Higgs Searches at LEP2

Marco Pieri
INFN Firenze

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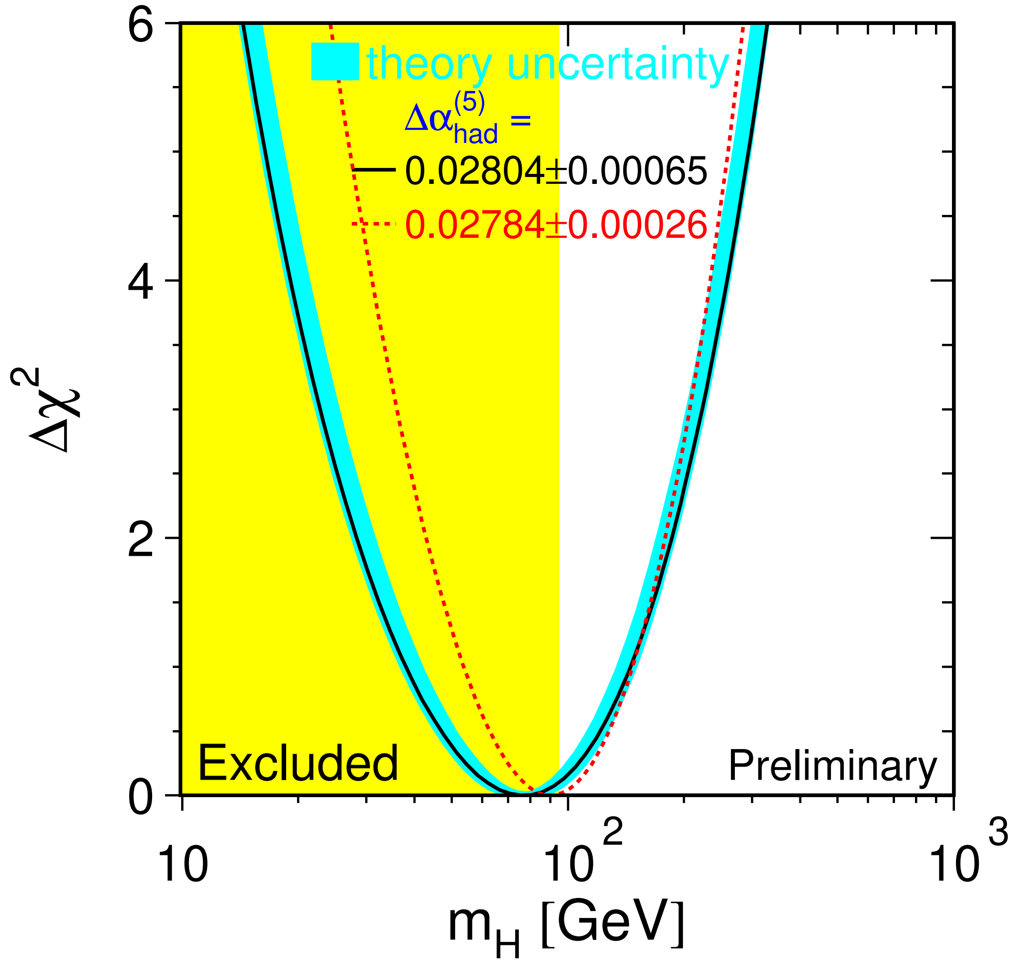
Outline

- Introduction
- Standard Model Higgs Boson
- Neutral Higgs Bosons in the MSSM
- Charged Higgs Bosons
- Invisible Higgs Decays
- Fermiophobic Higgs Boson
- Conclusions

All results are preliminary

SM Higgs from EW fits



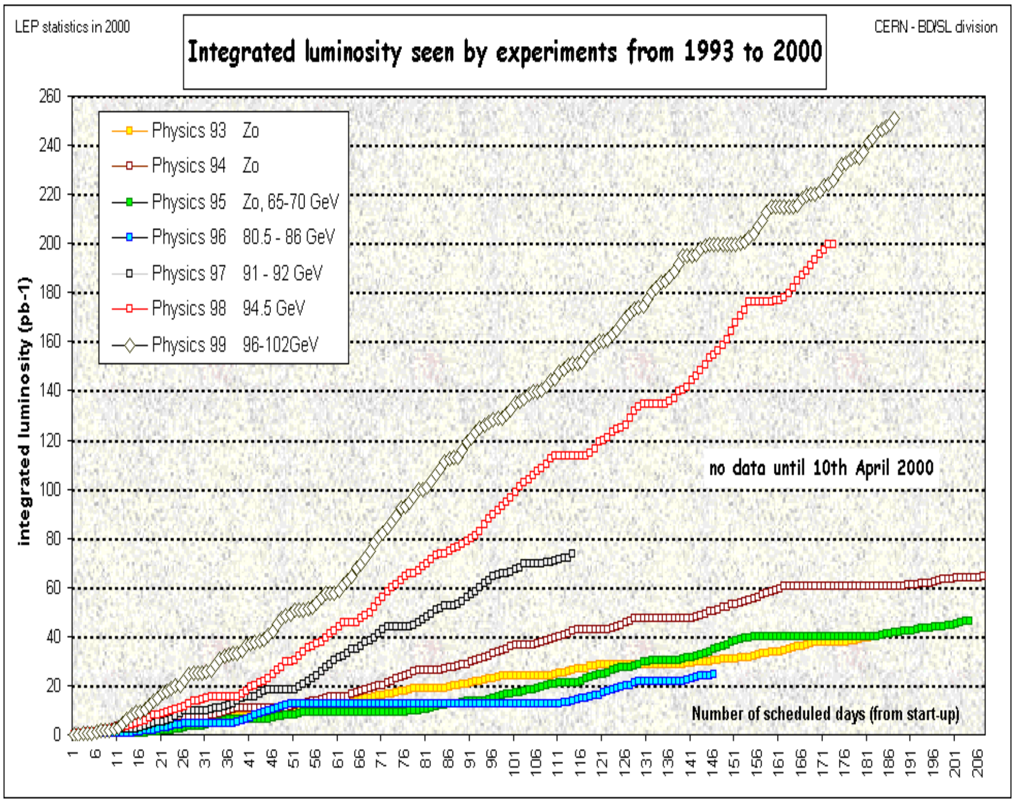
From SM fits of all data:

$m_{\rm H} = 76^{+68}_{-38}$ GeV

$m_{\rm H} < 215$ GeV at 95% C.L.

SM Higgs boson may be at reach at LEP

Collected Data at LEP2



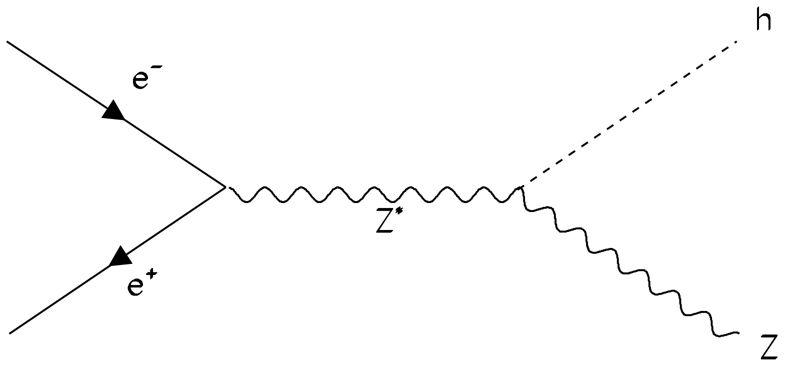
Integrated luminosity/experiment

Year	$\sqrt{s}$(GeV)	$\mathcal{L}$/exp. (pb^{-1})
1996	161-172	$\sim$ 20
1997	183	$\sim$ 55
1998	189	$\sim$ 170
1999	192	$\sim$ 30
	196	$\sim$ 90
	200	$\sim$ 90
	202	$\sim$ 40
Total		$\sim$ 500

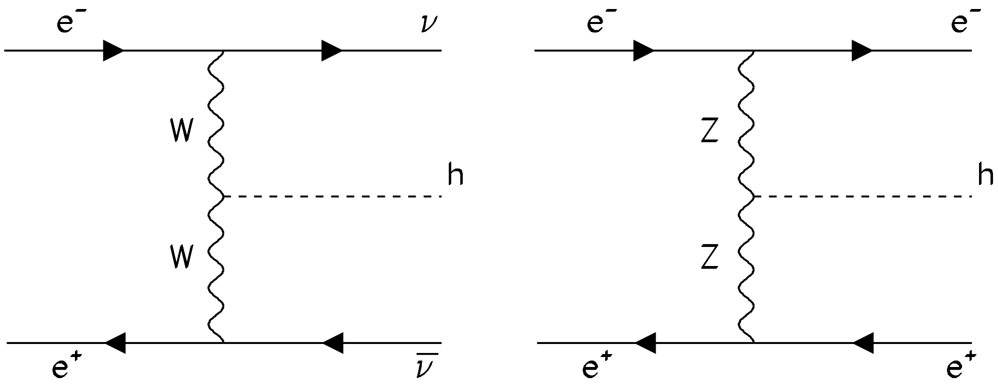
SM Higgs Boson

Higgs production processes at LEP2

Higgsstrahlung

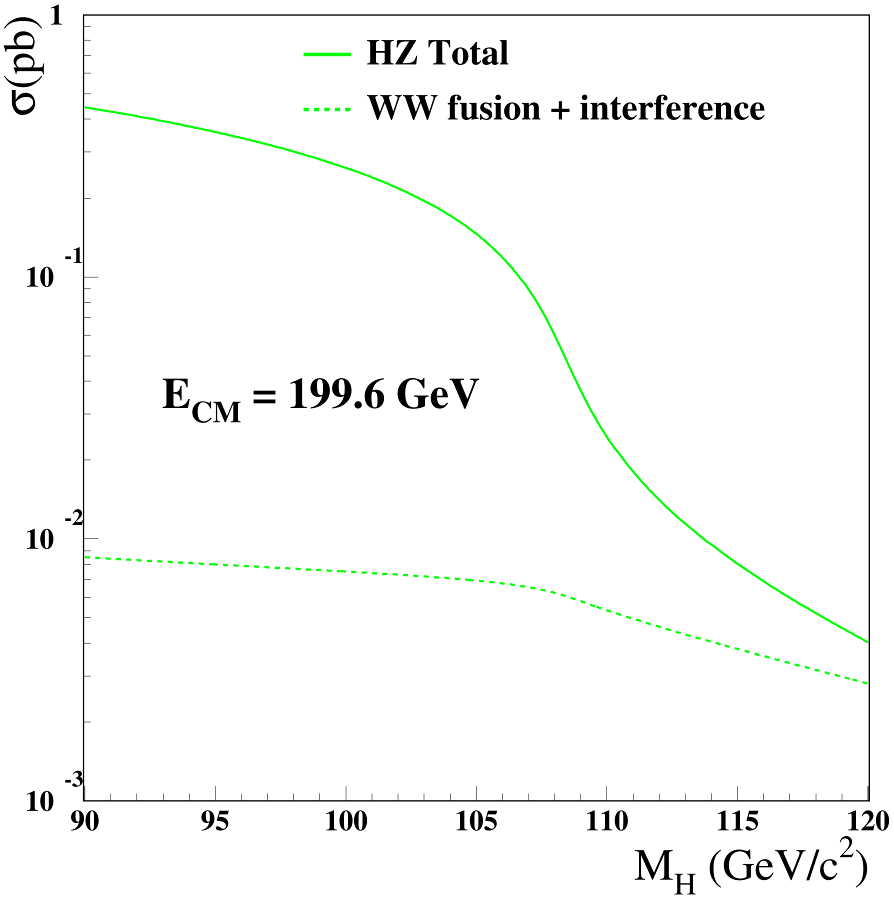


WW and ZZ fusion



Higgstrahlung much larger than fusion production

Production Cross Section



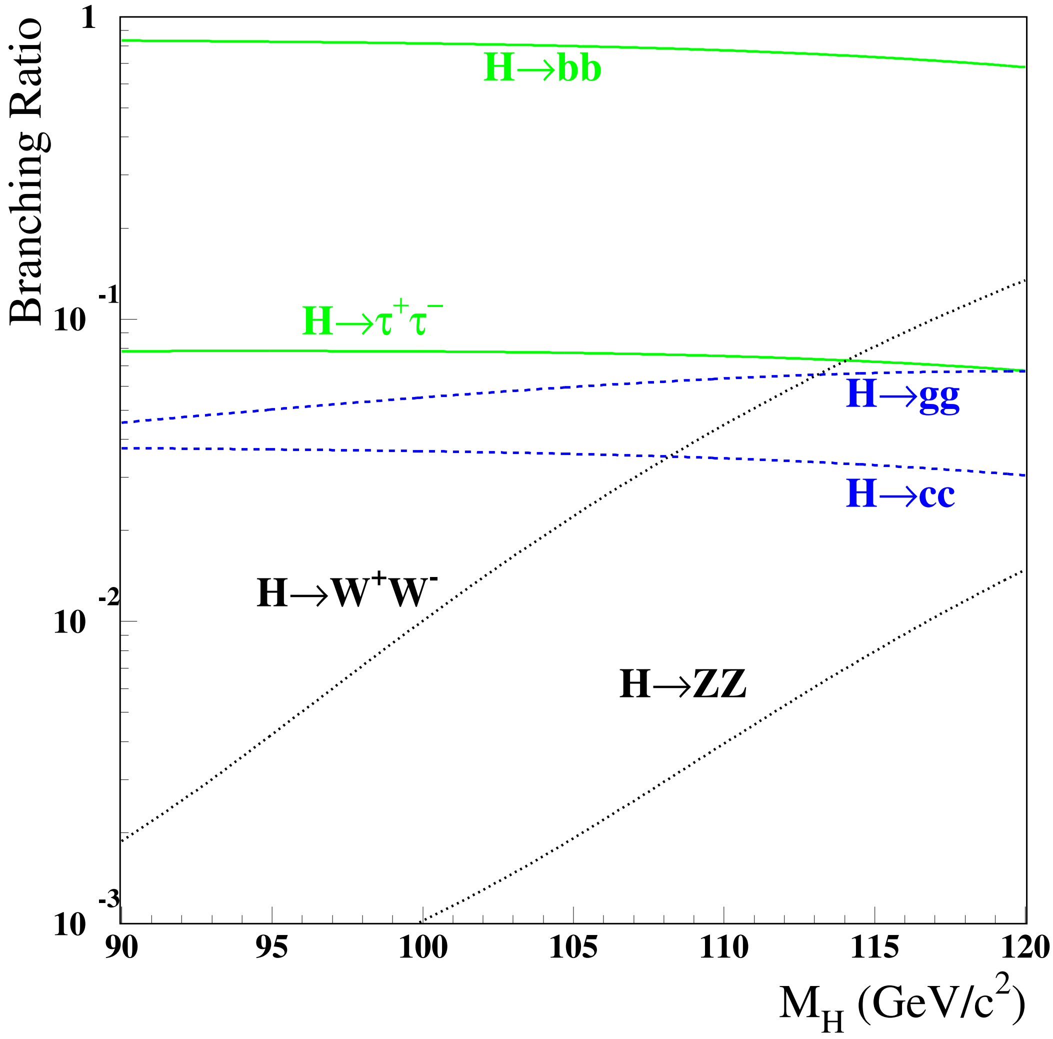
Main Backgrounds:

Process	Cross Section (pb)
$e^+e^- \rightarrow ff(\gamma)$	~ 100
$e^+e^- \rightarrow W^+W^-$	~ 17
$e^+e^- \rightarrow ZZ$	~ 1
$e^+e^- \rightarrow We\nu$	~ 1
$e^+e^- \rightarrow Ze^+e^-$	~ 3

SM Higgs Boson Decays

The Higgs boson couples to the mass of the fermions

Largest BR into the heaviest quarks and leptons

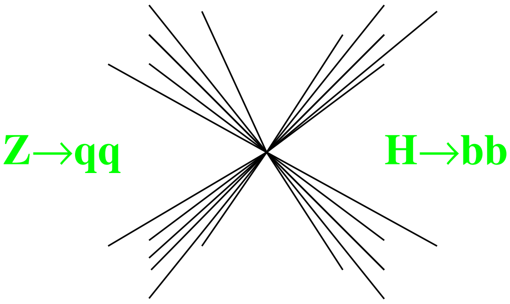


$\mathrm{BR}(\mathrm{H}\rightarrow \mathrm{b}\bar{\mathrm{b}}) \sim 80\%$

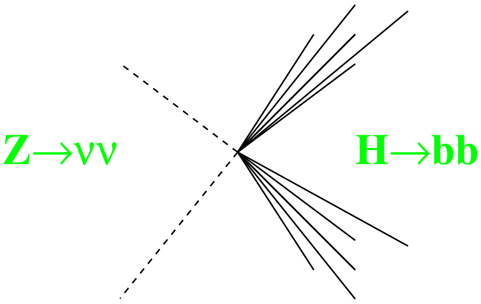
$\mathrm{BR}(\mathrm{H}\rightarrow \tau^+\tau^-) \sim 8\%$

SM Higgs Search Channels

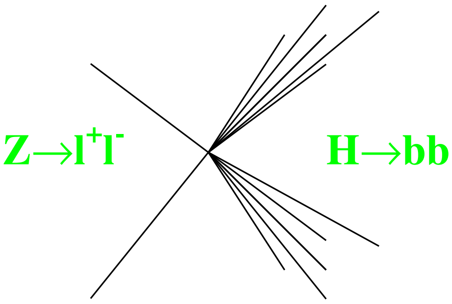
$\mathrm{HZ} \rightarrow$ 4 jets



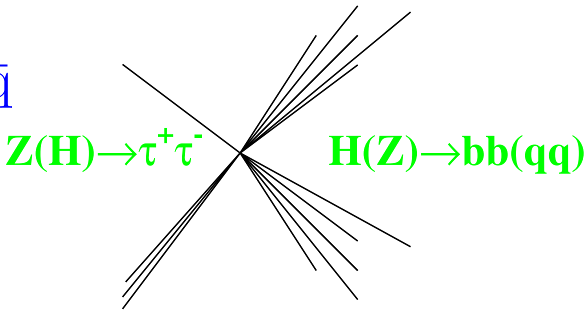
$\mathrm{HZ} \rightarrow \mathrm{b\bar{b}}\nu\bar{\nu}$



$\mathrm{HZ} \rightarrow \mathrm{b\bar{b}}\ell^+\ell^-$, $\ell = \mathrm{e}, \mu$



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



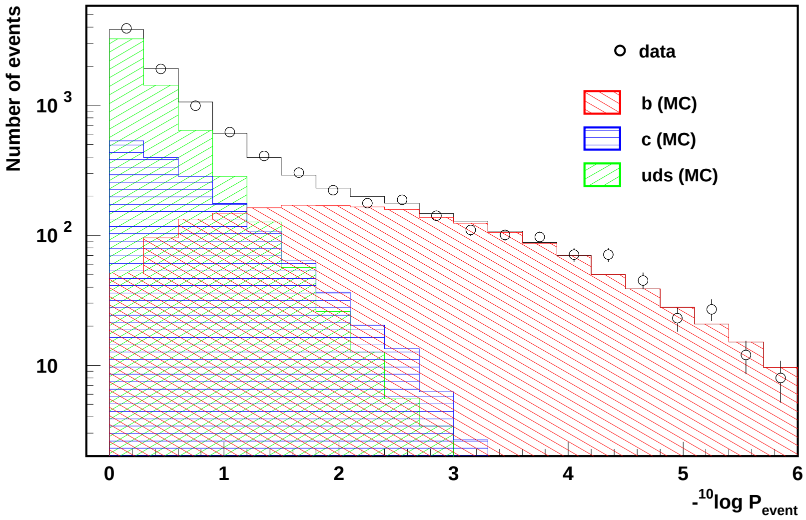
B-Tagging

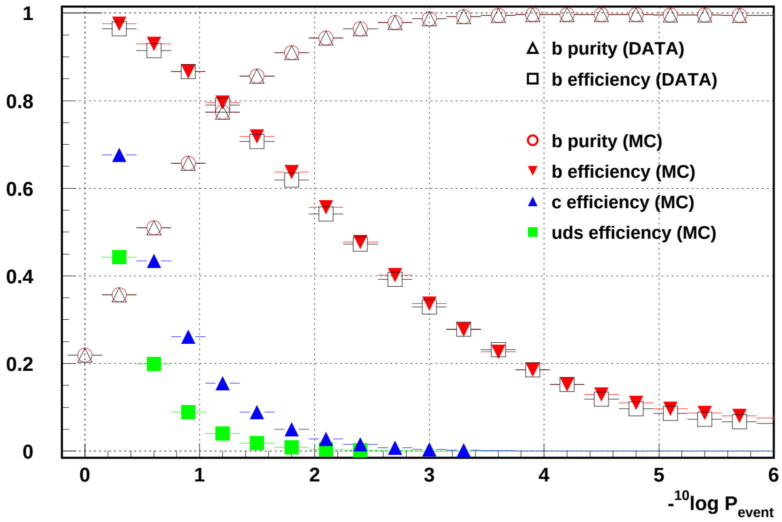
Largest Higgs Boson BR into $b\bar{b}$

b-hadron signatures:

- long lived
- inclusive leptons
- hard fragmentation

All experiments use neural networks to combine all the information and obtain a jet tag





L3

1999

Z-peak data

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Method of Analysis

Search in all channels

Selections are based on neural network or likelihood methods

To evaluate discovery or exclusion use mass of the candidates alone (OPAL) or in combination with other discriminating variable (b-tag, neural network output, likelihood)

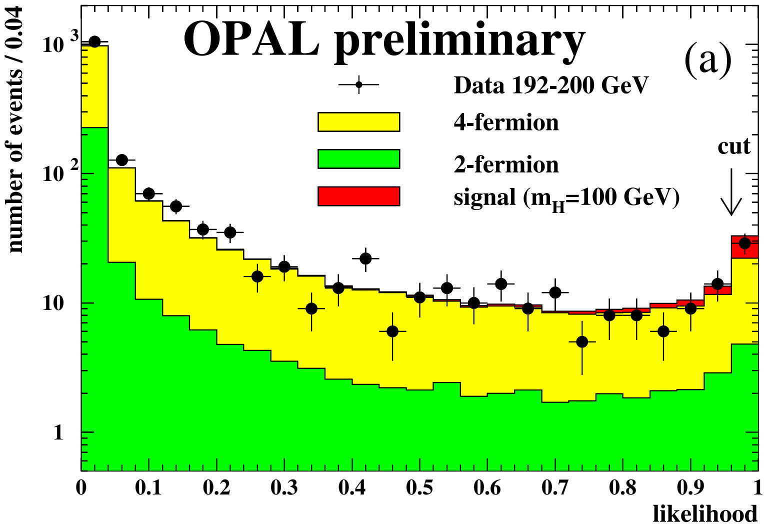
OPAL 192-200 GeV

Channel	Data	MC bkgd	Eff. m_{H}=100 GeV
$\mathrm{HZ} \to \mathrm{b\bar{b}q\bar{q}}$	29	22.1 ± 4.4	41%
$\mathrm{HZ} \to \mathrm{b\bar{b}}\nu\bar{\nu}$	4	7.6 ± 1.0	40%
$\mathrm{HZ} \to \mathrm{b\bar{b}}\ell^+\ell^-$	10	5.6 ± 1.4	59%
$\mathrm{HZ} \to \mathrm{b\bar{b}}\tau^+\tau^-$	5	5.4 ± 1.6	35%

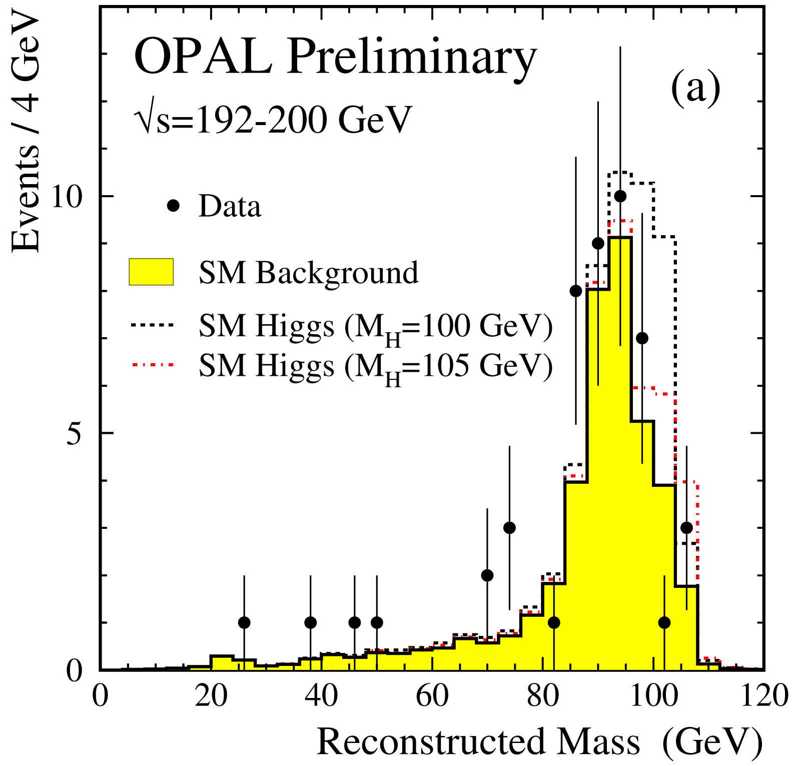
DELPHI and L3 have higher efficiency and higher background

SM Higgs Boson Search

OPAL HZ $\to b\bar{b}q\bar{q}$ channel



Mass spectrum for all channels combined



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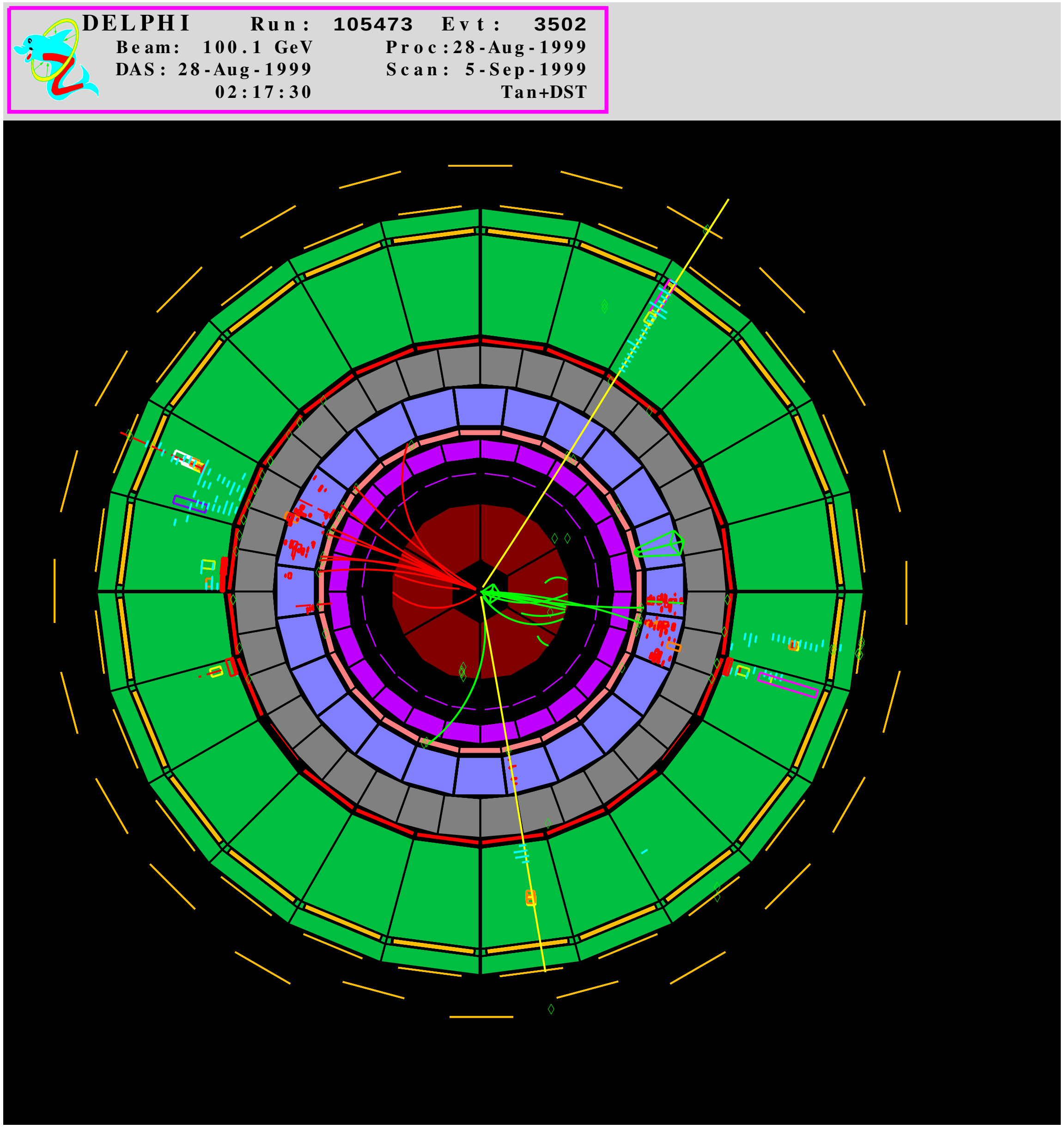
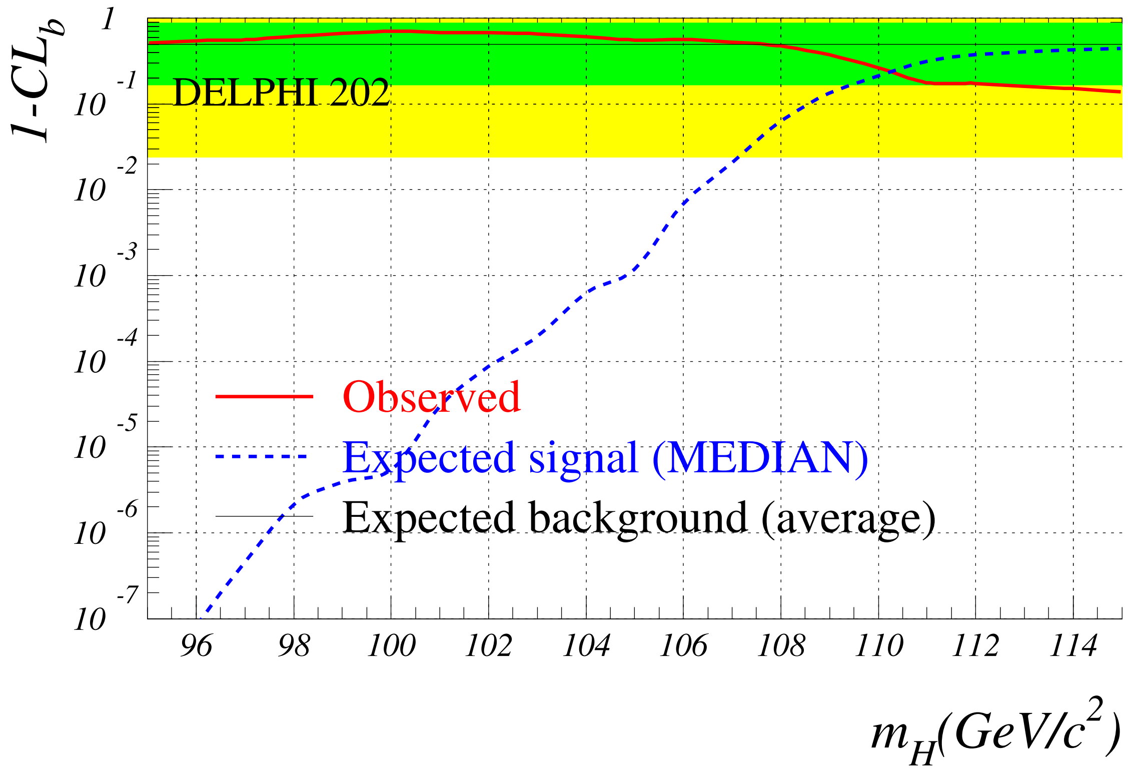
Candidates

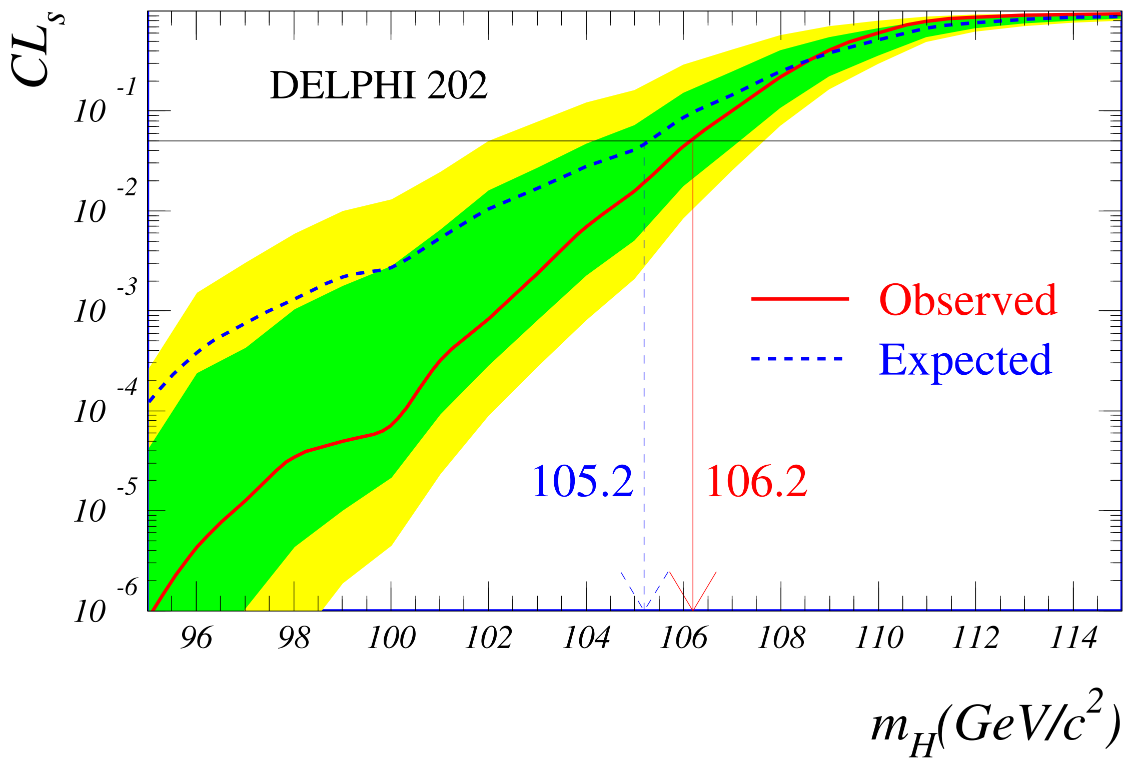
DELPHI candidate for $\mathrm{H}\mu^+\mu^-$

$\sqrt{s} = 200$ GeV



Confidence Levels





Results for SM

All 4 LEP experiments see no indications of a signal

Limits are derived at 95% C.L.

	ALEPH	DELPHI	L3	OPAL
Obs.(GeV)	107.7[1]	106.2	103	102.0[2]
Exp.(GeV)	106.8[1]	105.9	105[3]	101.9[2]

Note:
1) ALEPH uses a different background subtraction technique
2) OPAL results do not use all collected data in 1999
3) L3 quotes median for the expected

The LEP Higgs Working Group is in the process of combining 1999 results

Expected limit will be around 109 GeV

Higgs Sector in MSSM

Minimal SuperSymmetric Model (MSSM)

- Two CP-even Higgs bosons (h and H)
- One CP-odd Higgs boson (A)
- Two charged Higgs boson (H^+ and H^-)

$\mathrm{H}^{\pm}$ too heavy for LEP

h should be light:
$m_{\mathrm{h}} \lesssim 135$ GeV (latest calculations)

Mass relations, cross sections and BR depend on MSSM parameters:
M_{SUSY}, M_2, μ, $m_{\tilde{g}}$, A
Parametrized as function of $\tan\beta$, m_{A}

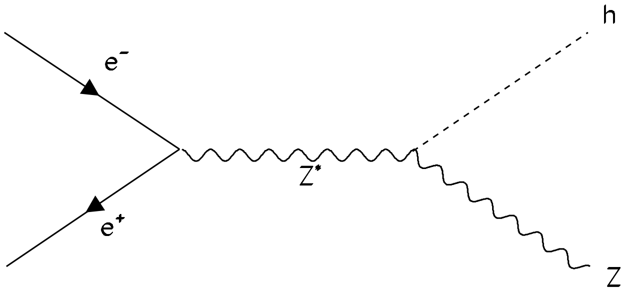
Usually consider no decays into SUSY particles, if light enough the could be discovered in direct searches

Benchmarks:

- No mixing in the stop sector
- Maximal mixing in the stop sector
- More general scans

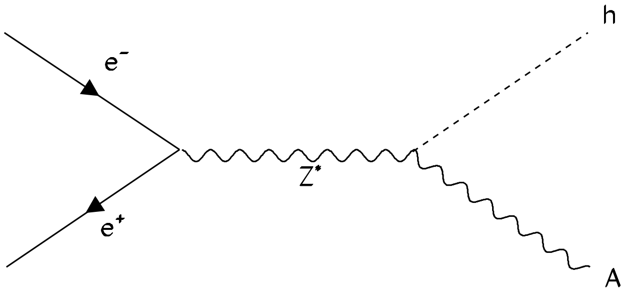
Production and Decay

h can be produced with the Higgsstrahlung as in SM (use SM search results)



$\propto \sin^2(\beta - \alpha)$

Pair production: $e^+e^- \to$ hA



$\propto \cos^2(\beta - \alpha)$

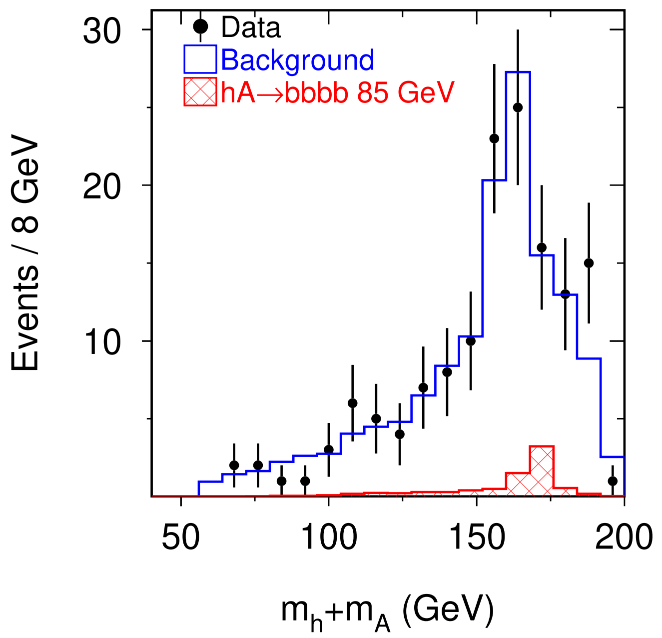
h and A mainly decay into $b\bar{b}$ and $\tau^+\tau^-$

Three main channels:

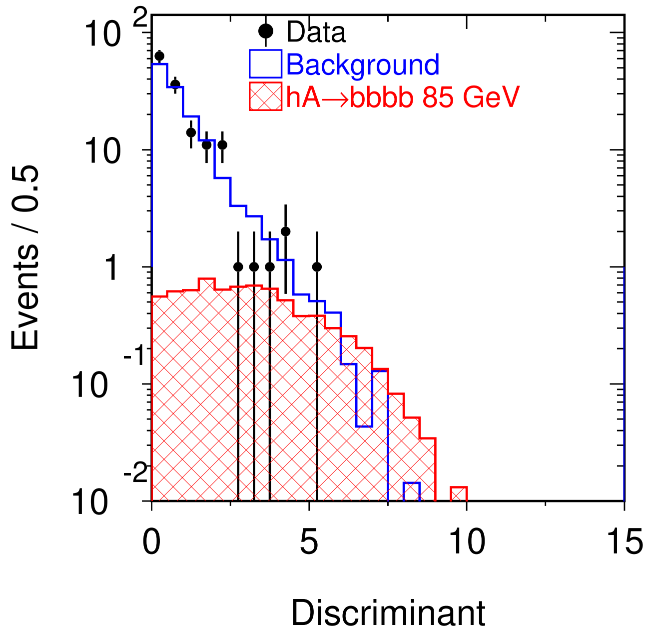
- $hA \to b\bar{b}b\bar{b}$ (b-tagging very effective)
- $hA \to b\bar{b}\tau^+\tau^-$
- $hA \to \tau^+\tau^-\tau^+\tau^-$ (Small BR, not used)

Pair Production Analysis

Channel $\mathrm{hA} \to \mathrm{b\bar{b}b\bar{b}}$ (L3)



Use mass χ^2 combined with b-tag event variable to obtain the final discriminant



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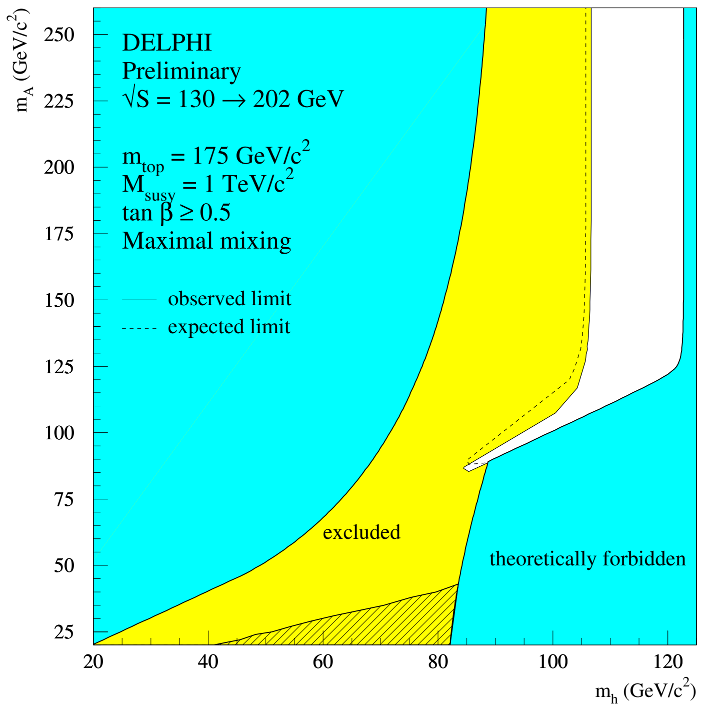
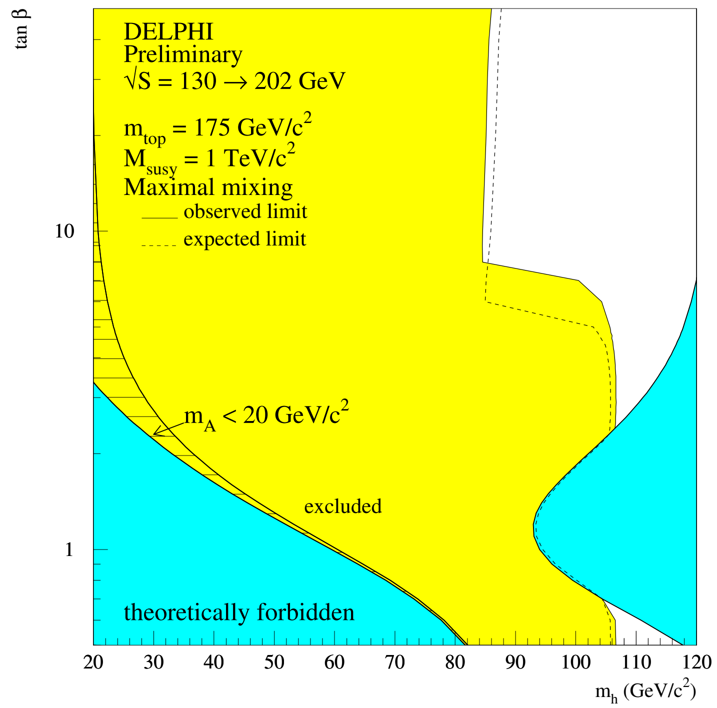
Results for MSSM

DELPHI results for maximal mixing





95% lower limits

$m_{\mathrm{h}} > 84.5\ \mathrm{GeV}$

$m_{\mathrm{A}} > 85.6\ \mathrm{GeV}$

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Lower limits on $m_{\rm h}$ and $m_{\rm A}$

No signal observed

95% C.L. lower limits on $m_{\rm h}$

	ALEPH	DELPHI	L3	OPAL
Obs.(GeV)	91.5[1]	84.5	81	77.1[2]
Exp.(GeV)	87.7[1]	84.9	83[3]	83.1[2]

95% C.L. lower limits on $m_{\rm A}$

	ALEPH	DELPHI	L3	OPAL
Obs.(GeV)	91.9[1]	85.6	82	78.2[2]
Exp.(GeV)	88.1[1]	87.3	83[3]	83.4[2]

Note:
1) ALEPH uses a different background subtraction technique
2) OPAL results do not use all collected data in 1999
3) L3 quotes median for the expected

General MSSM Scan

Going beyond the benchmarks some problematic MSSM points exist were:
either BR(h$\rightarrow$b$\bar{\mathrm{b}}$) is small ($\sin\alpha \sim 0$)
or m_{A} is large and $\sin^2(\beta-\alpha)$ is small

Using data al 189 GeV ALEPH studied the case $\tan\beta = \sqrt{2}$

350000 MSSM points have been investigated

Two additional searches developed for the cases:

- ZH$\rightarrow\nu\bar{\nu}$hh$\rightarrow\nu\bar{\nu}\tau^+\tau^-\tau^+\tau^-$
- Zh$\rightarrow\nu\bar{\nu}\mathrm{q}\bar{\mathrm{q}}$

All points have been excluded

Limit on m_{h} valid at 10^{-5} level

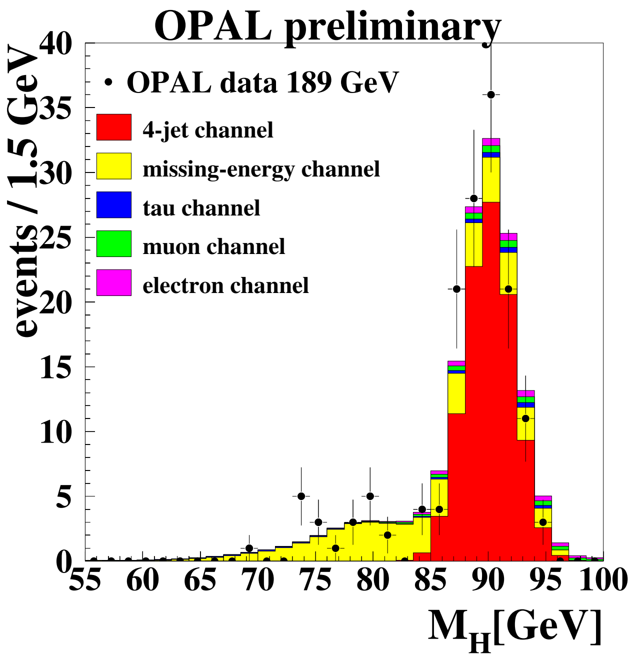
Limits on m_{h} are not very sensitive to MSSM parameters and m_{top}

$\tan\beta$ exclusions depend on the calculations and on the input parameters (example m_{top})

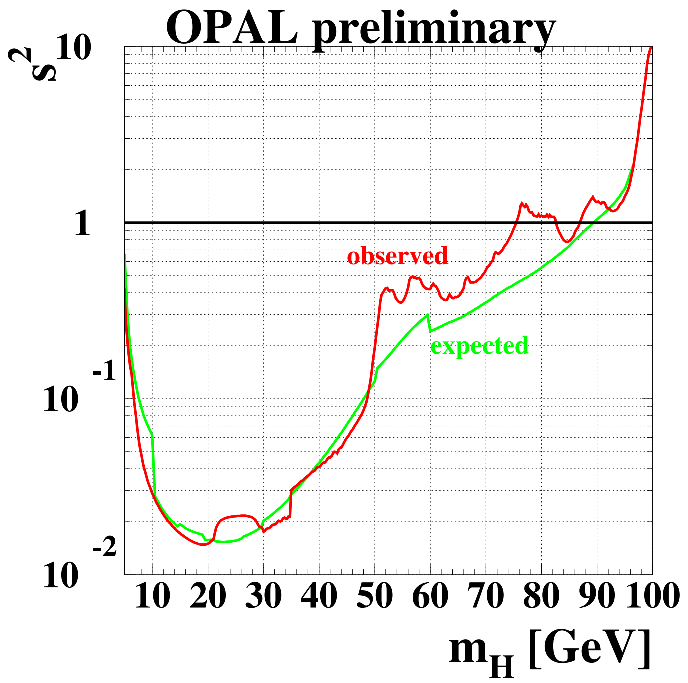
Recent calculations and new benchmarks ($m_{\mathrm{h}}^{\mathrm{max}}$) increase the maximum value of m_{h} for a given $\tan\beta$ of ~ 5 GeV

Flavour Independent Search

Flavour independent search for:
$e^+e^- \to hZ$
with $h \to$hadrons

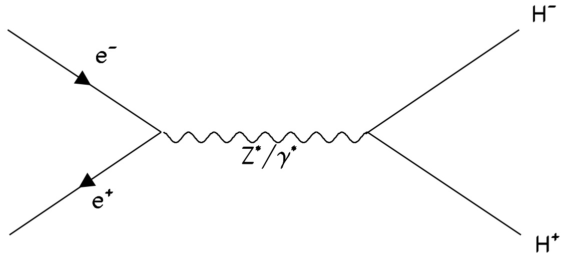


Model independent 95% C.L. limits on cross section
$\sigma_{hZ} = s^2 \sigma_{HZ}^{SM}$

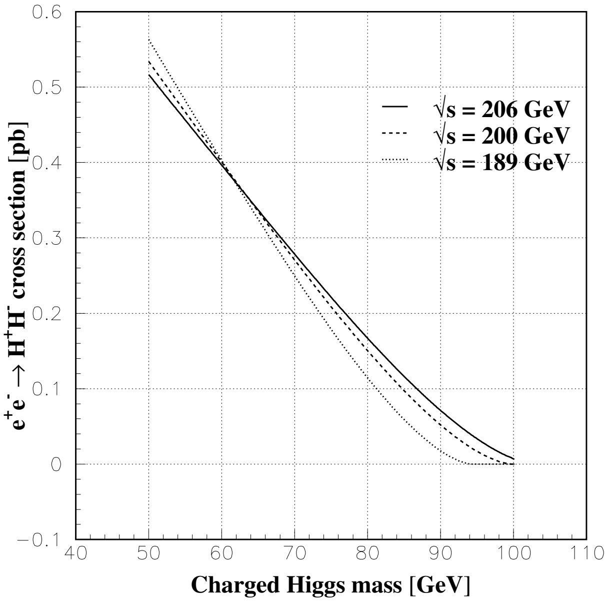


$m_h > 75.5$ GeV at 95%cl SM cross section
$m_h > 74.9$ GeV at 95%cl Type II 2HDM
$(s^2_{min} = 0.9)$

Charged Higgs Bosons



- Production cross section only depends on the mass
- $\mathrm{H}^+(\mathrm{H}^-)$ decays into $\mathrm{c\bar{s}}(\mathrm{\bar{c}s})$ or $\tau^+\nu_\tau(\tau^-\bar{\nu}_\tau)$



Search in all the channels:

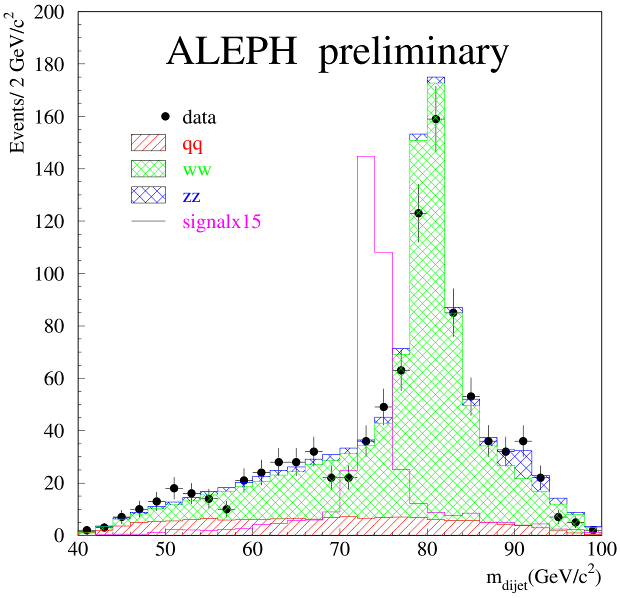
- $\mathrm{H^+H^-} \longrightarrow \mathrm{c\bar{s}\bar{c}s}$
- $\mathrm{H^+H^-} \longrightarrow \mathrm{c\bar{s}}\tau^-\bar{\nu}_\tau,\ \tau^+\nu_\tau\mathrm{\bar{c}s}$
- $\mathrm{H^+H^-} \longrightarrow \tau^+\nu_\tau\tau^-\bar{\nu}_\tau$

$\mathrm{W^+W^-}$ irreducible background for $m_{\mathrm{H}^\pm} = m_{\mathrm{W}}$

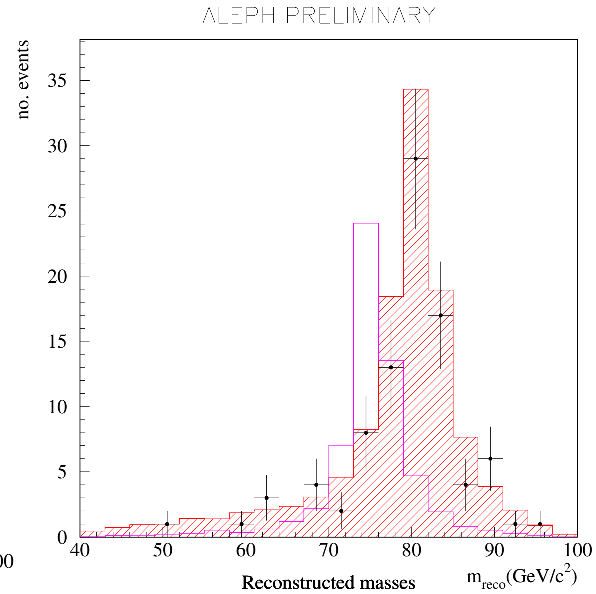
Charged Higgs Search

ALEPH preliminary

$c\bar{s}\bar{c}s$ channel



$c\bar{s}\tau\nu_\tau$ channel

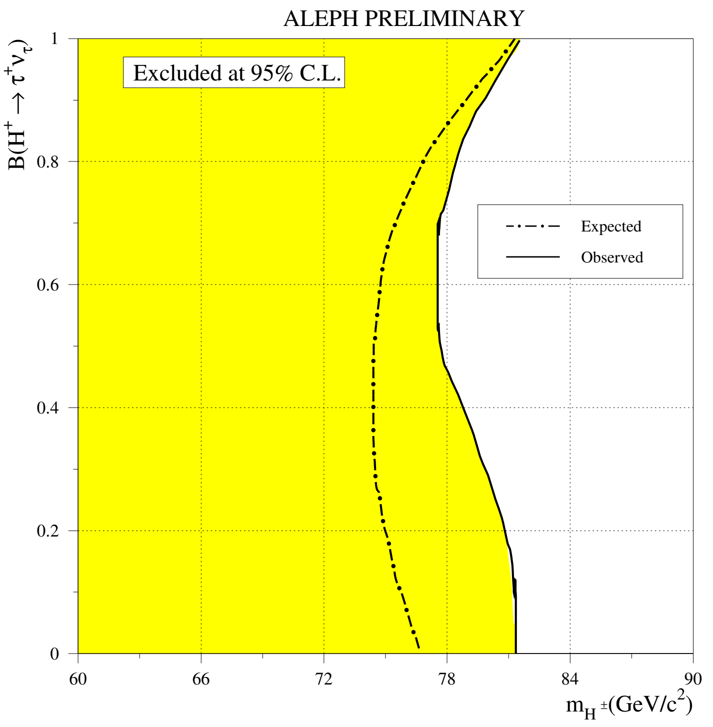


ALEPH 192-202 GeV

Channel	Data	MC bkgd	Eff. $M_{H^\pm}$=75 GeV
$c\bar{s}\bar{c}s$	979	1034.2	68%
$c\bar{s}\tau\nu_\tau$	90	113.1	43%
$\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$	36	35.5	35%

Charged Higgs Results

No signal observed



Lower limits at 95% C.L for any BR($\mathrm{H}^\pm \to \tau\nu$)

	ALEPH	DELPHI	L3	OPAL
Obs.(GeV)	77.7[1]	74.1	65.5	70.5
Exp.(GeV)	74.5[1]	70.8	73.5[2]	71.6

Note:

1) ALEPH uses a different background subtraction technique

2) L3 quotes median for the expected

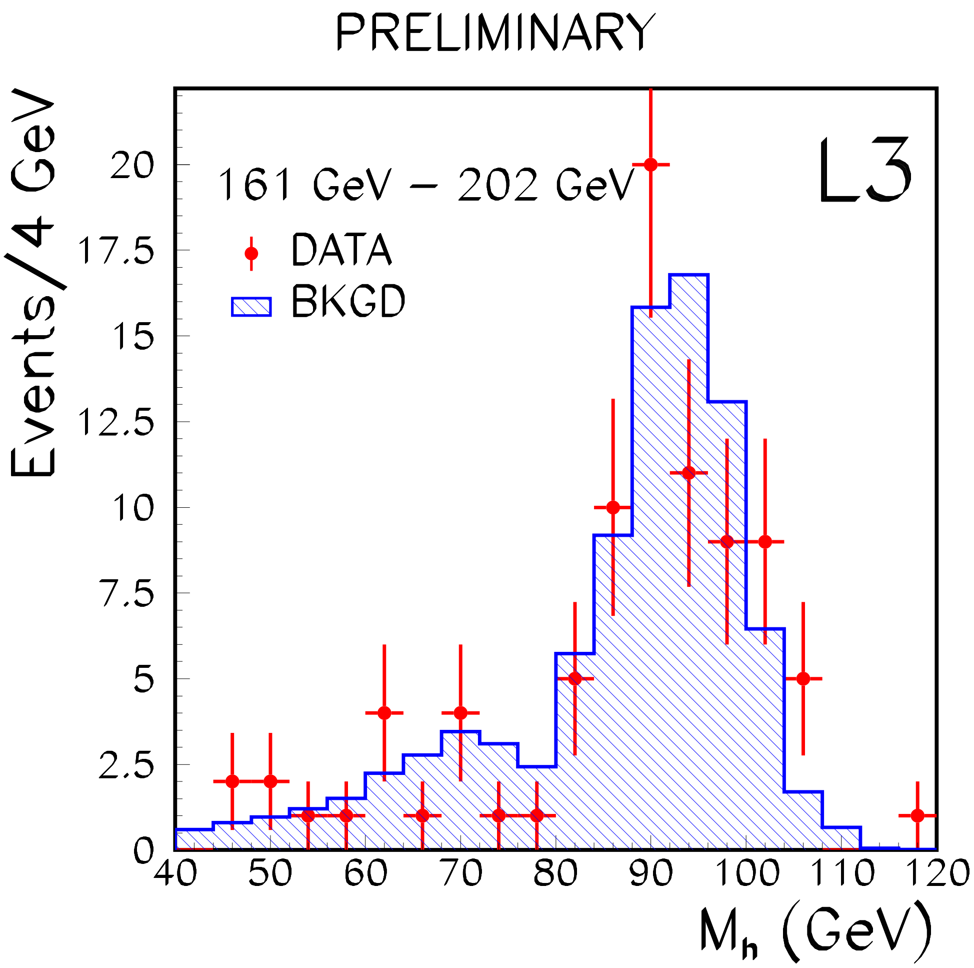
LEP combined at 189 GeV: 77.3 GeV obs., 74.9 GeV exp.

Invisible Higgs Boson

Higgs boson may decay to invisible final states (lightest neutralinos)

$e^+e^- \to hZ$ with $Z \to q\bar{q}$ and $h \to$ invisible

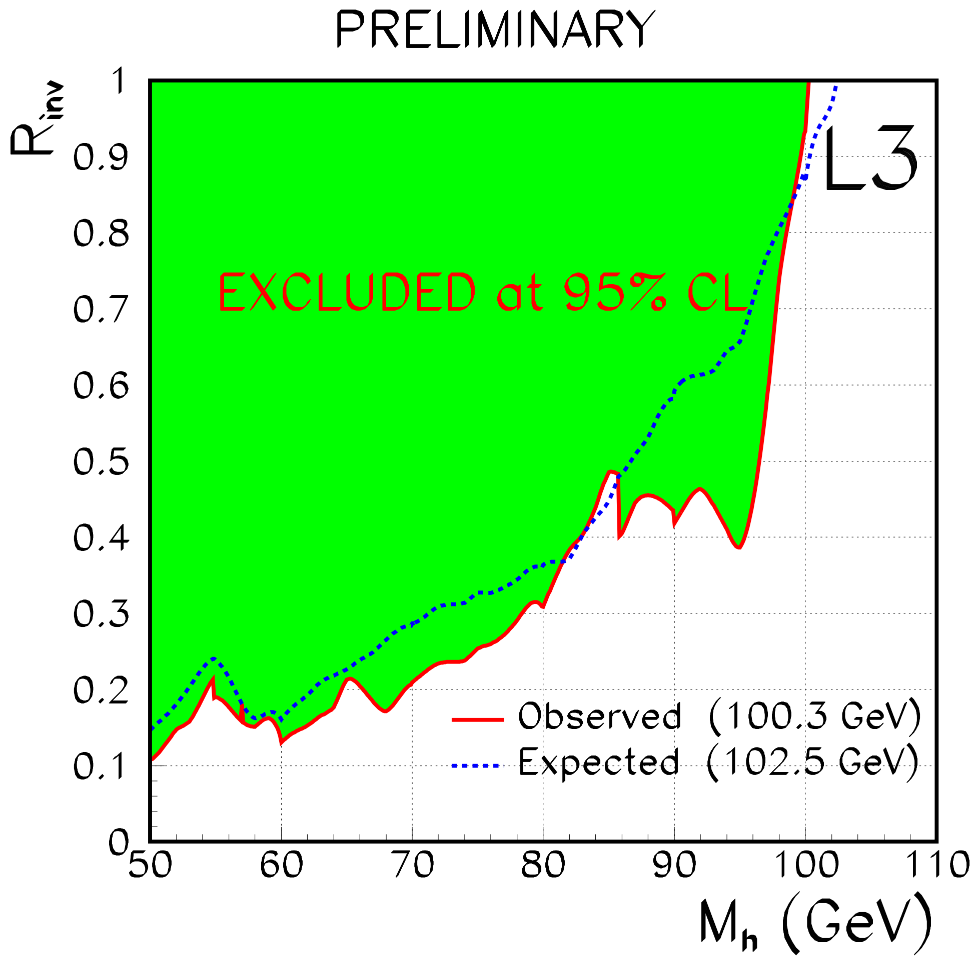
Search for hadronic events, consistent with Z decay, with missing energy and momentum



Invisible Higgs Results

Compute upper limit on:

$$R_{\rm inv} = {\rm BR}({\rm h} \to {\rm invisible}) \times \frac{\sigma({\rm hZ})}{\sigma({\rm H_{SM}Z})}$$



Lower limits at 95% C.L for $\rm R_{inv} = 1$

ALEPH	DELPHI	L3	OPAL
95.4 GeV	93.8 GeV	100.3[1] GeV	94.4[1] GeV

1) Updated with 192 – 202 GeV data

Search for $\mathrm{h} \rightarrow \gamma\gamma$

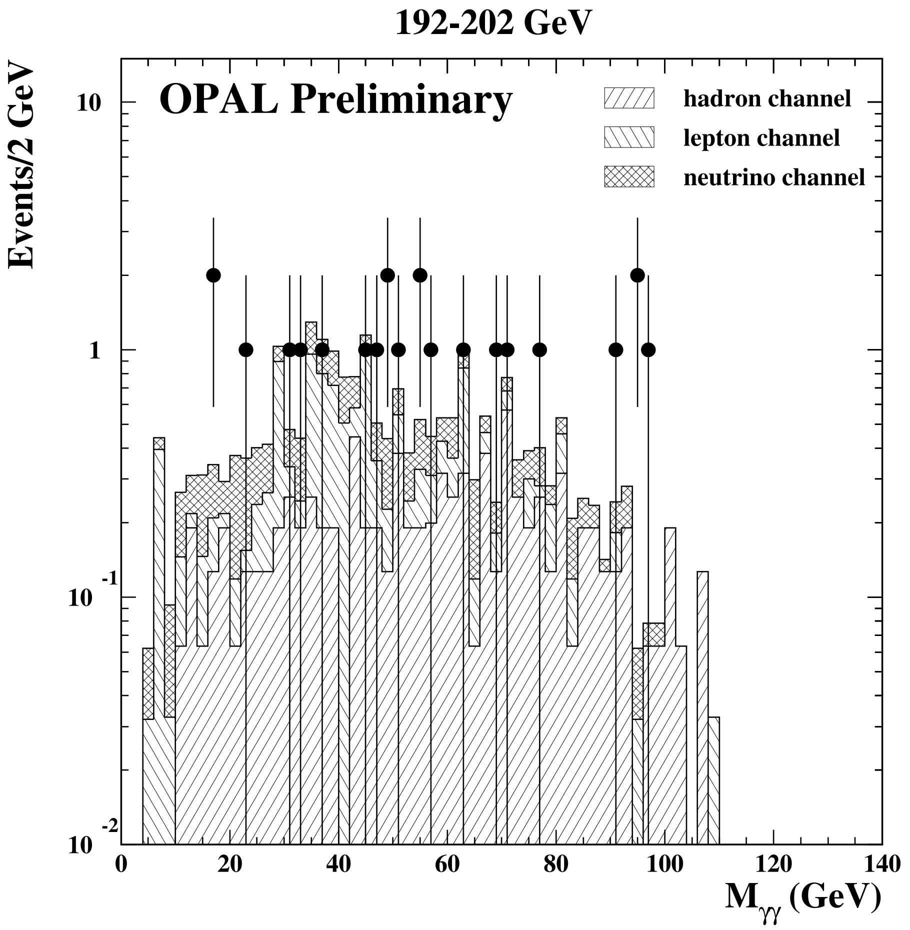
SM $\mathrm{BR}(\mathrm{h} \rightarrow \gamma\gamma) \sim 10^{-3}$

Can be enchanced in models where the Higgs boson does not couple to the fermions

OPAL 192-202 GeV

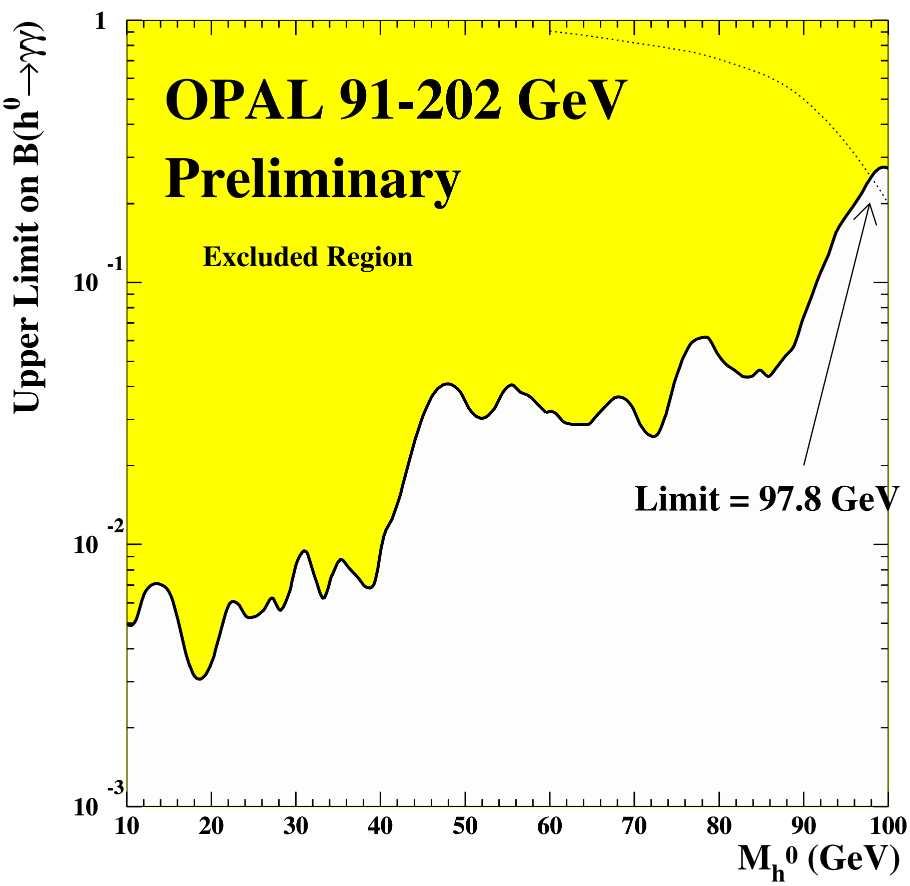
Channel	Data	MC bg.
$\mathrm{hZ} \rightarrow \gamma\gamma\mathrm{q\bar{q}}$	14	8.8 ± 0.7
$\mathrm{hZ} \rightarrow \gamma\gamma\nu\bar{\nu}$	3	6.2 ± 0.3
$\mathrm{hZ} \rightarrow \gamma\gamma\ell^+\ell^-$	5	7.5 ± 1.4

Efficiency from 27% to 67%



$h \to \gamma\gamma$ Results

OPAL preliminary upper limit on BR($h \to \gamma\gamma$) assuming SM cross section



Lower limits at 95% C.L for a fermiophobic Higgs boson:

ALEPH	DELPHI	L3	OPAL
96.0 GeV	96.0 GeV	94.8[1,2] GeV	97.8[1] GeV

1) Updated with 192 – 202 GeV data
2) Only searches in the $hZ \to \gamma\gamma q\bar{q}$ channel

Conclusions

- Higgs bosons from different models have been searched at LEP using all data collected
- No signal observed (yet)
- Exclusions at the level of expectations

Current preliminary 95% C.L. lower limits:

SM Higgs Boson	107.7 GeV
MSSM h	91.5 GeV
MSSM A	91.9 GeV
Charged Higgs	77.7 GeV
Invisible Higgs	100.3 GeV
Fermiophobic Higgs	97.8 GeV

LEP combined limits are expected to be higher

- Waiting for our last chance this year

Marco Pieri
INFN Firenze