# LEP Higgs Working Group Status Report

Higgs Searches up to $\sqrt{s} = 196$ GeV

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**Sept. 7, 1999**
LEPC meeting

(For the LEP Higgs Working Group)

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# History of the Group

Goal of the LEP Higgs Working Group:
to take advantage of the combined LEP luminosity to search for evidence of Higgs production with the greatest possible sensitivity.

With each new energy,
the group has expanded its horizons:

$\sqrt{s} \leq$ 172 GeV: Standard Model Higgs
$\sqrt{s} \leq$ 183 GeV: MSSM Benchmark Scans, Charged Higgs, HZZ Coupling
$\sqrt{s} \leq$ 189 GeV: Discovery Issues

The combined results of the group are summarized in:

CERN-EP/98-046
CERN-EP/99-060
Abstract 6-49, HEP-EPS'99, contributed paper

# Results for Tampere

The LEP Higgs working group has not (yet) seen evidence of Higgs production at LEP

Several 95% CL limits have been set using LEP data with $\sqrt{s} \leq 189$ GeV:

Standard Model Higgs:

$m_H > 95.2$ GeV/c$^2$

MSSM Neutral Higgs Benchmark Scans:

| No Mixing | Maximal Mixing |
|---|---|
| $m_h > 80.7$ GeV/c$^2$ | $m_h > 80.7$ GeV/c$^2$ |
| $m_A > 80.9$ GeV/c$^2$ | $m_A > 80.9$ GeV/c$^2$ |
| $\tan\beta$ excluded: | $\tan\beta$ excluded: |
| 0.6-2.6 | 0.9-1.6 |

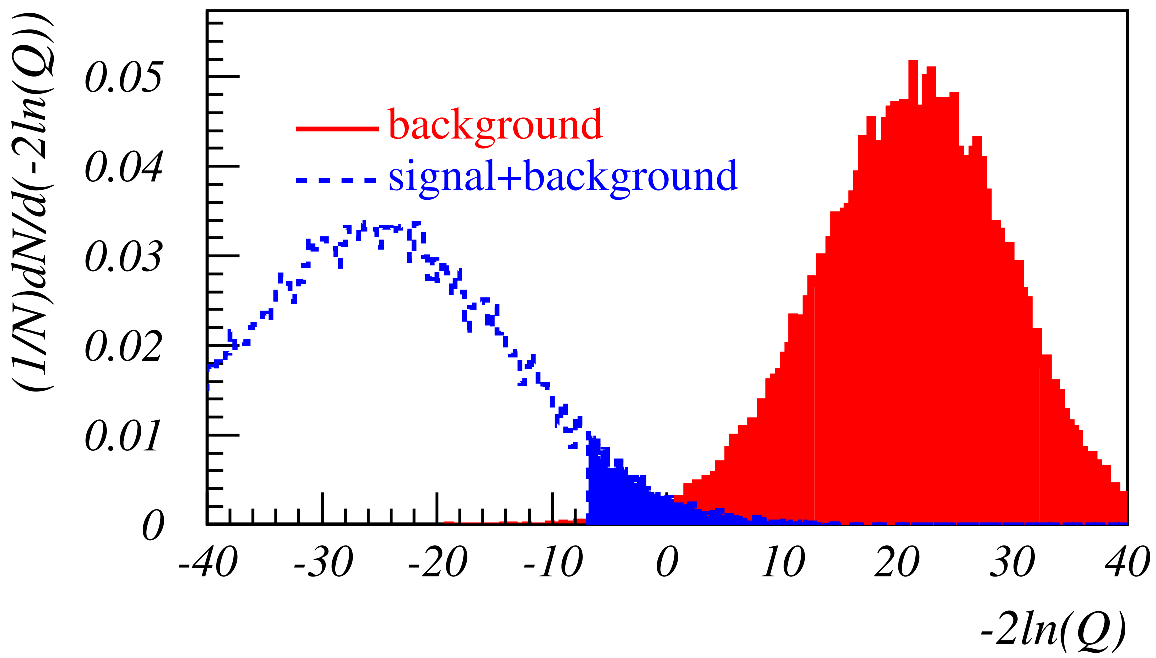
Charged Higgs:

$m_{H^\pm} > 77.3$ GeV/c$^2$

# Confidence Levels

The analysis of all data in the Higgs working group
(both limit setting and discovery)
is done with frequentist confidence level techniques.

A test-statistic $\epsilon$ is defined.




Given an observed value $\epsilon_{obs}$ of the test-statistic

The Confidence Level for the Hypothesis x is:

$$CL_x = \int_{\epsilon_{obs}}^{\infty} \rho_x(\epsilon)\, d\epsilon$$

# Limits

If there is no signal, $CL_{s+b}$ will be small.

Define a "signal confidence level"

$$\boxed{CL_s = \frac{CL_{s+b}}{CL_b}}$$

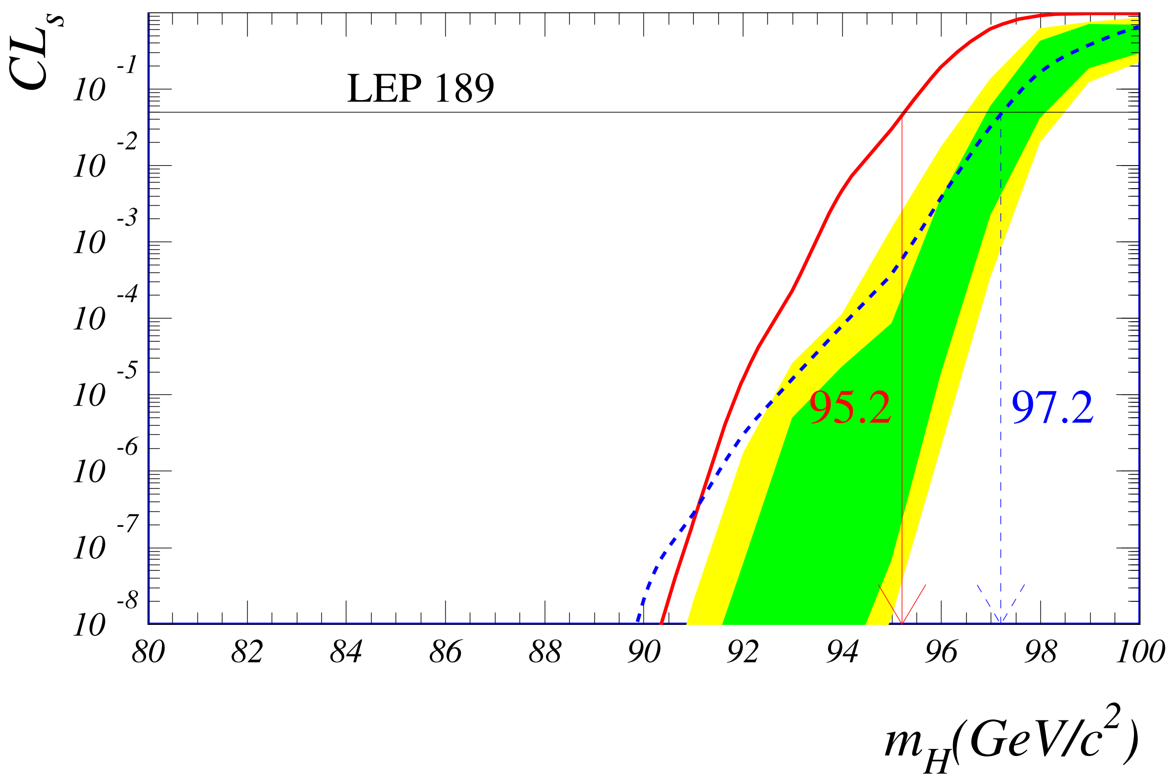
$CL_s \leq 0.05 \Rightarrow$ hypothesis is excluded at the 95% Confidence Level.

Several different test-statistics are used within LEP Higgs working group

Only points excluded by **all** test-statistics are considered excluded

# Limit Setting Example
# Standard Model Higgs

For $\sqrt{s} \leq 189$ GeV:




This plot shows:

Observed $CL_s$

Mean $CL_s$ for no signal hypothesis

Bands of probability around Median $CL_s$
for no signal hypothesis (68%, 90%)

# Discovery

If there is a signal, $1 - CL_b$ will be very small.

Significant discovery is equivalent to a
5 Standard Deviation fluctuation:

$$1 - CL_b \approx 10^{-7}$$

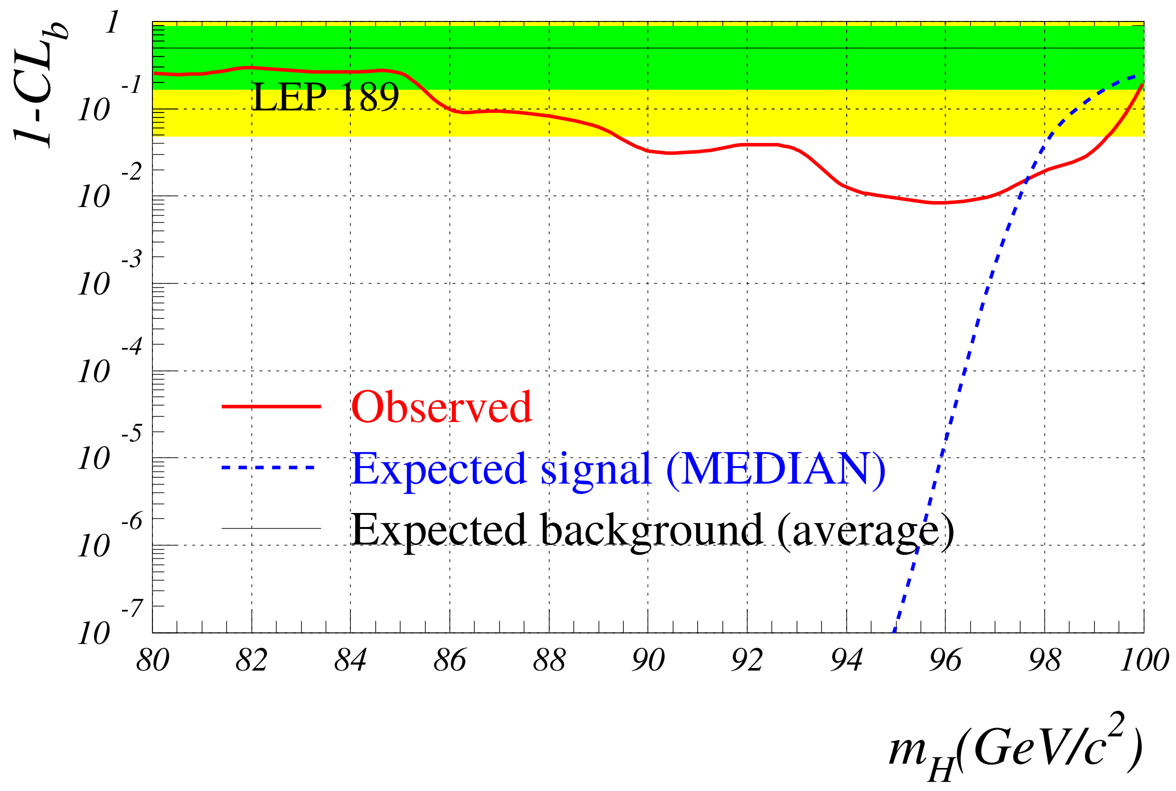
Note:
Probability of observing $1 - CL_b^{MAX} = 0.01$
larger than 1%.

With resolution of $\approx 3$ GeV/c$^2$
in a 15 GeV/c$^2$ window

Probability $\approx 5$ times larger
than $1 - CL_b^{MAX}$

# Discovery Plot Example
# Standard Model Higgs

$\sqrt{s} \leq$189 GeV data,




Most significant point at 96 GeV$/c^2$

$$1 - CL_b^{MAX} \approx 10^{-2}$$

Probability of observing this $1 - CL_b^{MAX} \approx 5\%$

This is far from $10^{-7}$ required for discovery

# Rapidity test

In 2000, we must be able to observe
new physics quickly.

How quickly can we perform a combination?

Starting August 16 (3 weeks ago):

The Working group began a ‘Rapidity Test’

Goal: combine $\sqrt{s} = 192 - 196$ GeV data
with previously published results (Tampere)

Combine All analyses in three weeks:

Standard Model Higgs
MSSM Neutral Higgs
Charged Higgs

# Data Exchanged for Rapidity Test

## Standard Model Higgs combination:

| $\sqrt{s}$ (GeV) | Luminosity (pb$^{-1}$) |
|---|---|
| 189 | 683 |
| 192 | 112 |
| 196 | 265 |

## MSSM Neutral Higgs combination:

| $\sqrt{s}$ (GeV) | Luminosity (pb$^{-1}$) |
|---|---|
| 189 | 683 |
| 192 | 84 |
| 196 | 185 |

## Charged Higgs combination:

| $\sqrt{s}$ (GeV) | Luminosity (pb$^{-1}$) |
|---|---|
| 189 | 690 |
| 192 | 55 |
| 196 | 132 |

# Combination Procedure

For each search channel, experiments provide:

Efficiencies, resolutions, background levels,
and candidates in a common format

Inputs are checked by independent teams,
using different test-statistics.

Combined Results are produced.

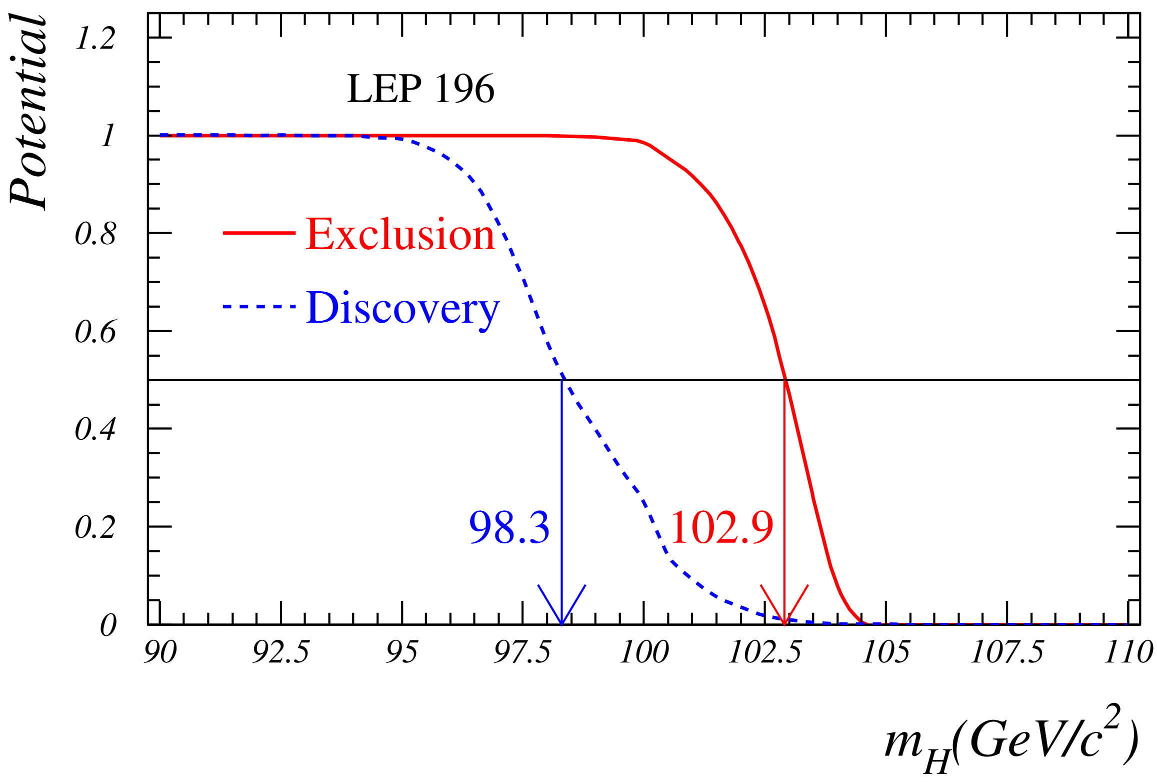
Results from independent teams are very similar
(within $\approx$ 200 MeV for SM Higgs, for example)
as expected from differences in only
test-statistics and systematic error handling

The verification stage was successful,
but took 2 of 3 available weeks.

This will be faster in the future

# Standard Model Higgs Search Sensitivity

In Standard Model search, Higgs mass is scanned

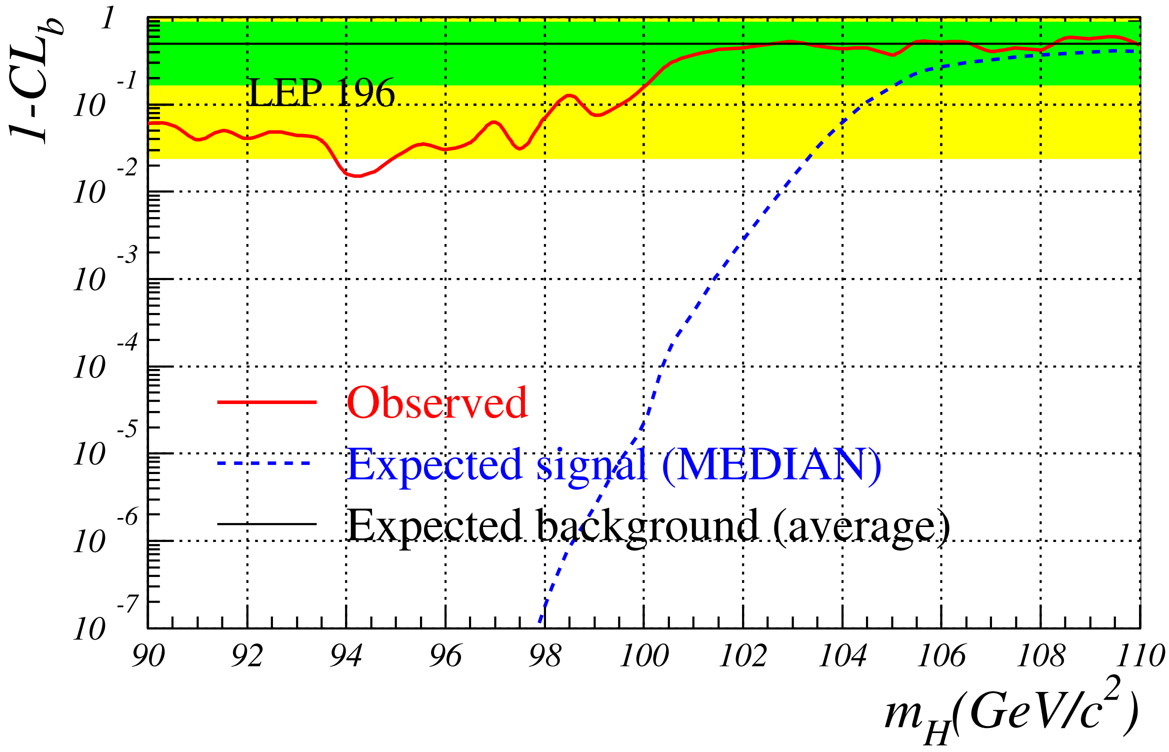



If there is no signal, Higgs masses below 102.9 GeV/$c^2$ will be **excluded** (at 95%) on average.

If there is a signal, Higgs masses below 98.3 GeV/$c^2$ will be **discovered** (at $5\sigma$) on average.

# Discovery Confidence Levels

To determine if there is a discovery, examine $1 - CL_b$ curve:



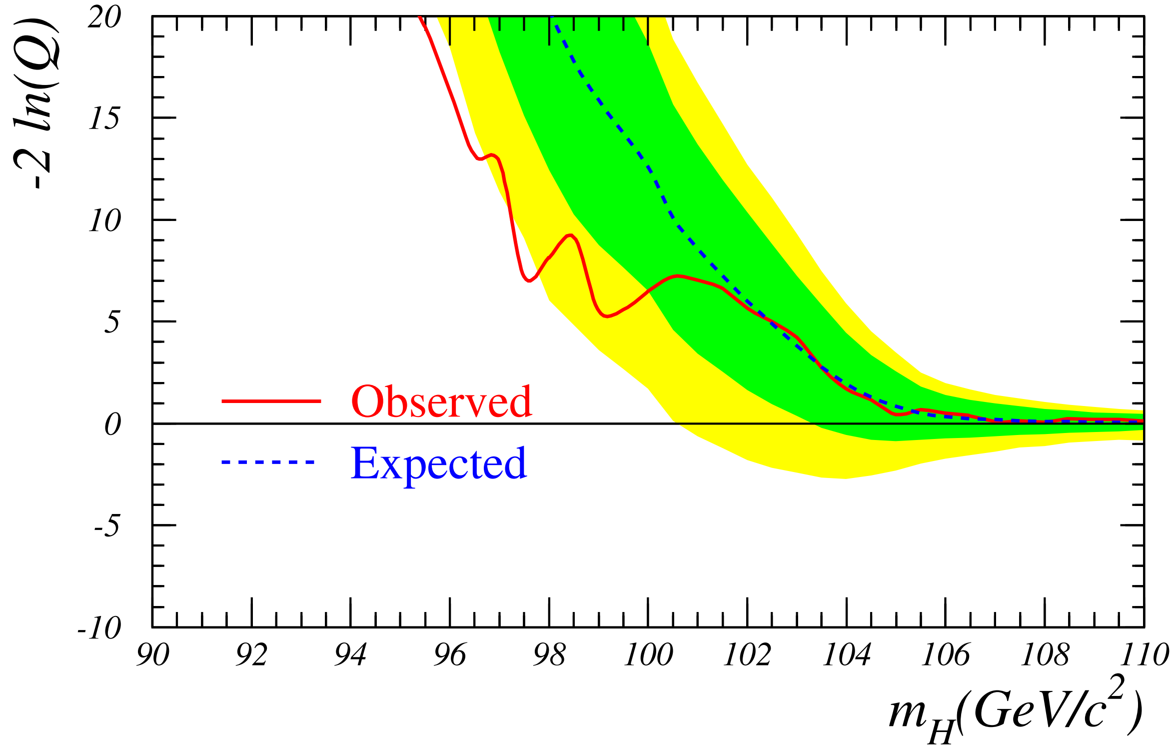

A discovery should have $1 - CL_b \approx 10^{-7}$.

There is no evidence of a signal in this data set.

# Likelihood Ratio

Look at the test-statistic values:

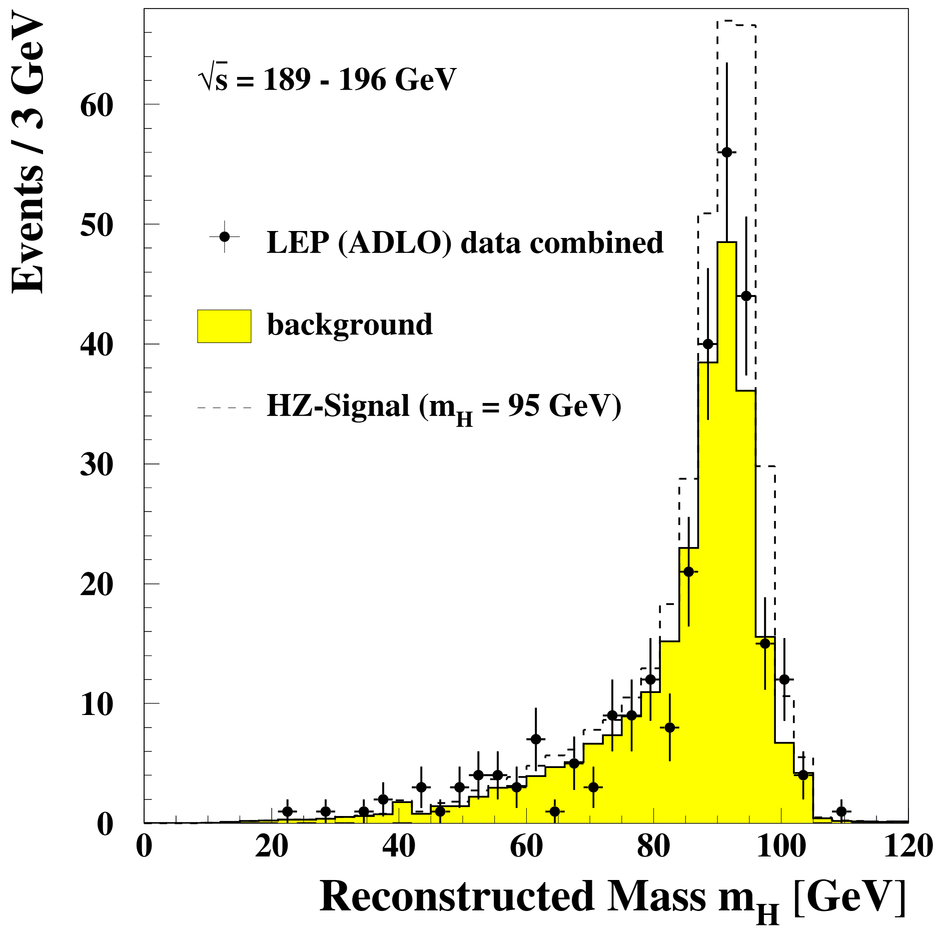
Compare observed curve with background
($\pm$ 1,2 Standard Deviation bands)




Observed Curve is consistent with
background hypothesis

This curve can be incorporated into Electroweak fits.

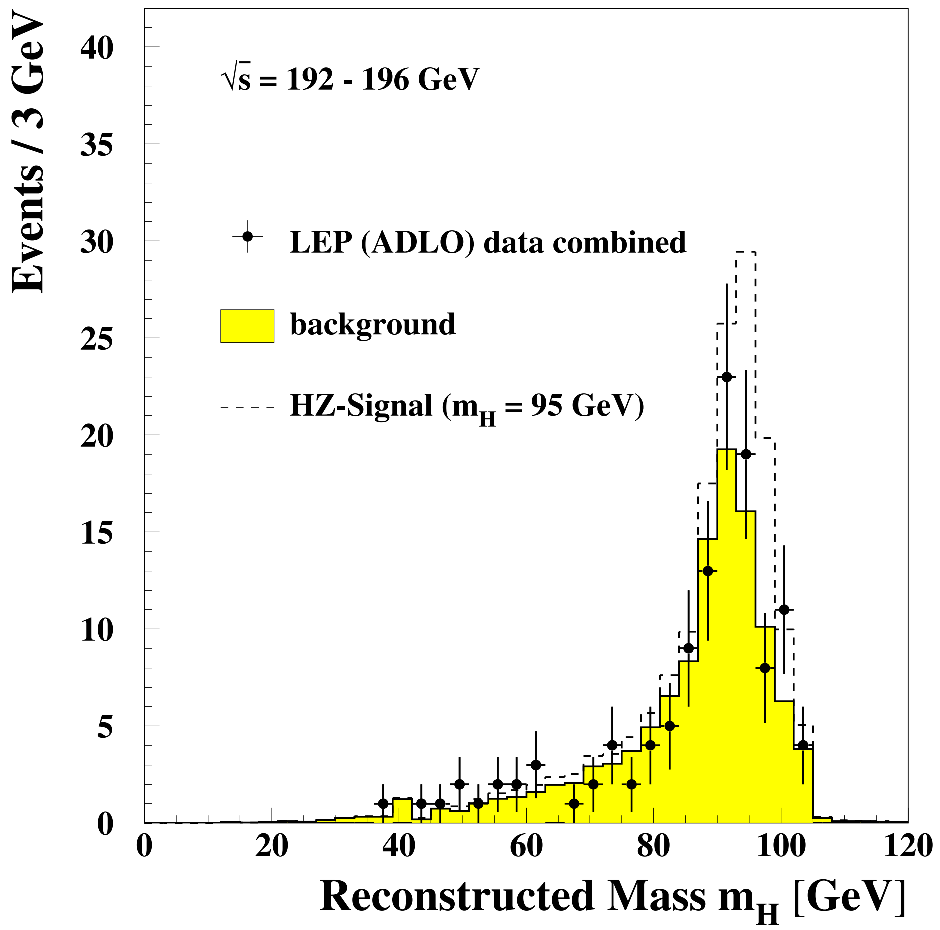
# Standard Model Higgs Mass Distribution




Expected Events(background): 253.6
Expected Events(95 GeV signal): 101.8
Observed Events: 270

Note: Mass distribution for illustration purposes only.
Confidence Levels use much more information.

# Standard Model Higgs Mass Distribution




Expected Events(background): 113.8

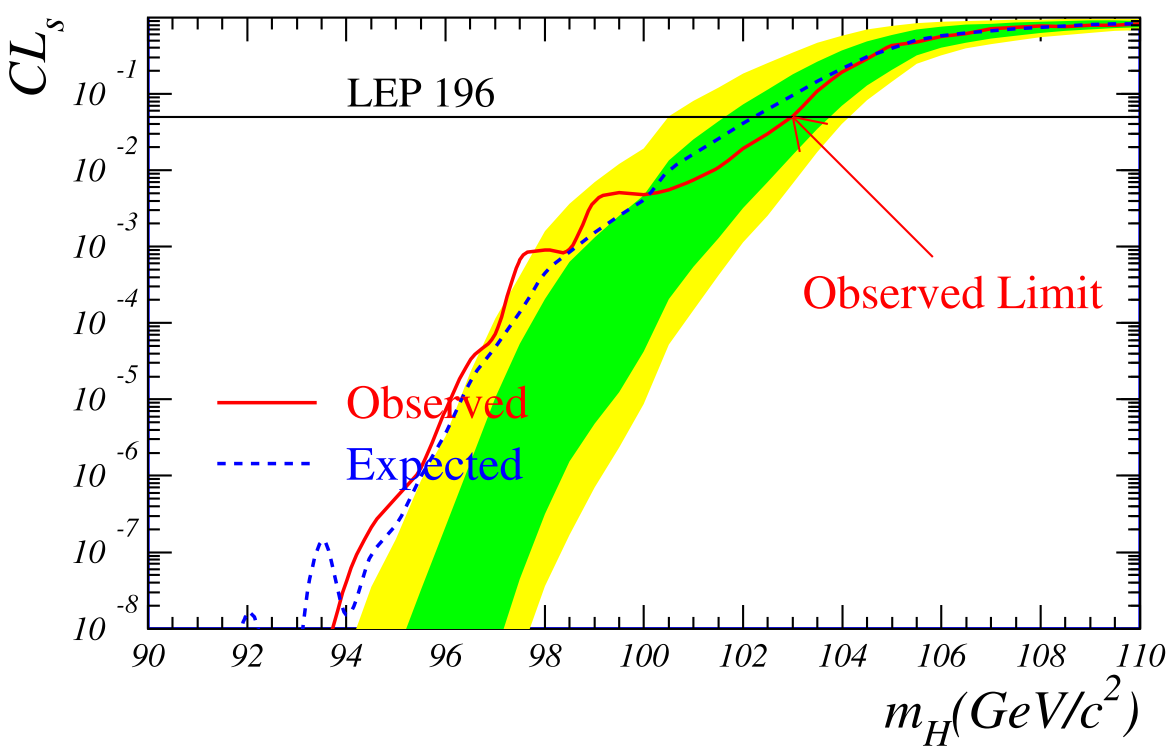
Expected Events(95 GeV signal): 45.3

Observed Events: 118

Note: Mass distribution for illustration purposes only.
Confidence Levels use much more information.

# Standard Model Higgs Limit

To set limits on Higgs mass hypothesis, look at $CL_s$:




For all combination methods,
all $m_H \leq 102.6$ GeV/c$^2$, $CL_s \leq 0.05$.

Therefore, a limit on the Higgs mass is set:

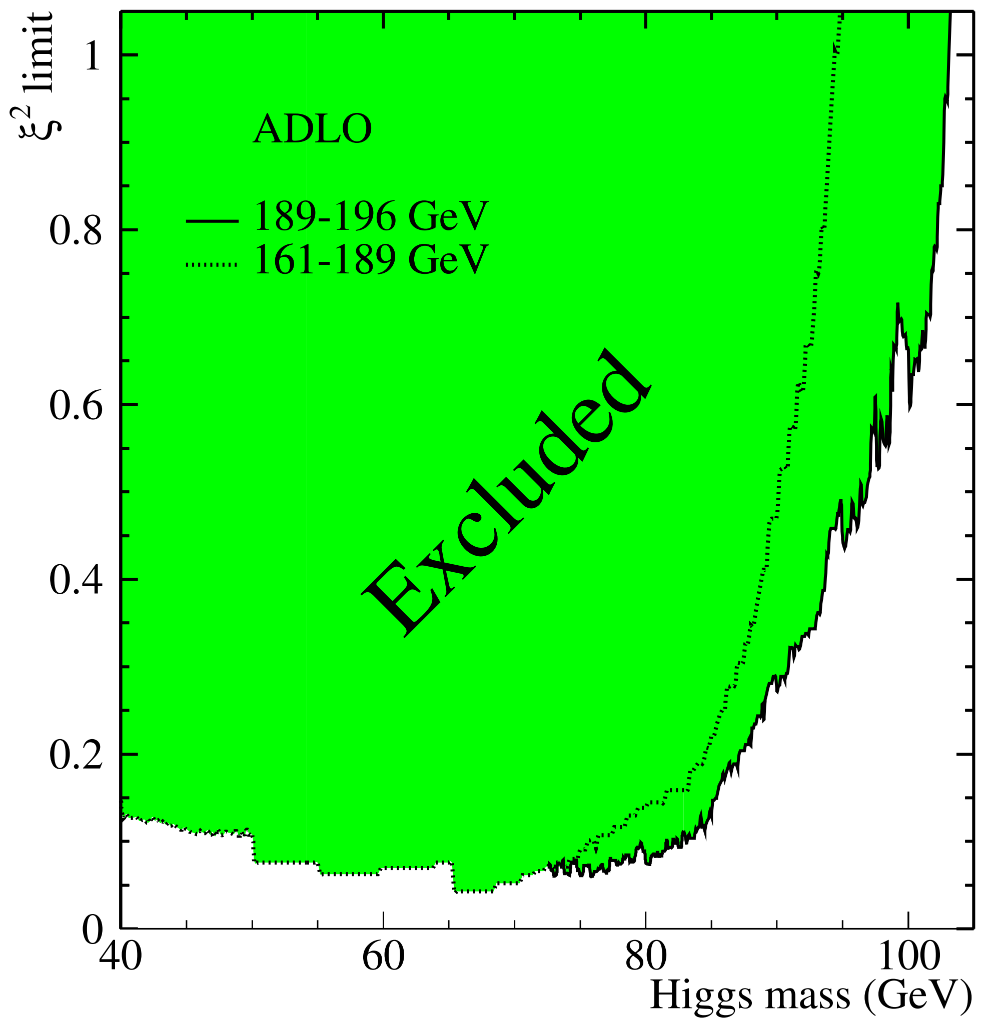
$\boxed{m_H > 102.6 \text{ GeV/c}^2 \text{ @ 95\% C.L.}}$

(with 102.3 GeV/c$^2$ expected)

# Limits on HZZ Coupling

Many models predict a reduced Higgs production rate.

$$\boxed{\sigma(HZ) = \sigma(HZ)_{\mathrm{SM}} \cdot \xi^2}$$




For the Higgs boson decay, the SM branching fractions are assumed.

# MSSM Higgs Combined Result

In MSSM there are several free parameters:

Most parameters are fixed to obtain two benchmark scenarios

| *No Mixing* | *Maximal Mixing* |
|---|---|
| $A_t = 0$ | $A_t = \sqrt{6}$ TeV |
| $m_2 = 1.63$ TeV | $m_2 = 1.63$ TeV |
| $\mu =$ -100 GeV | $\mu =$ -100 GeV |
| $m_{SUSY} = 1$ TeV | $m_{SUSY} = 1$ TeV |
| $m_t = 175$ GeV | $m_t = 175$ GeV |

$\boxed{\text{Scan over } \tan\beta \text{ and } m_A}$

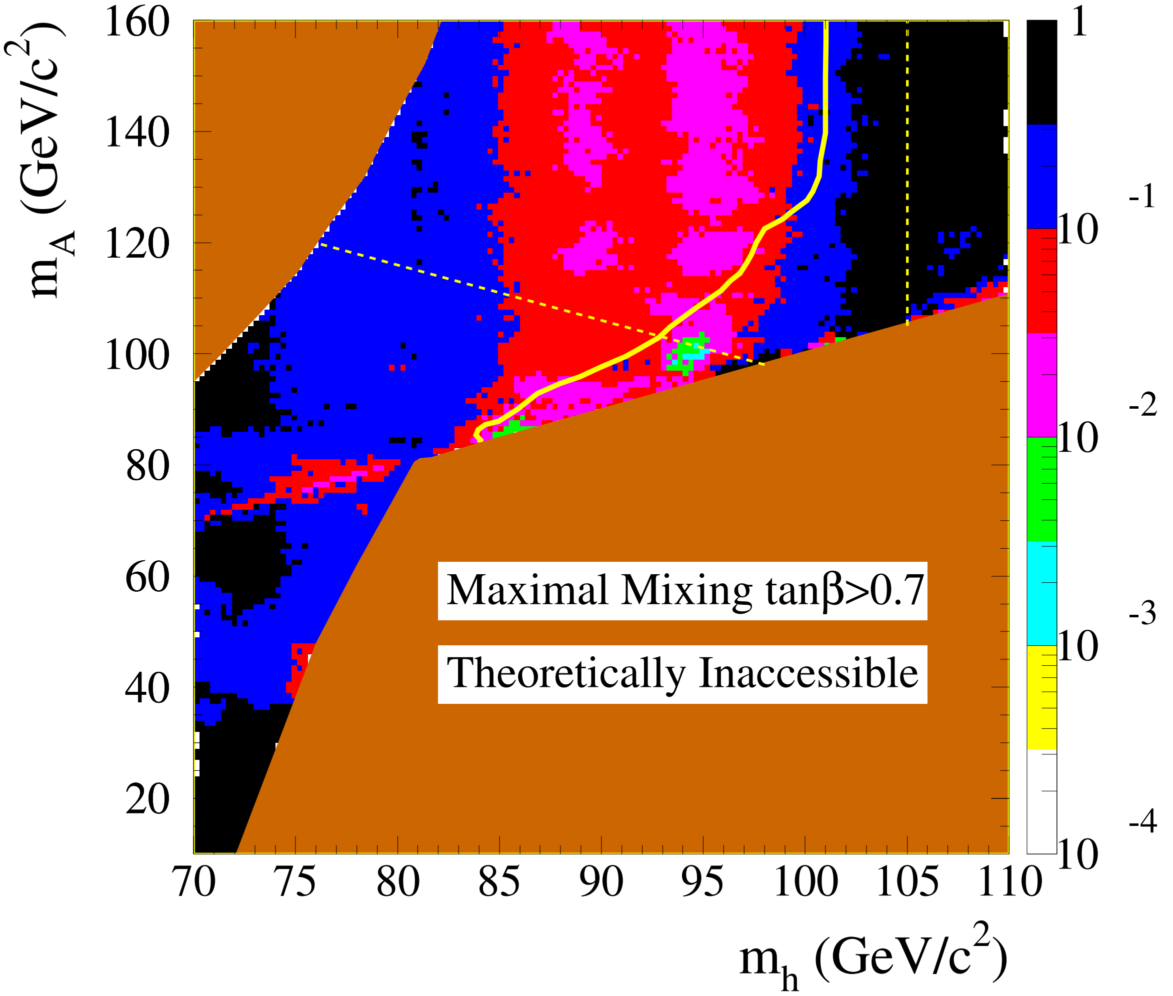
$CL_s$ and $CL_b$ framework used to determine if scan points are discovered or excluded

Two Higgs production mechanisms are considered:

$e^+e^- \rightarrow hA$ and $e^+e^- \rightarrow hZ$

# MSSM Discovery Confidence Levels

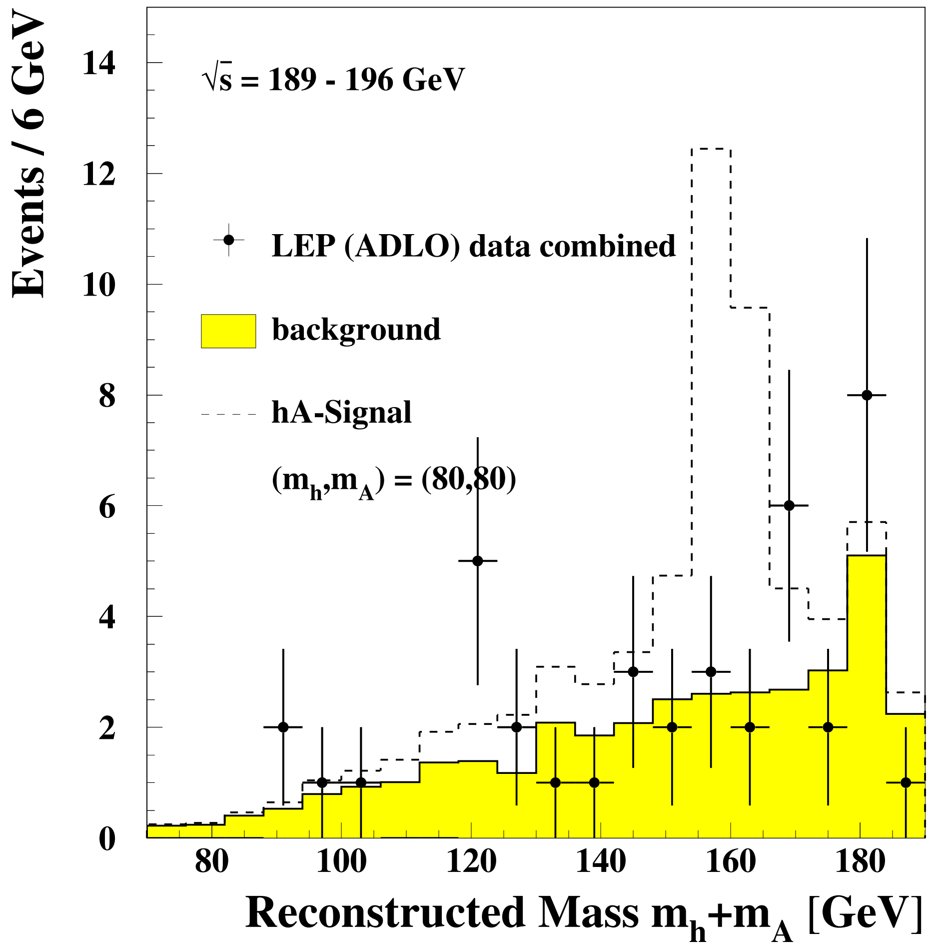
To determine if there is a discovery, examine $1 - CL_b$.




$1 - CL_b \approx 10^{-3}$ in some regions

It is never close to $10^{-7}$
so there is no evidence of a discovery.

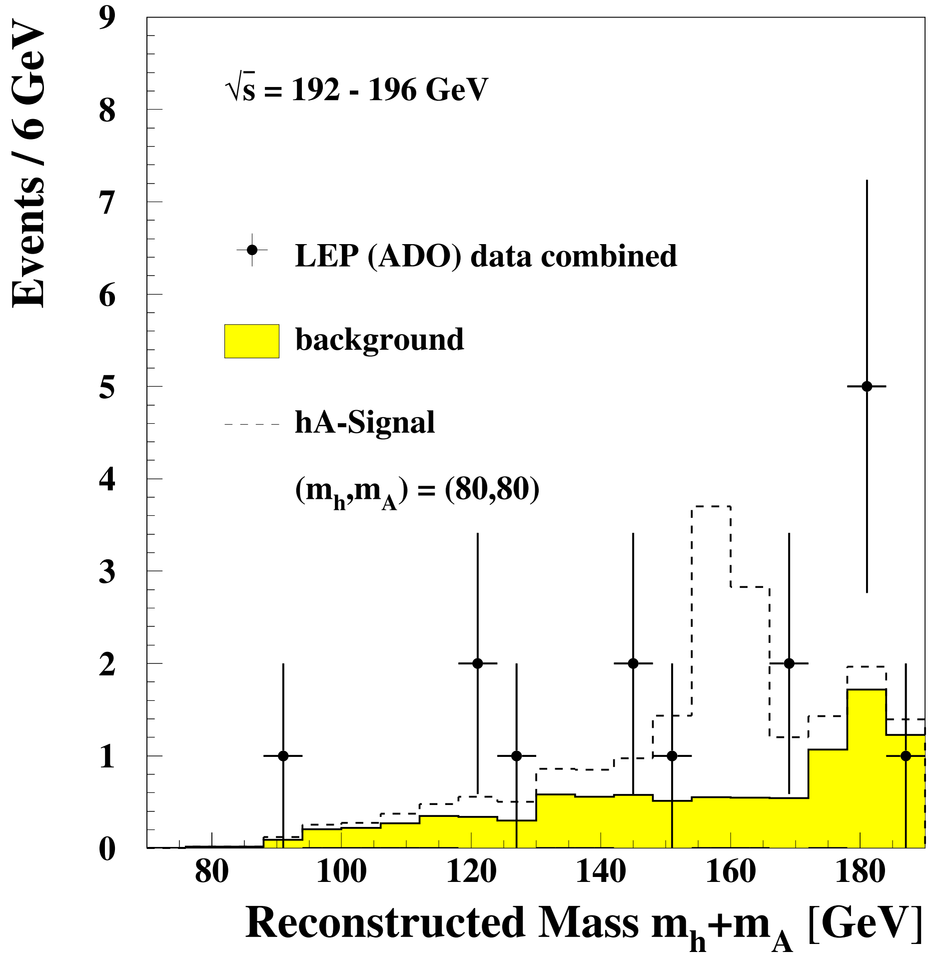
# MSSM Higgs Mass Distribution




Expected Events(background): 34.9
Expected Events((80,80) GeV signal): 29.4
Observed Events: 40

Note: Mass distribution for illustration purposes only.
Confidence Levels use much more information.

# MSSM Higgs Mass Distribution




Expected Events(background): 9.7

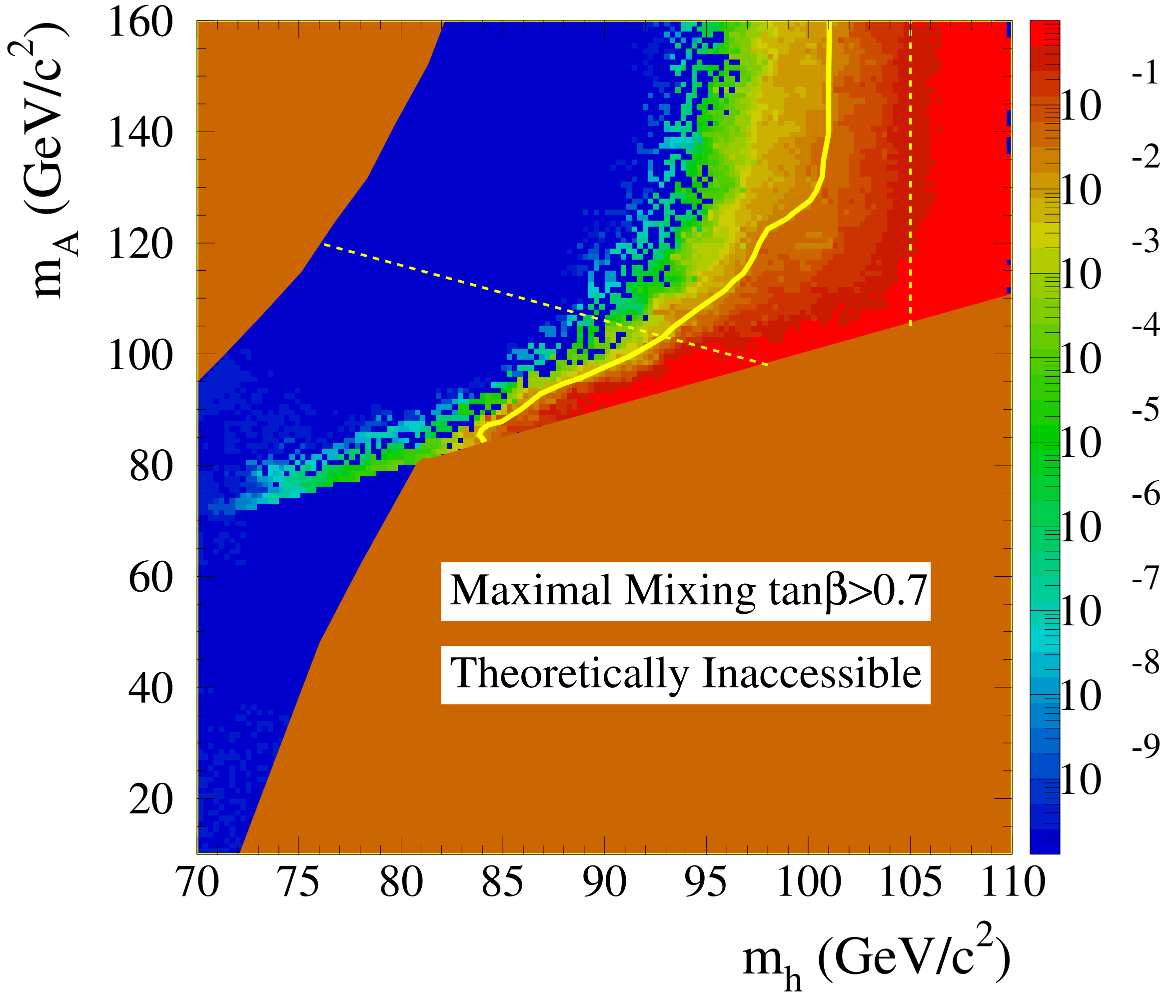
Expected Events((80,80) GeV signal): 9.6

Observed Events: 15

Note: Mass distribution for illustration purposes only. Confidence Levels use much more information.

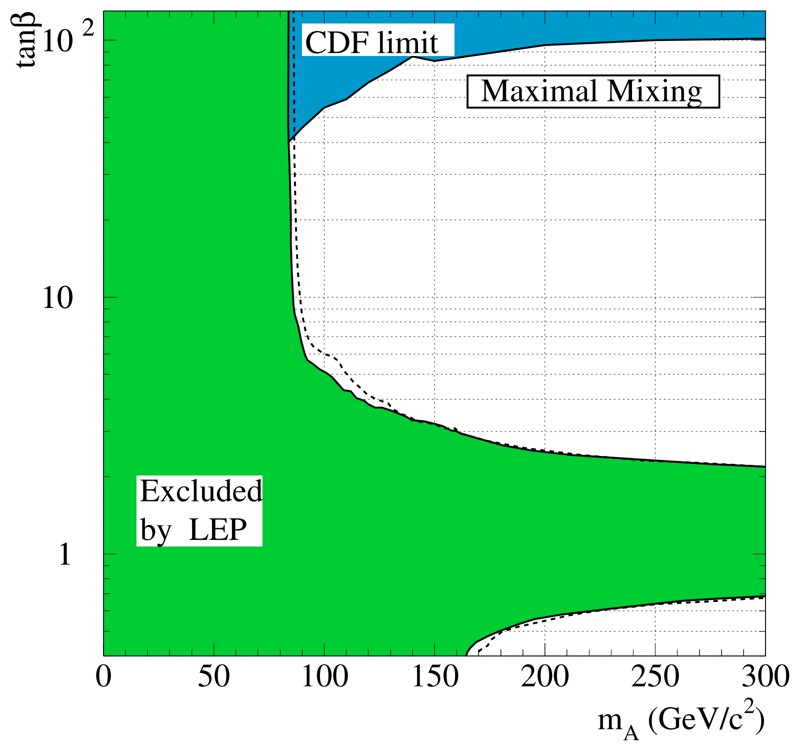
# MSSM Limits - m$_h$ vs m$_A$

To set limits in the MSSM, look at $CL_s$



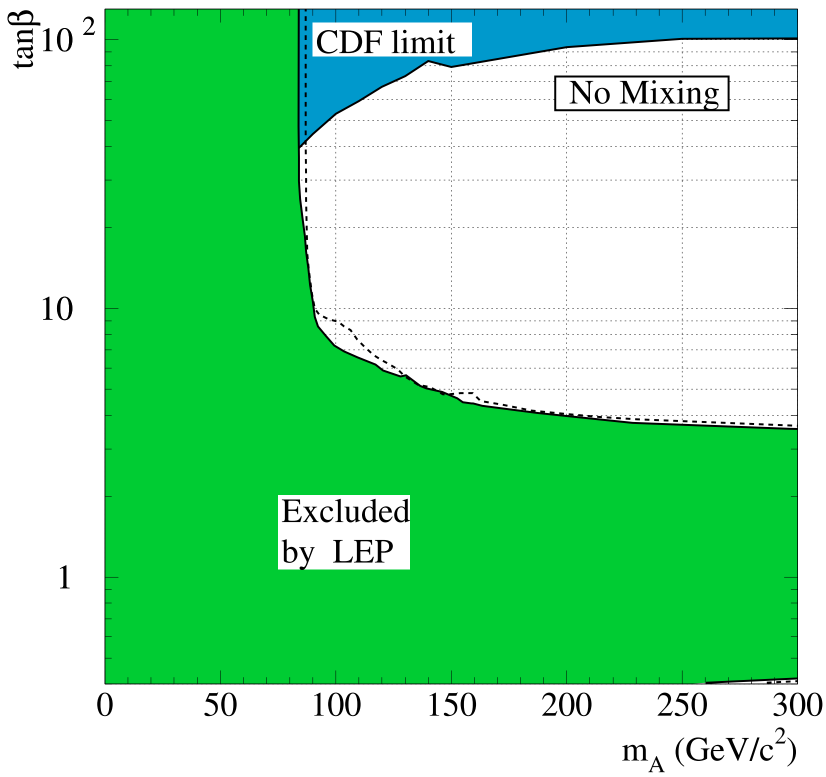

All hypotheses to left of yellow line are excluded at 95% Confidence Level

# MSSM Limits - $m_A$ vs $\tan\beta$




Maximal mixing:

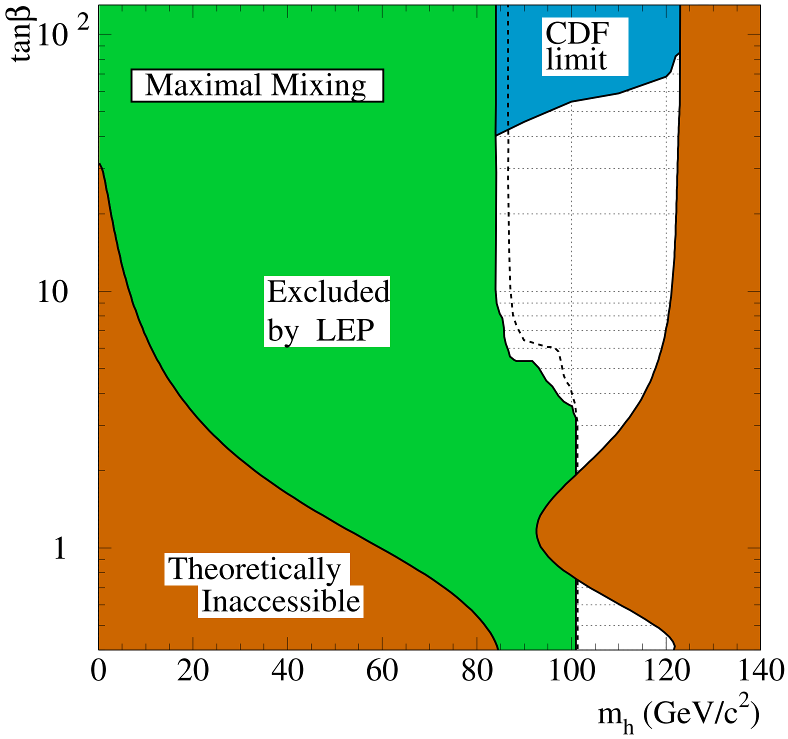
95% CL Limit on $m_A$: 84.5 $GeV/c^2$




No mixing:

95% CL Limit on $m_A$: 84.7 $GeV/c^2$

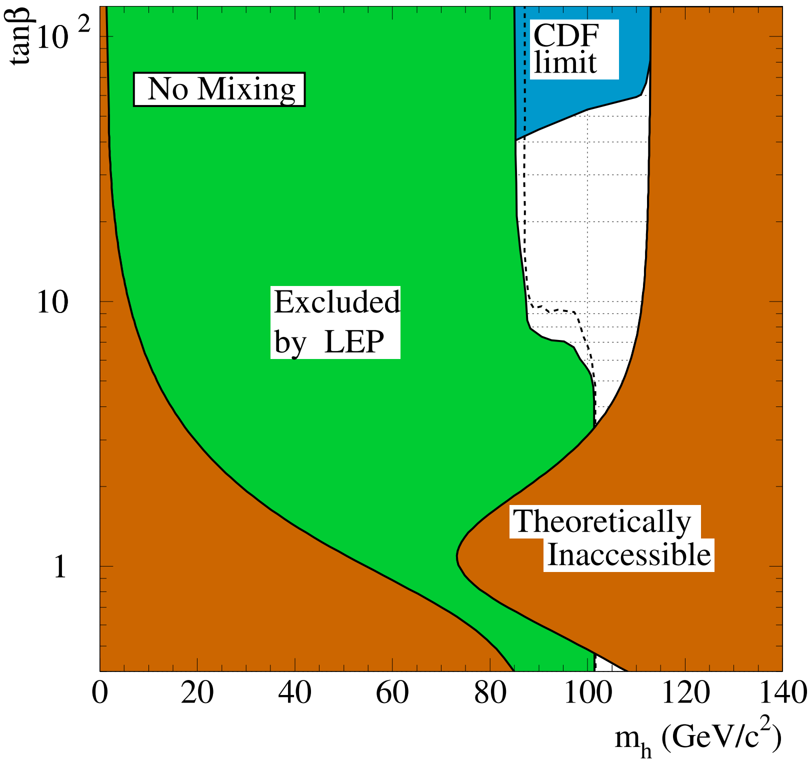
# MSSM Limits - m$_h$ vs $\tan\beta$




Maximal mixing:

95% CL Limit on m$_h$: 84.3 GeV/c$^2$

Exclude $\tan\beta$: $0.8 - 1.9$




No mixing:

95% CL Limit on m$_h$: 84.5 GeV/c$^2$

Exclude $\tan\beta$: $0.5 - 3.2$

# Charged Higgs Combined Result

Charged Higgs bosons are predicted in 2 Higgs doublet models.

Assuming two decays

$H^+ \longrightarrow c\bar{s}$ and $H^+ \longrightarrow \tau^+\nu$

exhaust available width

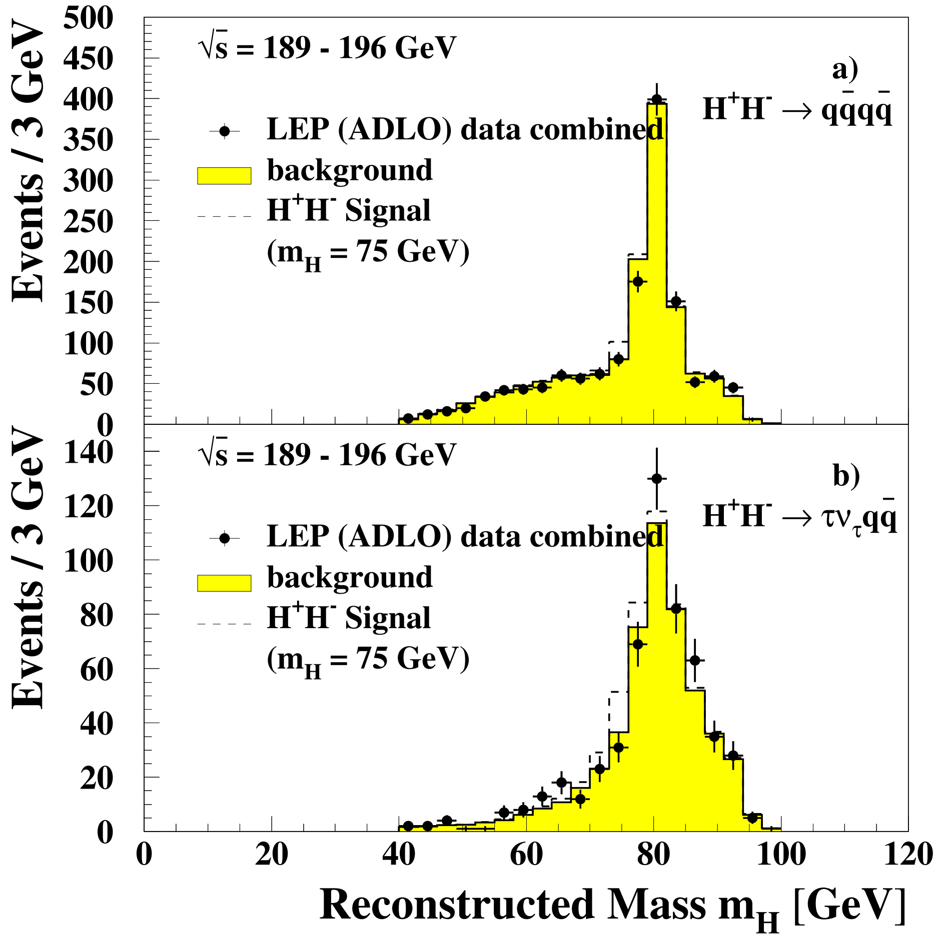
but Branching ratios are not constrained

**Scan in $m_{H^\pm}$ and $BR(H^\pm \longrightarrow \tau\nu)$**

$CL_s$ and $CL_b$ framework used to determine if scan points are discovered or excluded

Sensitivity of $cscs$ and $cs\tau\nu$ searches is below $m_W$ because of large $W^+W^-$ background.

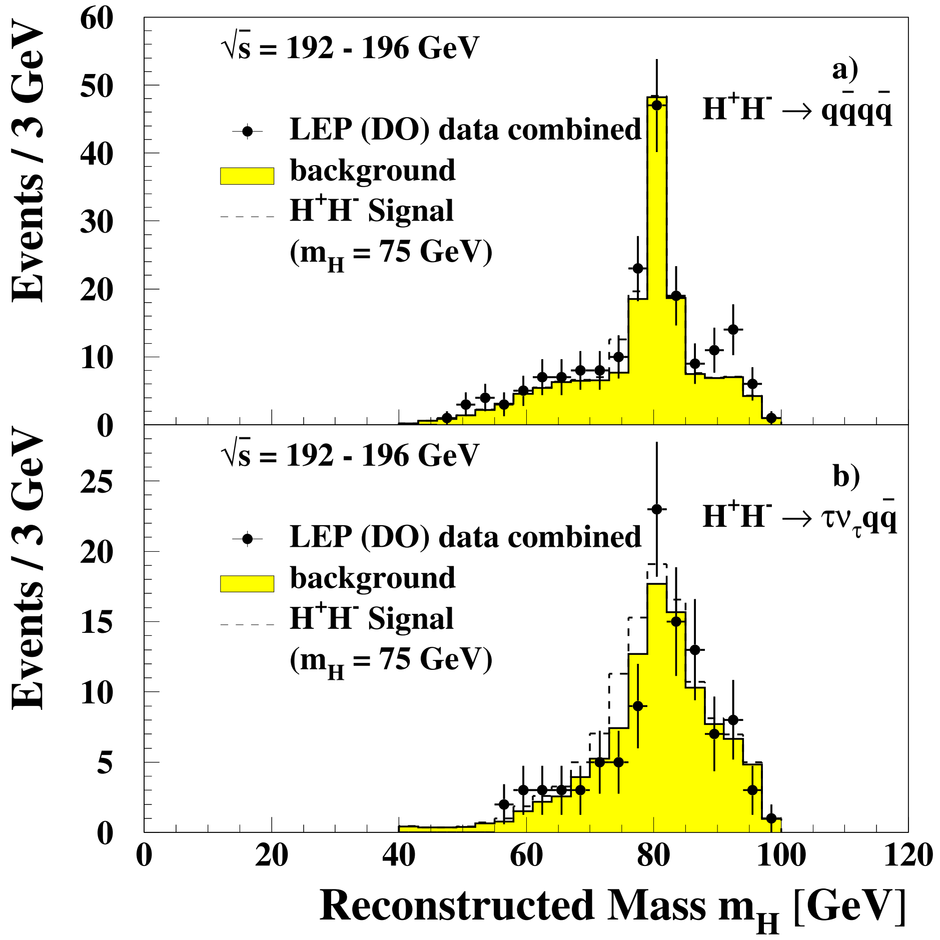
# Charged Higgs Mass Distribution




| | *cscs* | *cstν* |
|---|---|---|
| Expected (background): | 1393.6 | 510.1 |
| Expected (75 GeV signal): | 44.6 | 44.1 |
| Observed: | 1365 | 535 |

Note: Mass distribution for illustration purposes only.
Confidence Levels use much more information.

# Charged Higgs Mass Distribution

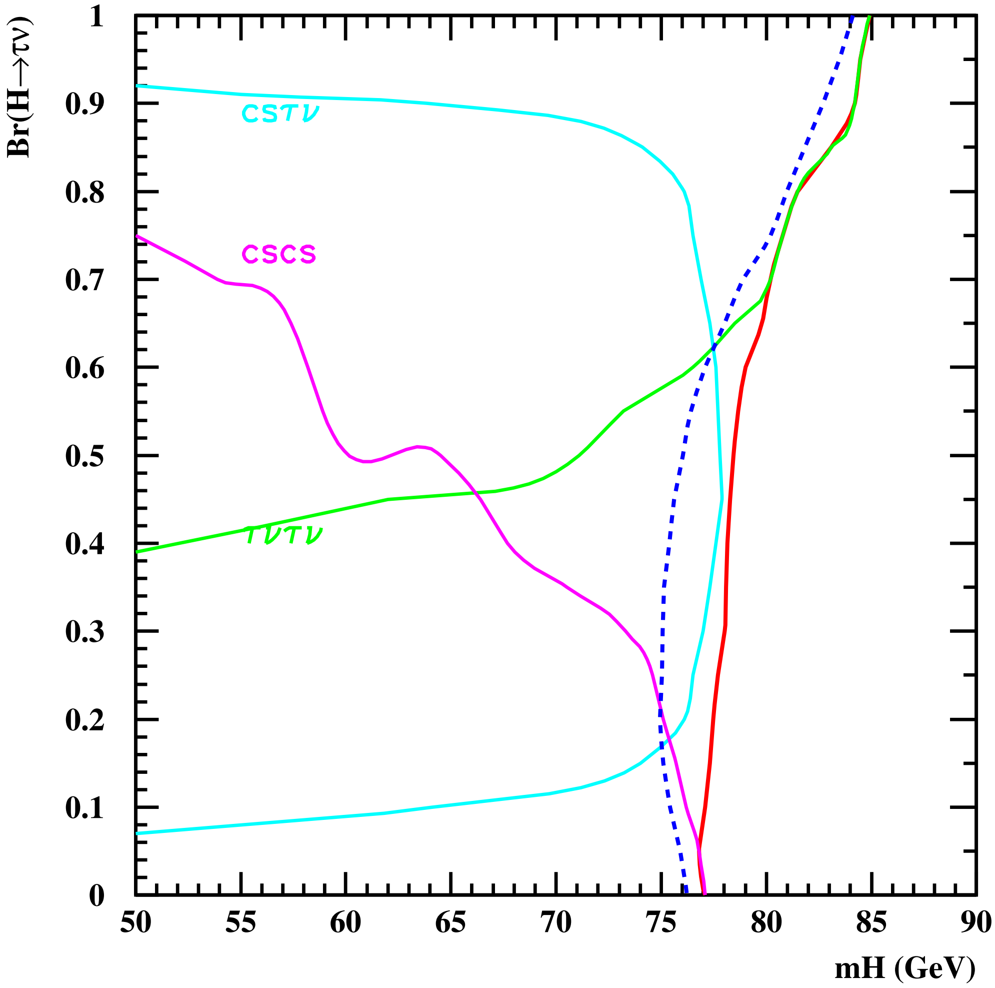



| | *CSCS* | *CSTV* |
|---|---|---|
| Expected (background): | 157.3 | 102.3 |
| Expected (75 GeV signal): | 7.8 | 14.8 |
| Observed: | 186 | 103 |

Note: Mass distribution for illustration purposes only.
Confidence Levels use much more information.

# Charged Higgs Limits

To set limits on $m_{H^\pm}$, look at $CL_s$:




At 95% Confidence Level:

BR($\tau\nu$=1.0): $m_{H^\pm} > 84.9$ GeV/c$^2$
BR($\tau\nu$=0.5): $m_{H^\pm} > 78.4$ GeV/c$^2$
BR($\tau\nu$=0.0): $m_{H^\pm} > 77.1$ GeV/c$^2$

**Any BR($\tau\nu$): $m_{H^\pm} > 77.0$ GeV/c$^2$**

# Assessment of Exercise

This rapidity test was quite successful.
Complete sets of results (with confirmations) were produced in less than 3 weeks.

*Places to improve:*

Preparation of efficiencies, resolutions, background rates, data by experiments

Less that 100% of luminosity was combined for some searches

Verification of inputs

This consumed $\approx$ 2 weeks

CPU intensive parts of procedure

Some scans now take several days

# Plans for next year

Much of the slow portion of this work could be done well in advance of any deadlines.

After this groundwork is done final data can be combined in $\approx$ 1 week

Disclaimer: Though we LOVE new energies we may need a bit more than 1 week to get "warmed up" for a new energy

# Additional Physics Goals

The group intends to continue to set ambitious goals

## Systematic Error handling

Systematic errors have a small effect on limits
($\approx$ 200 MeV)
but are treated differently by different experiments
making combined treatment difficult

## MSSM scan - testing $\tan\beta$ in a less model-dependent way.

By extending the scan in MSSM parameter space,
the significance of these results will be enhanced

# Summary of Results

The LEP Higgs working group has (still) not seen significant evidence of Higgs production at LEP

Several 95% CL limits have been set using LEP data with $\sqrt{s} \leq 196$ GeV:

## Standard Model Higgs:

$\mathrm{m}_H > 102.6\ \mathrm{GeV/c^2}$

## MSSM Neutral Higgs:

| No Mixing | Maximal Mixing |
| --- | --- |
| $\mathrm{m}_h > 84.5\ \mathrm{GeV/c^2}$ | $\mathrm{m}_h > 84.3\ \mathrm{GeV/c^2}$ |
| $\mathrm{m}_A > 84.7\ \mathrm{GeV/c^2}$ | $\mathrm{m}_A > 84.5\ \mathrm{GeV/c^2}$ |
| $\tan\beta$ excluded: 0.5-3.2 | $\tan\beta$ excluded: 0.8-1.9 |

## Charged Higgs:

$\mathrm{m}_{H^\pm} > 77.0\ \mathrm{GeV/c^2}$