MSSM Higgs Searches at LEP2

Andy Hocker
OPAL/University of Chicago
(on behalf of the LEP collaborations)

- The MSSM Higgs Sector
- Experimental Approach
- Results from the Experiments
- LEP-Combined Results
- Conclusions and Outlook

All results are (very) PRELIMINARY!

The MSSM Higgs Sector

A Two-Higgs-Doublet Model:

5 physical Higgs Bosons

2 CP-even neutral Higgses	$\mathrm{h}^0, \mathrm{H}^0$	$m_\mathrm{h} < m_\mathrm{H}$
1 CP-odd neutral Higgs	A^0	
2 charged Higgses	$\mathrm{H}^\pm$	(Heavy!)
Free parameters:	$\tan\beta = v_2/v_1$	(VEV ratio)
	α	(mixing angle of h,H)

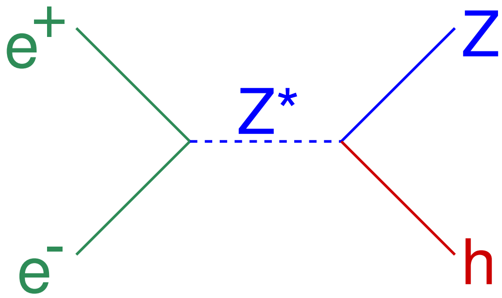
At tree level $m_\mathrm{h} < m_\mathrm{Z} < m_\mathrm{H}$, but large radiative corrections!

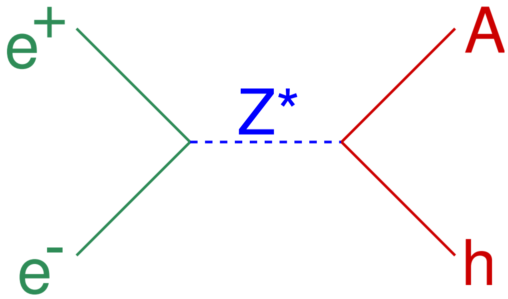
$$\Delta m_\mathrm{h}^2 \sim \frac{m_\mathrm{top}^4}{m_\mathrm{W}^2} \times \left(\log \frac{m_{\tilde{\mathrm{t}}_1}^2 m_{\tilde{\mathrm{t}}_2}^2}{m_\mathrm{top}^4} + \ldots\right)$$

Introduces a host of unknown SUSY parameters, but nearly always:

$$m_\mathrm{h} \lesssim \text{ 130 GeV!}$$

Production Mechanisms/Search Topologies





"Higgsstrahlung"

$$\sigma = \sin^2(\beta - \alpha)\,\sigma_{\mathrm{HZ}}^{\mathrm{SM}}$$

- favored at smaller $\tan\beta (\approx 1.4)$
- Looks like SM Higgs!

"Pair Production"

$$\sigma = \cos^2(\beta - \alpha)\,\bar{\lambda}\sigma_{\nu\bar{\nu}}^{\mathrm{SM}}$$

- favored at larger $\tan\beta (> 15)$
- heavy fermion final states:

$$\mathrm{Ah} \to \mathrm{b\bar{b}b\bar{b}},\ \mathrm{Ah} \to \tau^+\tau^-\mathrm{b\bar{b}}$$

In addition, one can consider:

$$\mathrm{h} \to \mathrm{AA}$$

a small subset of the MSSM parameter space

- **Higgsstrahlung (ZAA)**

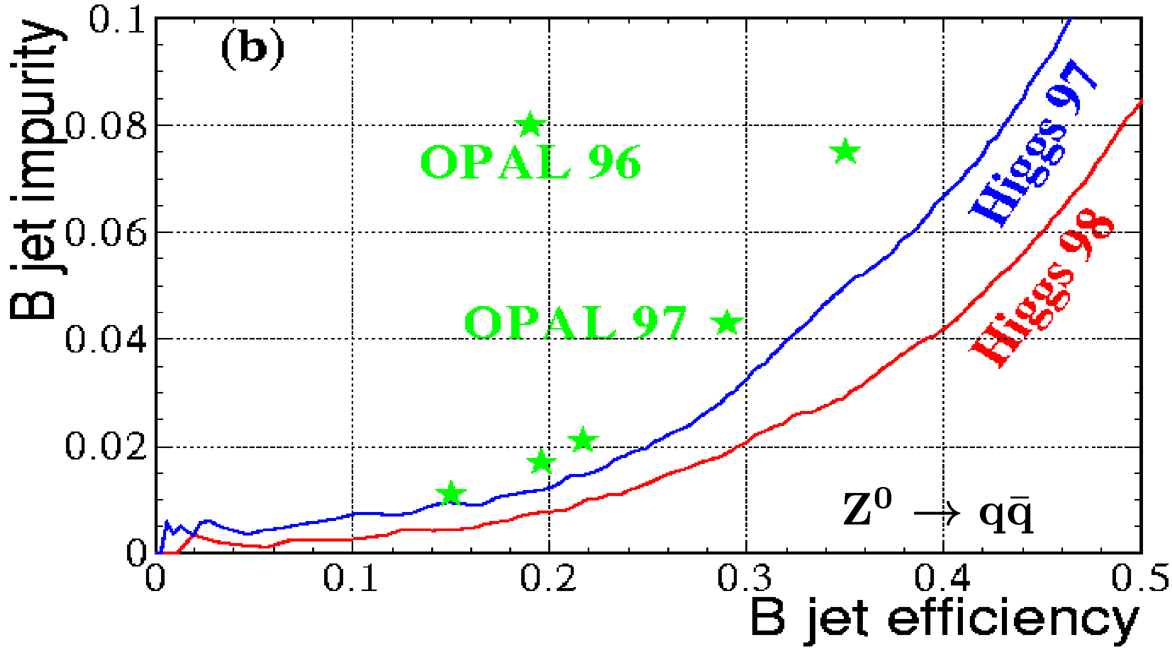
$\longrightarrow$ **SM searches still efficient**

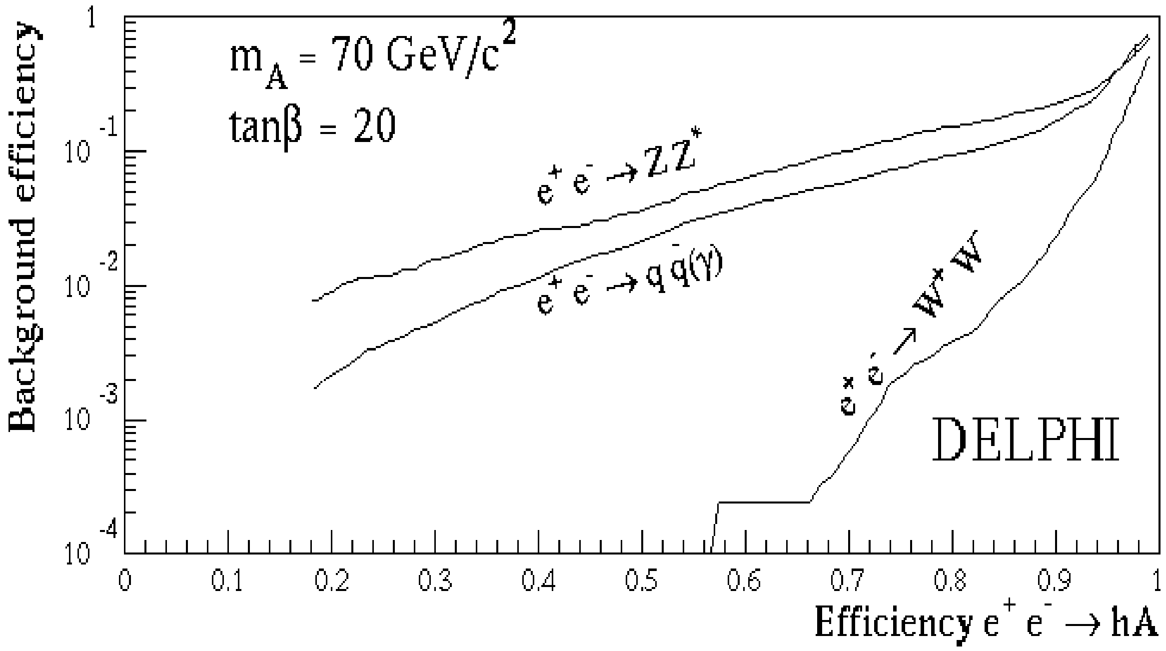
- **Pair-production (AAA):**

$\longrightarrow$ **dedicated search for $\mathrm{b\bar{b}b\bar{b}b\bar{b}}$ (OPAL)**

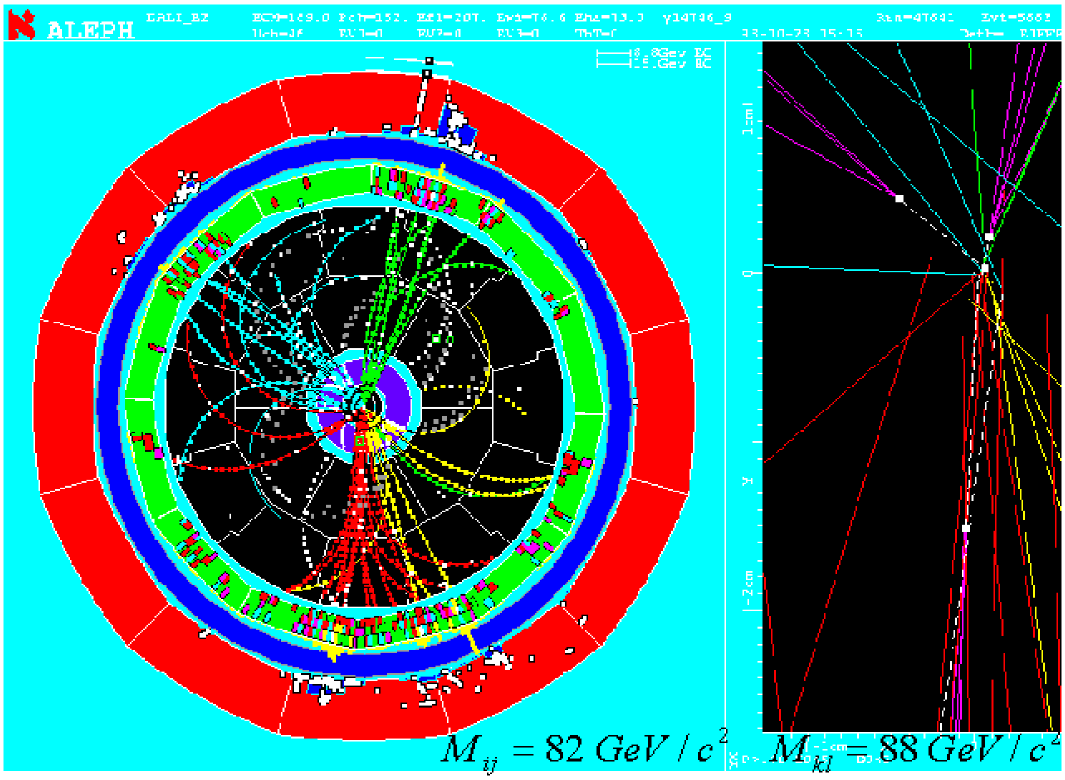
b-tagging

Si μVTX detectors and complex algorithms have yielded high-performance b-jet identification:





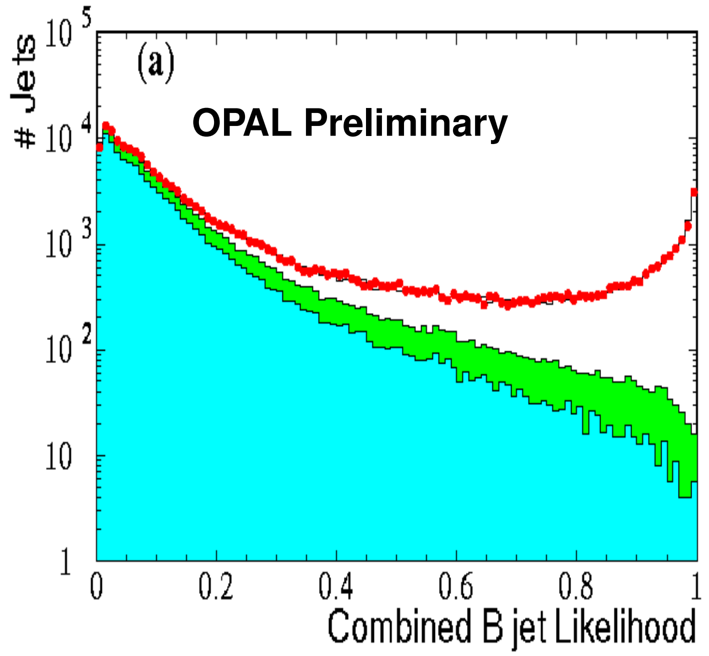
$hA \to b\bar{b}b\bar{b}$



	analyzed $\mathcal{L}(\mathrm{pb}^{-1})$ at 189 GeV	N_{exp}	N_{obs}	typical efficiency
ALEPH	35.7	1.9	3	60%
DELPHI	158.0	11.1	11	65%
L3	32.9	n/a, but no excess		
OPAL	151.0	7.0	12	50%

More on 4b Analyses

Analysis strategies are *complex* (ANN's, likelihoods, etc.), but well-understood:



points: data, $\sqrt{s} = m_{Z^0}$

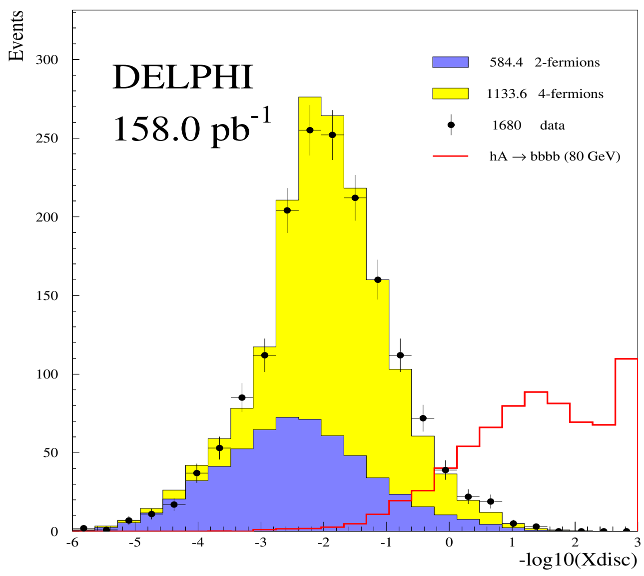
open histo: Monte Carlo

Also systematic cross-checks at high energy:

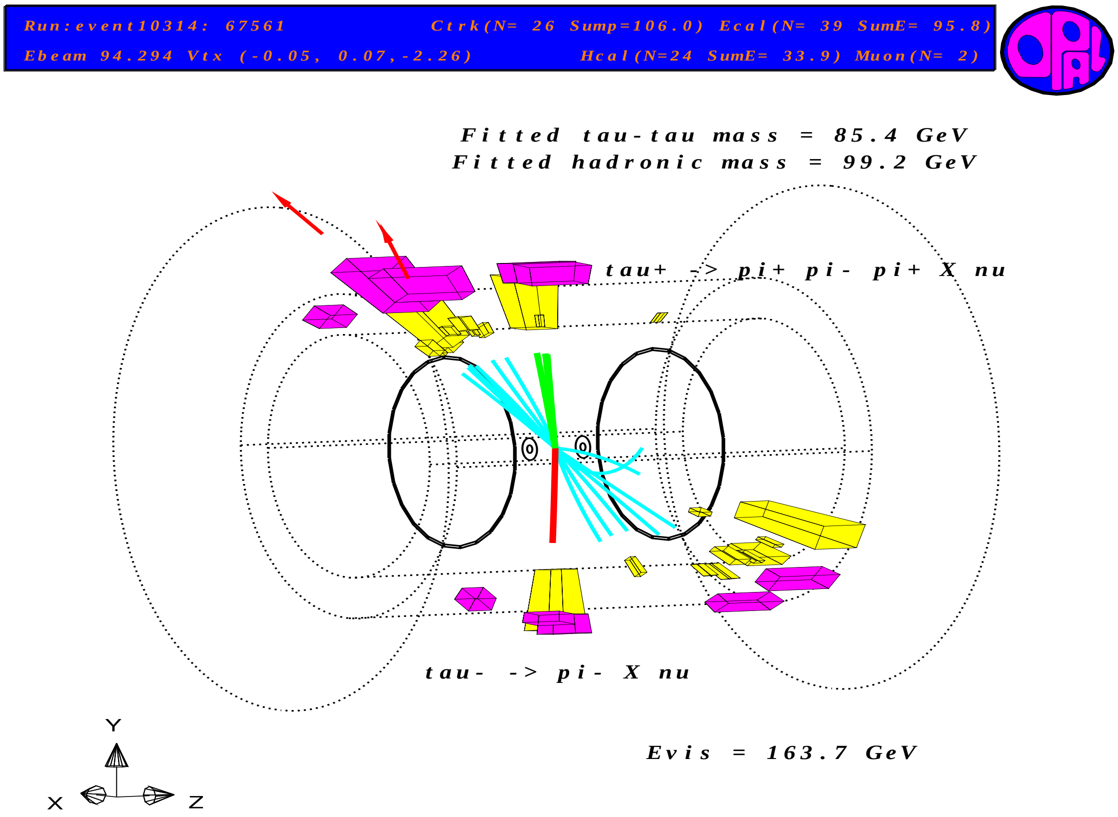
- **rad. returns to Z^0**
- **W pairs**

DELPHI 4b ANN output

$\longrightarrow$ data well-described by SM Monte Carlo



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



	analyzed $\mathcal{L}(\mathrm{pb}^{-1})$ at 189 GeV	N_{exp}	N_{obs}	typical efficiency
ALEPH	35.7	0.1	0	30%
DELPHI	158.0	0.6	0	20%
L3	32.9	n/a, but no excess		
OPAL	149.4	4.8	5	40%

$\mathrm{hA} \to \mathrm{AAA} \to \mathrm{b\bar{b}b\bar{b}b\bar{b}}$

- **Six jets, all b-flavored**
  $\Rightarrow$ certainly a striking topology!

- **We can afford a simple analysis (no ANN's, likelihoods, etc.)**

  $\Rightarrow$ Cuts on
  - **charged multiplicity**
  - **jet resolution parameters (y_{cut})**
  - **b-tags**

  are sufficient to achieve good efficiency with manageable background

- **No explicit mass reconstruction**

	analyzed $\mathcal{L}(\mathrm{pb}^{-1})$ at 189 GeV	N_{exp}	N_{obs}	typical efficiency
OPAL	151.0	7.3	8	60%

Combining the Search Channels

For a candidate j in channel i with mass m_{ij} assign a weight:

$$f_i(m_0, m_{ij}) = \frac{s_i(m_0, m_{ij})}{s_i^{max}(m_0)}$$

where s_i is the distribution of masses reconstructed from signal test mass m_0

$\Rightarrow$ suppresses candidates far from signal region

Different channels have different efficiencies, backgrounds, resolutions... scale their importance accordingly via factor:

$$c_i(m_0) = \left[\delta + \frac{B_i(m_0)}{S_i(m_0)s_i^{max}(m_0)}\right]^{-1}$$

$B_i \equiv$ background at m_0

$S_i \equiv$ fraction of signal in channel i (BRs, efficiencies...)

s_i^{max}: as above, inversely proportional to resolution

δ: regularizes c_i for low-background channels

Extracting a Limit

- The overall weight given to candidate j in channel i is:

$$w_{ij}(m_0) \propto c_i(m_0) f_i(m_0, m_{ij}) \qquad \text{(from prev. slide)}$$

- Determine weight sum instead of total candidates N:

$$w_N = \sum_{i,j} w_{ij} \qquad\qquad (w_N < N)$$

- Use w_N to determine 95% CL upper limit on signal rate

$\Rightarrow$ Note: w_N not Poisson-distributed – distribution must be determined numerically (computer-intensive)

This is the formalism adopted by OPAL; ADL use different methods

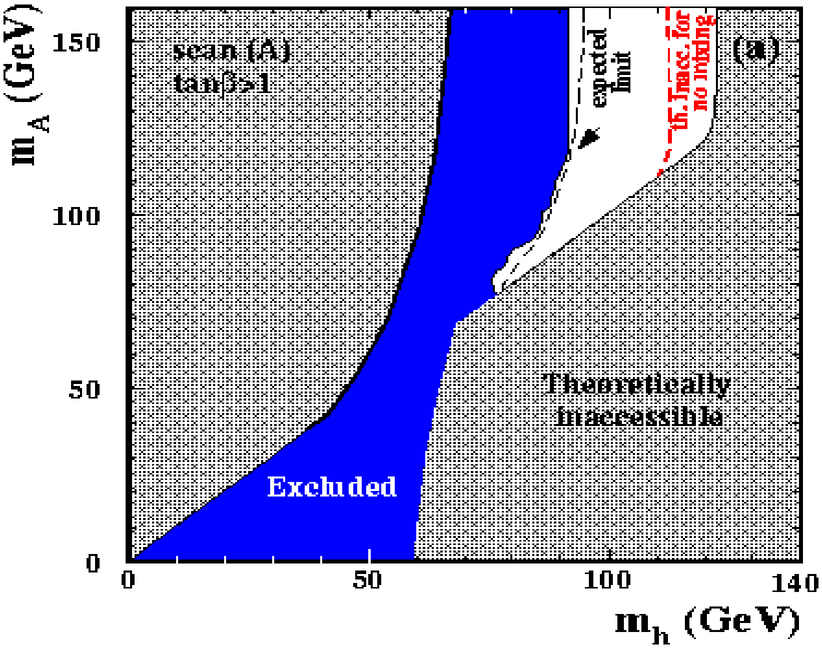
$\Rightarrow$ Studies of the different approaches for the LEP-wide SM Higgs limit show that they yield similar results

Results: Excluding the MSSM Parameter Space

"Benchmark" Scan:

- soft SUSY breaking masses (m_0, M_2) fixed at 1 TeV
- m_{top} fixed at 175 GeV, μ at -100 GeV
- minimal ($A = 0$) or maximal ($A = \sqrt{6}$ TeV) $\tilde{\mathrm{t}}$-mixing
- $m_{\mathrm{A}}, \tan\beta$ varied

OPAL 189 GeV PRELIMINARY



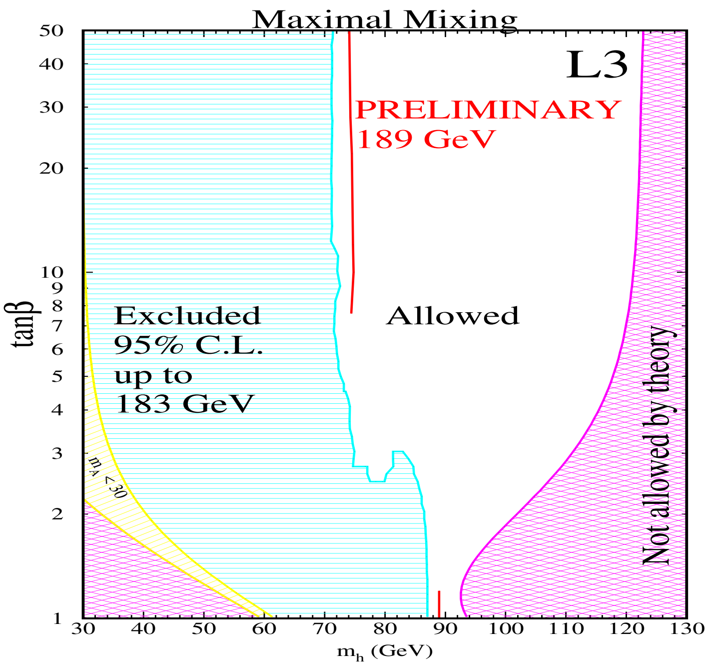
95% CL mass limits for $\tan\beta > 1$

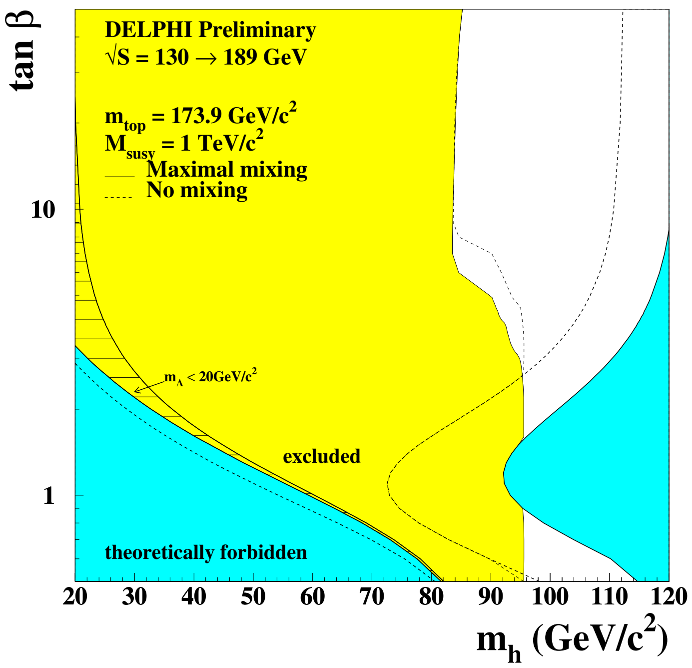
(recall expt's have analyzed varying portions of full data set)

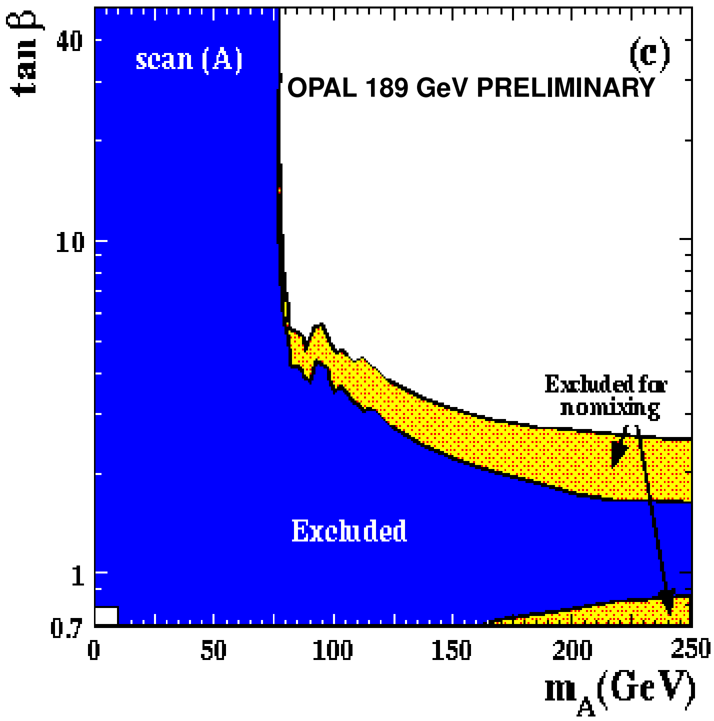
189 GeV	ALEPH	DELPHI	L3	OPAL
m_{h}	79.7*	83.5	74	76
m_{A}	79.7*	84.5	74	77

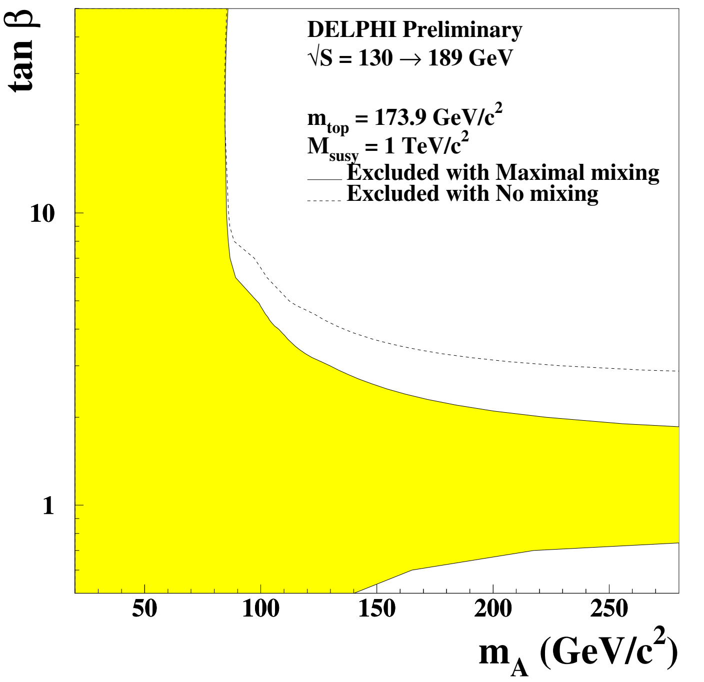
*hA search only

More Benchmark Projections





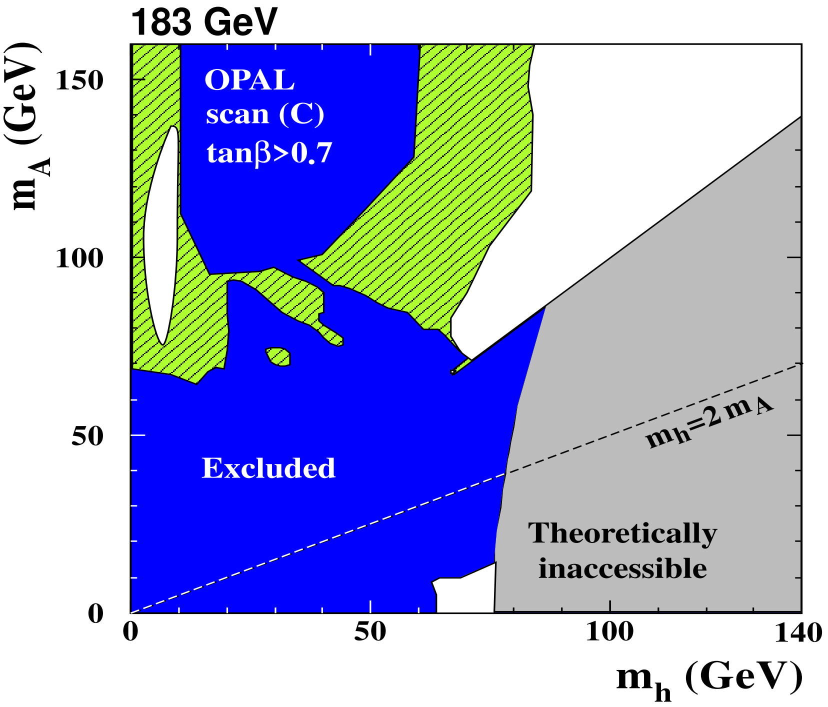




NEW! $\tan\beta$ exclusions for ANY mixing! (but $m_{\rm top}$ could be 185 GeV...)

Going further... “General Scans”

What happens to the limits when we let *everything* vary?



Some helpful constraints:

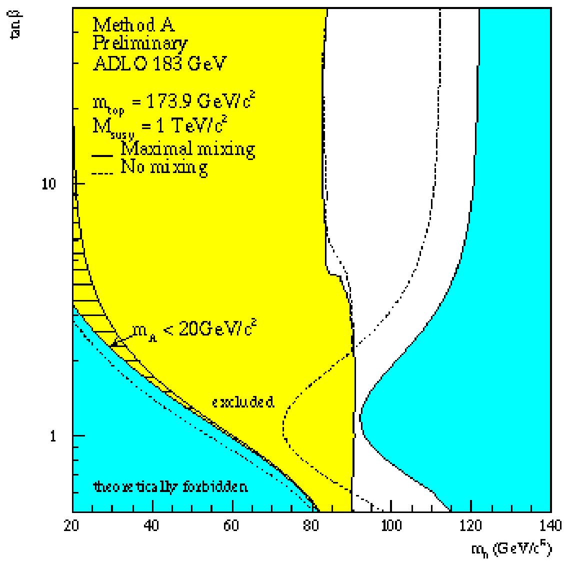
- reject parameter sets yielding MSSM Lagrangians with charge/color-breaking minima
- reject parameter sets yielding $\tilde{\chi}^0, \tilde{t}$ masses already excluded by direct searches

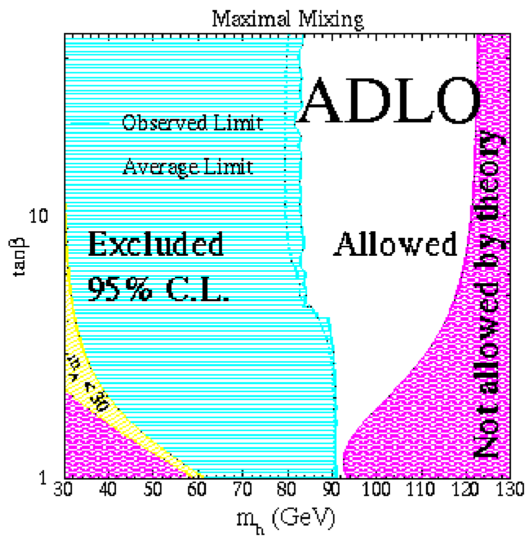
General conclusions:

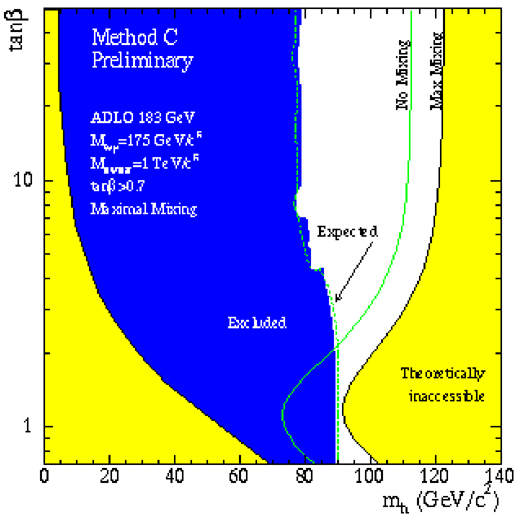
- ALEPH: limit-weakening sets constitute 0.01-0.1% of those scanned
- Usually sets with small $\sin^2(\beta-\alpha)$ (no hZ) but an A too heavy for LEP2
- DELPHI/OPAL: absolute limits generally 5-10 GeV worse than benchmark limits

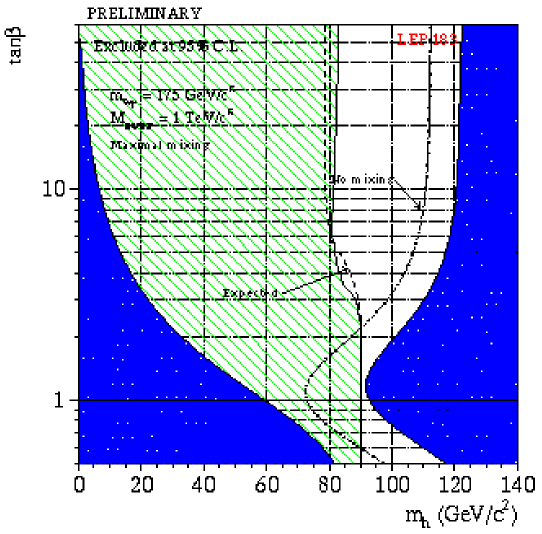
Combining the LEP Experiments

Four methods (A, B, C, D) investigated to pool the results of the four collaborations (more lumi pushes us closer to kinematic limit):





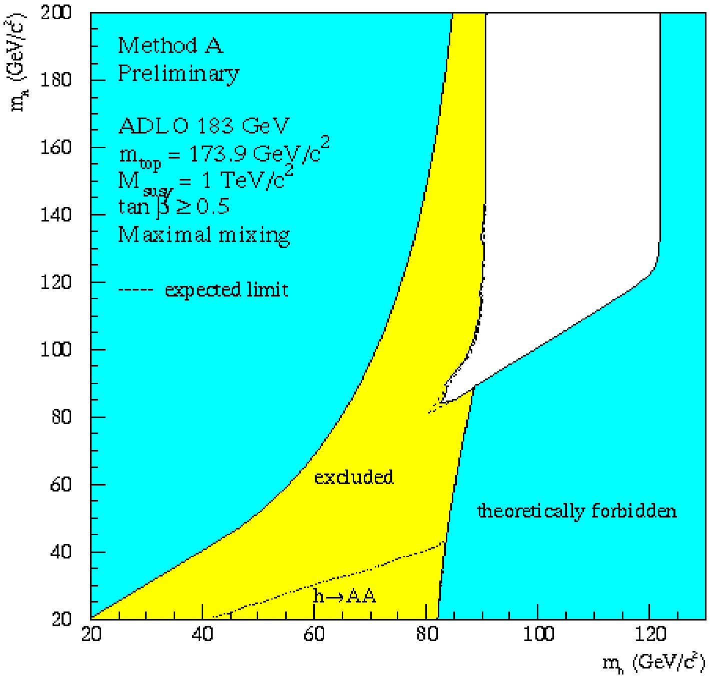




No Mixing: Excluded $0.8 \lesssim \tan\beta \lesssim 2.1$

(benchmark scan at 183 GeV)

LEP-Combined Mass Limits

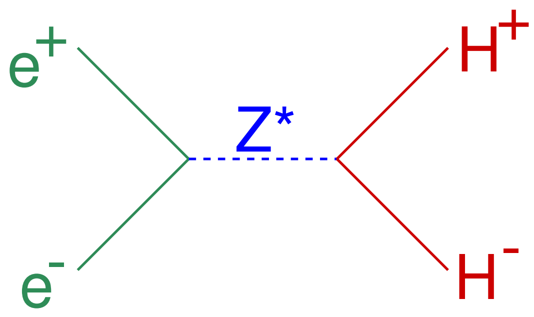


LEP mass limit up to 183 GeV (Preliminary)

	A	B	C	D	Spread
h^0 Obs. limit	82.6	81.9	78.8	80.5	±1.9
h^0 Exp. limit	80.5	79.4	76.3	79.0	±2.1
A^0 Obs. limit	82.9	81.6	79.1	82.6	±1.9
A^0 Exp. limit	80.9	79.8	76.3	79.0	±2.3

Gain of about 10 GeV wrt the individual experiments

What About The Charged Higgs?



- Only a few MSSM scenarios put $m_{\mathrm{H}^\pm}$ within LEP2 reach

- Light $\mathrm{H}^\pm$ can exist in some non-minimal 2HDM

- Searches done for $\mathrm{c\bar{s}\bar{c}s}$, $\mathrm{cs}\tau\nu$ and $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$ final states
  $\Rightarrow$ Assume $\mathrm{BR}(\mathrm{H}^\pm \to \tau^\pm\nu_\tau) + \mathrm{BR}(\mathrm{H}^\pm \to \mathrm{q\bar{q}'}) = 1$

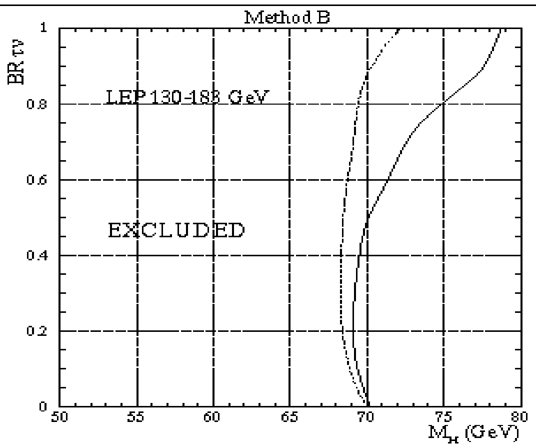
- 95% CL lower mass limits from 183 GeV:

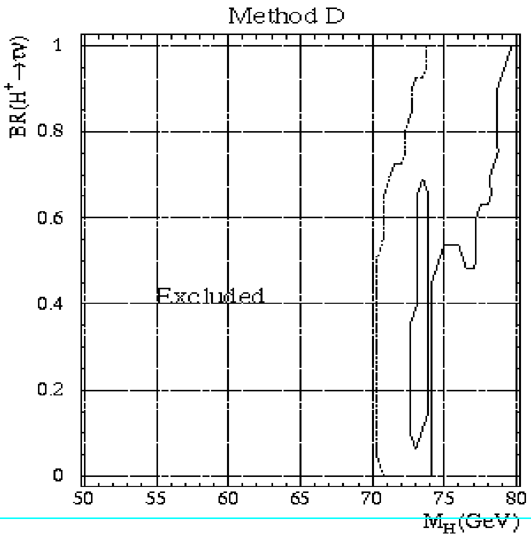
	ALEPH	DELPHI	L3	OPAL
$m_{\mathrm{H}^\pm} <$	59 GeV	56.5 GeV	57 GeV	56 GeV

- tough search — large $\mathrm{W^+W^-}$ background

Charged Higgs LEP Combination

The “wheels are in motion” — here’s a first look from 183 GeV:





LEP mass limit up to 183 GeV			
	B	D	Spread (GeV)
Obs. limit (GeV)	68	72	±2
Exp. limit (GeV)	69	70	±0.5

Conclusions

- No MSSM Higgs signal observed yet at LEP2

- Combined benchmark LEP mass limits at 183 GeV:

  $m_{\rm h} > 78.8$ GeV

  $m_{\rm A} > 79.1$ GeV

- Combined 183 GeV LEP $\tan\beta$ exclusion with minimal $\tilde{\rm t}$-mixing and $m_{\rm top} = 175$ GeV:

  $0.8 < \tan\beta < 2.1$ excluded

- Individual 189 GeV results currently (or about to) leapfrog combined results:

	$m_{\rm h}$ limit	$m_{\rm A}$ limit	$\tan\beta$ exclusion, ANY mixing
OPAL (part. lumi):	76.0 GeV	77.0 GeV	$1.1 < \tan\beta < 1.3$
DELPHI:	83.5 GeV	84.5 GeV	$0.9 < \tan\beta < 1.5$
			($m_{\rm top} = 175$ GeV)

- Stay tuned as LEP goes for highest possible $E_{\rm CM}$ this year!