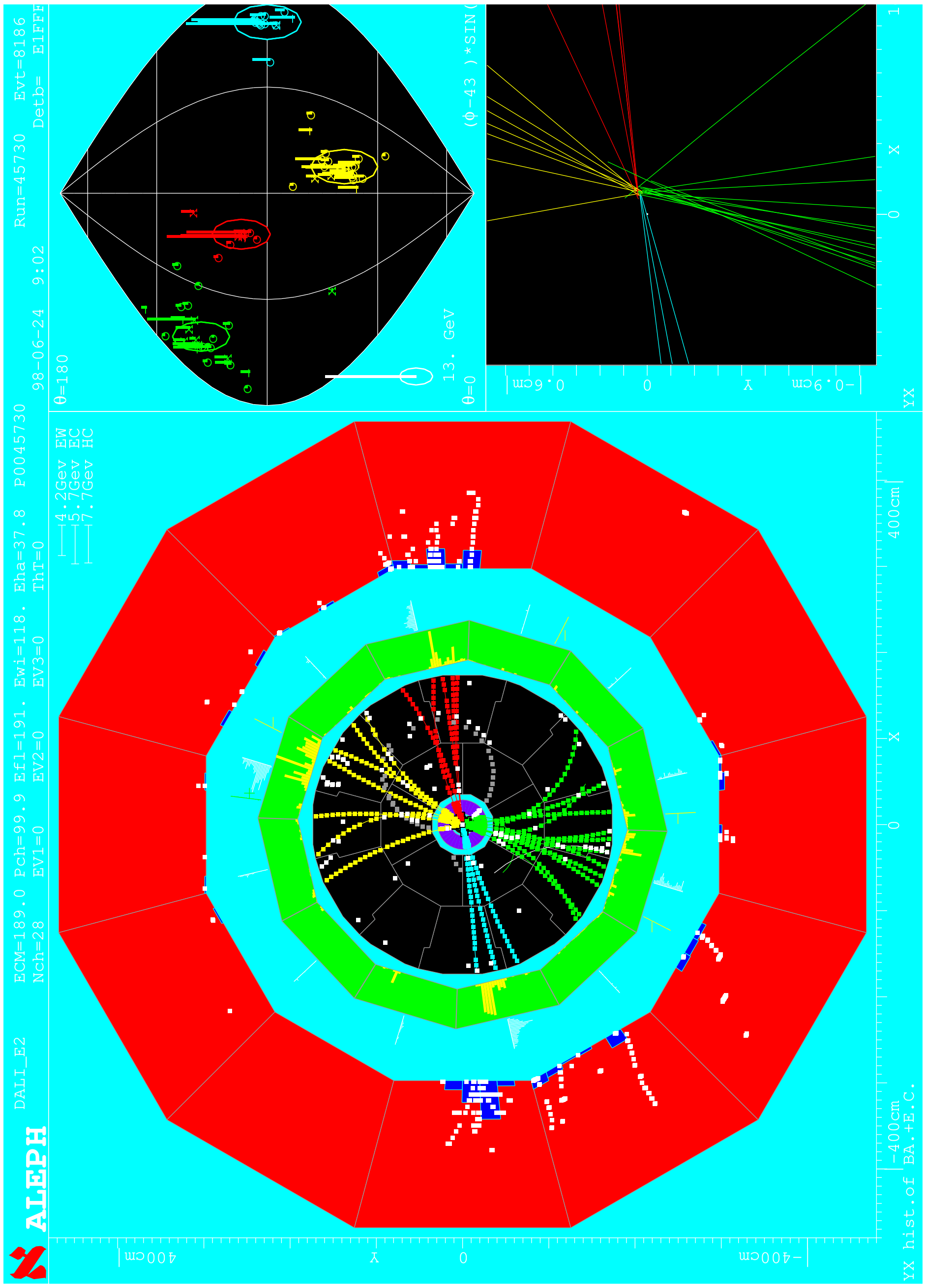

PRELIMINARY
Events
• ALEPH data
$e^+e^- \to q\bar{q}(\gamma)$
$e^+e^- \to W^+W^-$
$e^+e^- \to Z^0Z^0$
$e^+e^- \to hA$
$F(B_+,\Theta_{min})$


ALEPH
preliminary
Entries/0.04
NN output

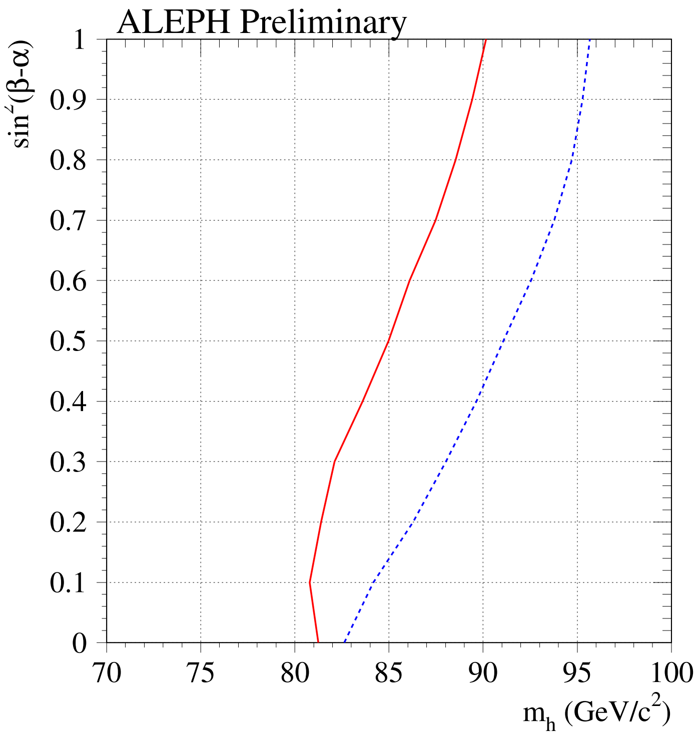

(a)
ALEPH
Preliminary
events/2 GeVc^{-2}
m_h


(b)
ALEPH
Preliminary
m_h

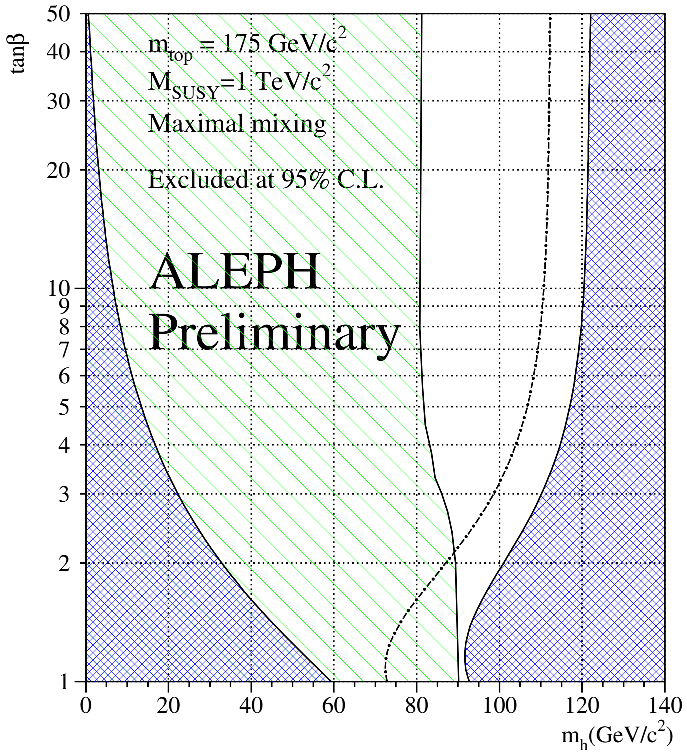
ALEPH: Nice $b\bar{b}q\bar{q}$ Candidate



ALEPH

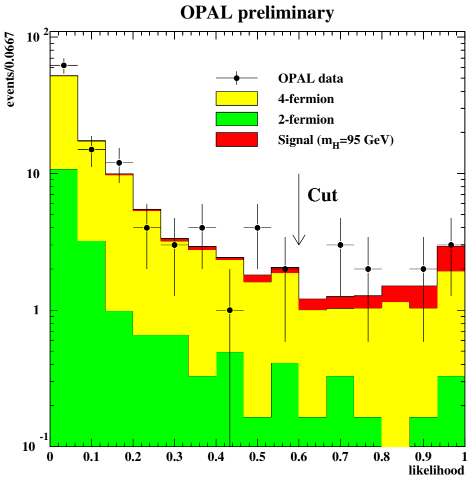


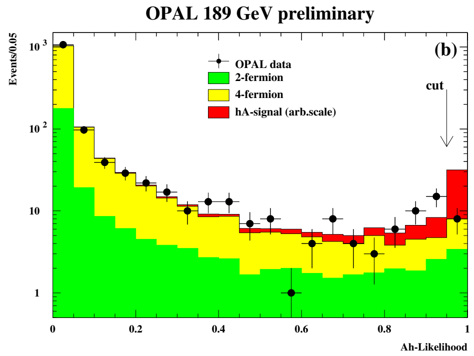
ALEPH Preliminary
$\sin^2(\beta-\alpha)$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
70
75
80
85
90
95
100
m_h (GeV/c^2)

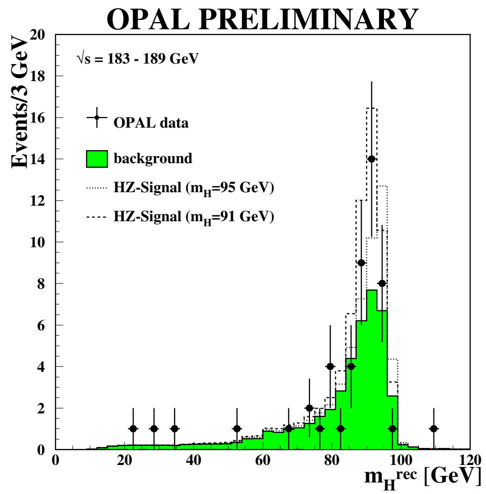


m_{top} = 175 GeV/c^2
M_{SUSY}=1 TeV/c^2
Maximal mixing
Excluded at 95% C.L.
ALEPH
Preliminary
tanβ
50
40
30
20
10
9
8
7
6
5
4
3
2
1
0
20
40
60
80
100
120
140
m_h(GeV/c^2)

OPAL



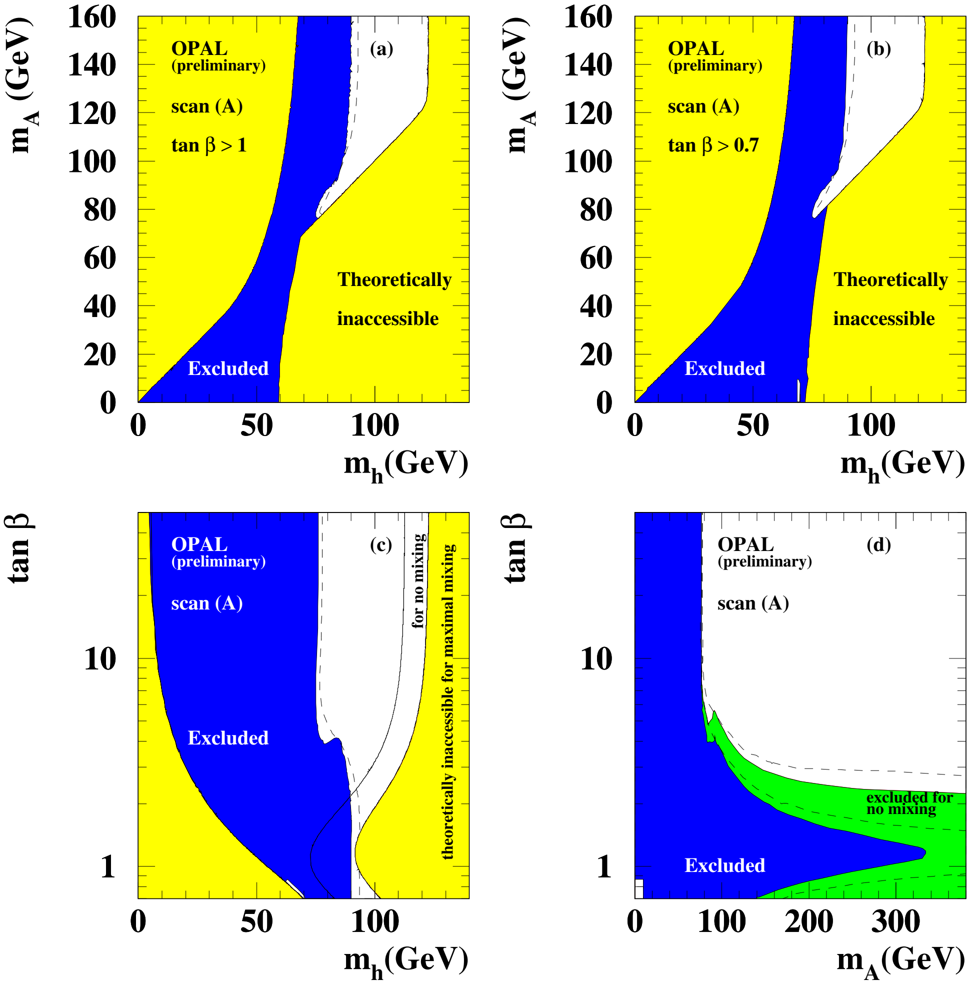




Data: $\sim 170\ \mathrm{pb}^{-1}$ at $\sqrt{s} = 188.6\ \mathrm{GeV}$

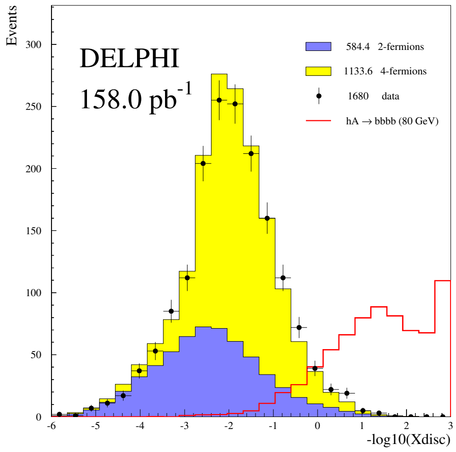
- Use a likelihood discriminant for almost every channel (very similar to L3's (F_{hZ} and F_{hA} lepton analyses.)
- For the time being, only OPAL considers $\mathrm{h} \to \mathrm{AA}$ for 189 GeV searches.
- Reconstructed mass used as final var. to calculate CL.

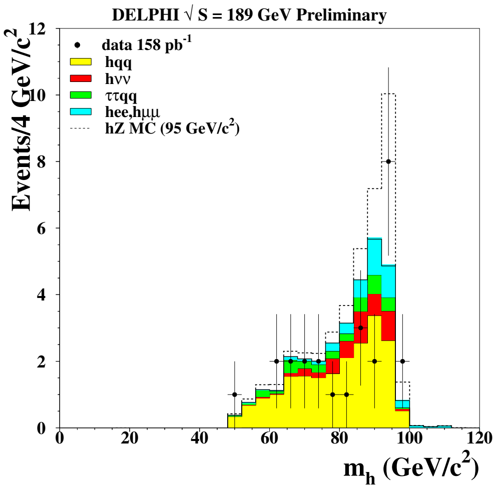
OPAL



- In "general" scan, these limits are somewhat lower (for $\tan\beta > 1$):
  - $m_\mathrm{h} > 72.2$ GeV
  - $m_\mathrm{A} > 76.0$ GeV

DELPHI





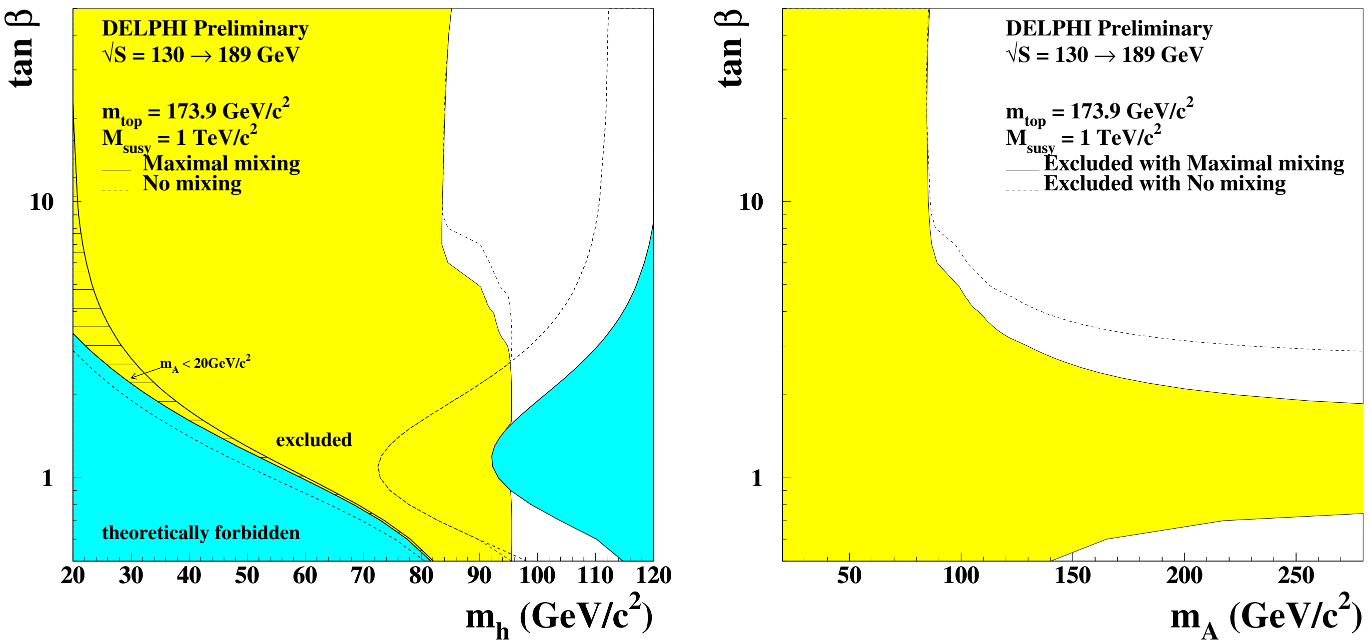
Data: 158 pb^{-1} at $\sqrt{s} = 188.6$ GeV

- Use a likelihood discriminant for $\mathrm{hA} \to \mathrm{b\bar{b}b\bar{b}}$ very similar to L3's (F_{hZ} and F_{hA}) lepton analyses and OPAL's analyses.

- Neural network used for $\mathrm{hZ} \to \mathrm{b\bar{b}q\bar{q}}$

- These results are from LEPC in Nov. '98, but they will have updated analyses released *very shortly!*

DELPHI


DELPHI Preliminary
√S = 130 → 189 GeV
m_top = 173.9 GeV/c²
M_susy = 1 TeV/c²
Maximal mixing
No mixing
m_A < 20GeV/c²
excluded
theoretically forbidden
tan β
m_h (GeV/c²)
DELPHI Preliminary
√S = 130 → 189 GeV
m_top = 173.9 GeV/c²
M_susy = 1 TeV/c²
Excluded with Maximal mixing
Excluded with No mixing
tan β
m_A (GeV/c²)

Summary

No Evidence of Neutral Higgs at LEP!

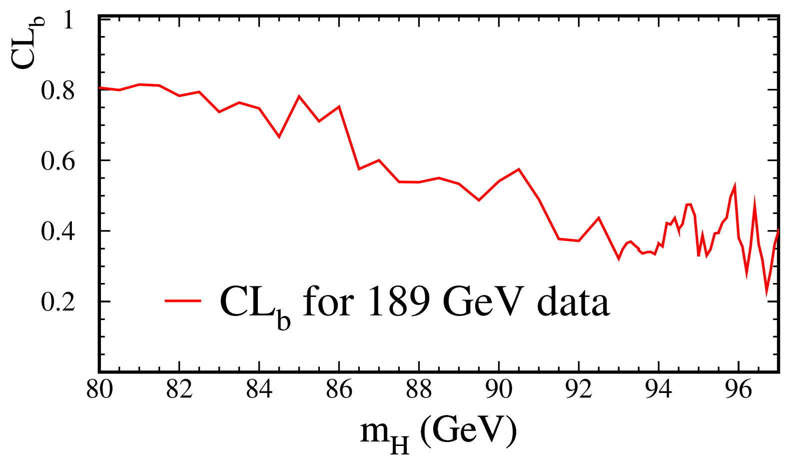
95% CL Lower Mass Limits at $\sqrt{s} = 189$ GeV

Exp.	SM $(m_{\rm H})$	MSSM $(m_{\rm h}, m_{\rm A})$	Remarks
L3	95.3 GeV	$(77$ GeV$, 78$ GeV$)$	SM limit final
ALEPH	90.2 GeV	$(80.8$ GeV$, 81.2$ GeV$)$	
OPAL	91.0 GeV	$(74.8$ GeV$, 76.5$ GeV$)$	Final. Benchmark scan
DELPHI	95.2 GeV	$(83.5$ GeV$, 84.5$ GeV$)$	Update soon

LEPHWG expects to have combined mass limits for SM, MSSM and (hopefully) $\rm H^{\pm}$ by EPS 99 in July, 1999.

L3: Combined $e^+e^- \to Z^* \to hZ$ Results

Selection		Mass hypothesis $m_H = 85$ GeV			$m_H = 90$ GeV			$m_H = 95$ GeV		
H	Z	SIG	BG	DATA	SIG	BG	DATA	SIG	BG	DATA
$b\bar{b}$	$q\bar{q}$	21.2	73.3	78	17.6	78.4	90	8.6	53.7	51
$b\bar{b}$	$\nu\bar{\nu}$	9.0	21.3	22	5.9	16.0	17	2.3	9.2	4
$b\bar{b}$	e^+e^-	1.8	3.0	3	1.2	3.5	1	0.6	2.3	1
$b\bar{b}$	$\mu^+\mu^-$	1.7	5.5	5	1.1	3.0	3	0.5	1.9	1
$b\bar{b}$	$\tau^+\tau^-$	0.7	1.2	0	0.4	0.8	0	0.2	0.5	0
$\tau^+\tau^-$	$q\bar{q}$	1.6	5.0	3	1.1	4.0	3	0.4	2.4	2



- Calculate CL_b, CL from final variable spectra
- No large values of CL_b $\Rightarrow$ no clear excess anywhere