

# 12 Years of Higgs Hunt at LEP or...

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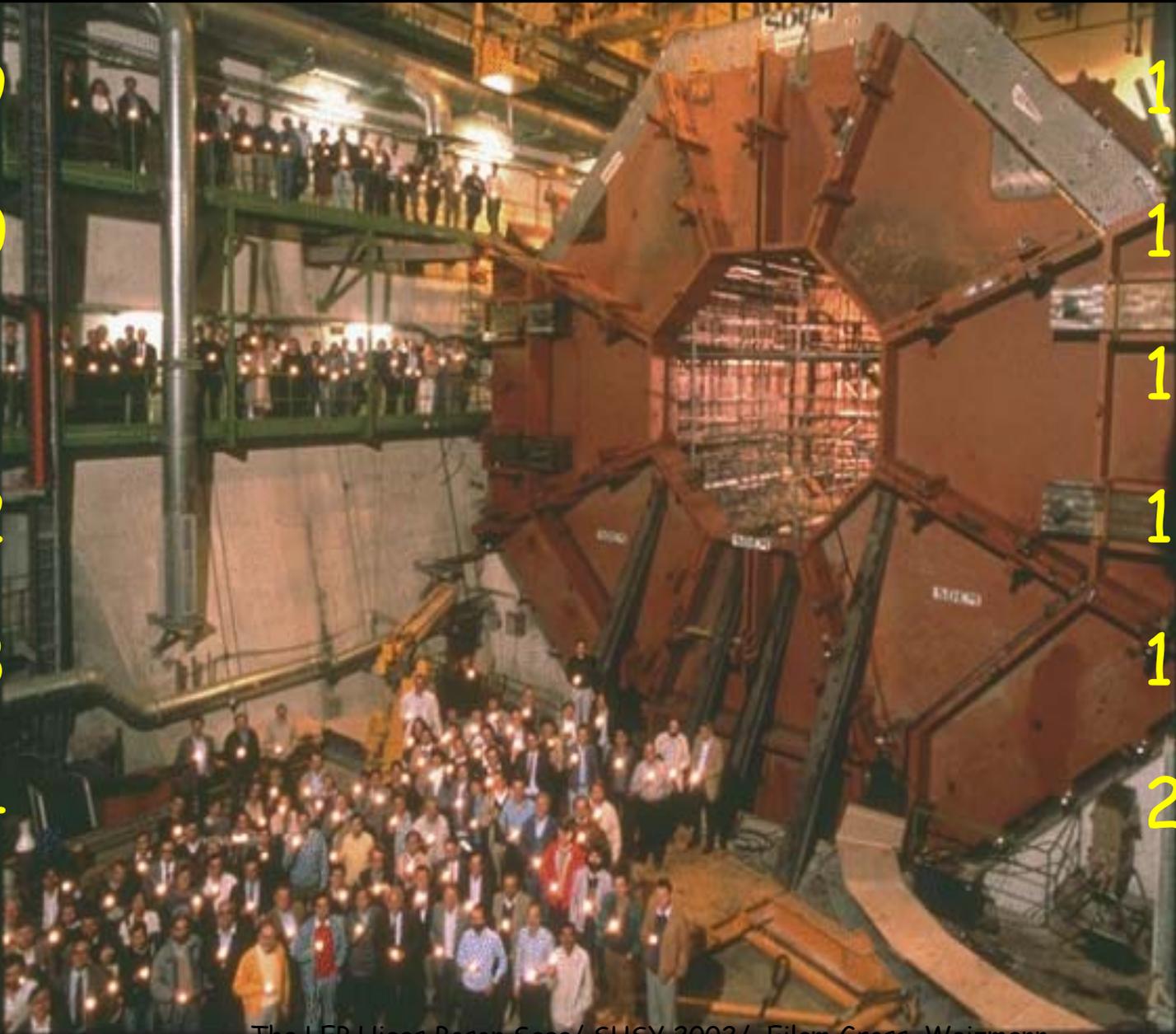
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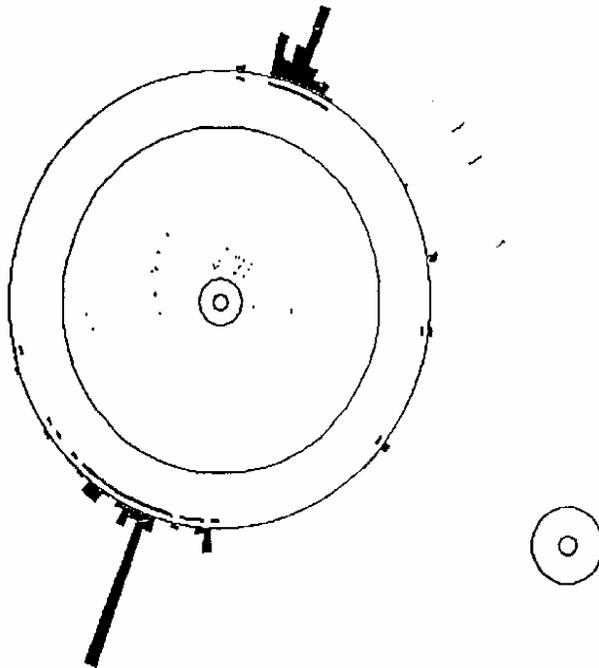


# The LEP Higgs Boson Saga

- August 1989 - Nov 2000
- 12 Years of Higgs Hunt

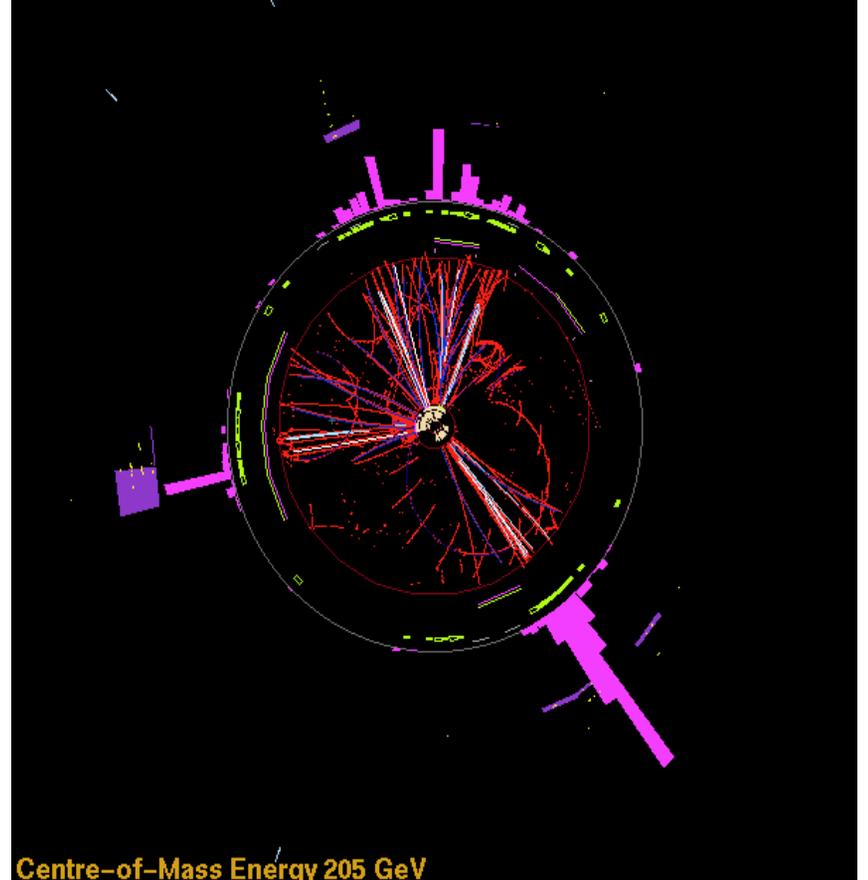
Eilam Gross, Weizmann  
Institute of Science

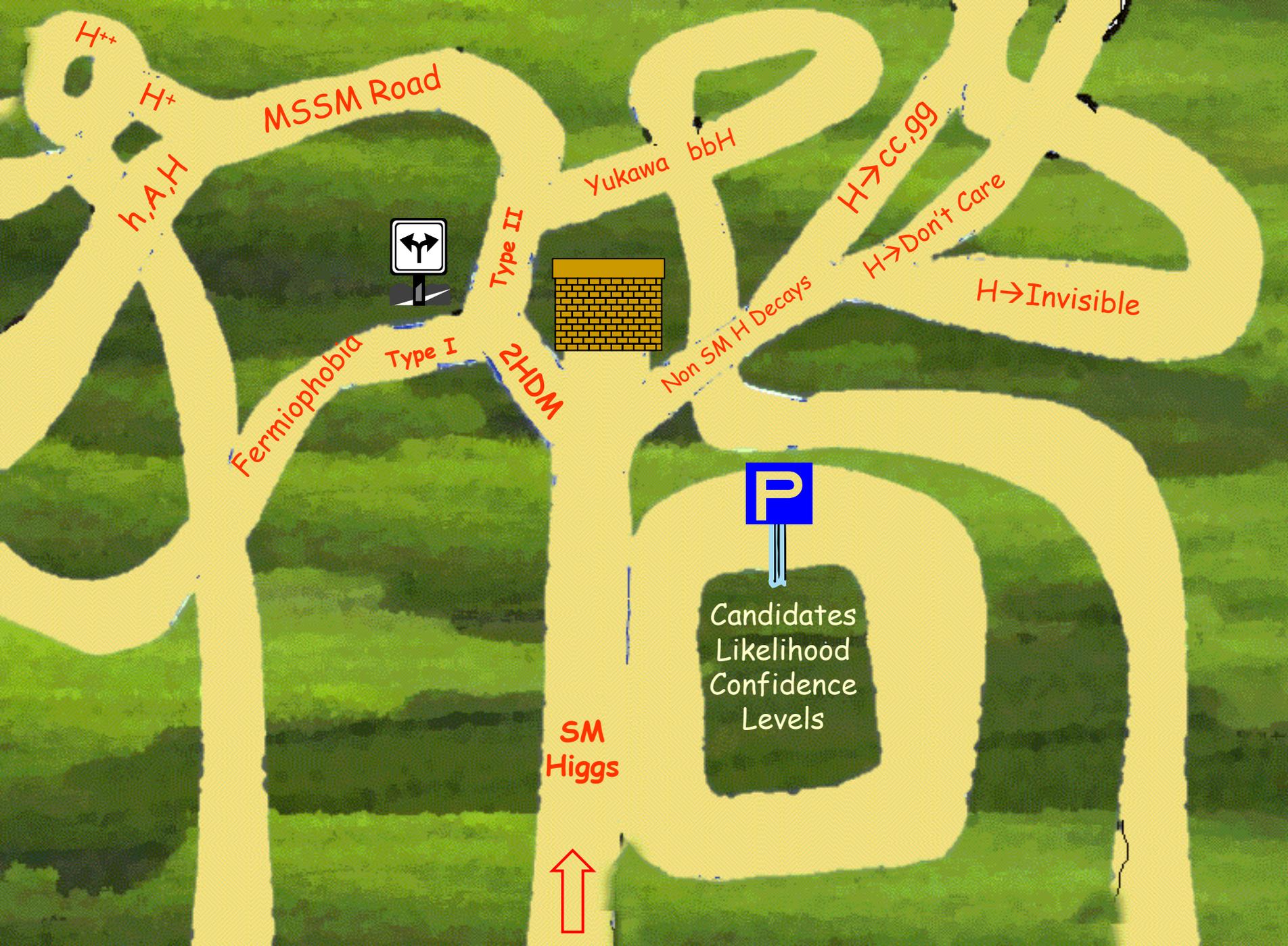
Run 443 EDT 22734 Total E(EB): 34.0 GeV, in cl: 31.8 GeV Clusters(EB): 1314000 Trkr: 0 Filter: 1 Trigger Bits  
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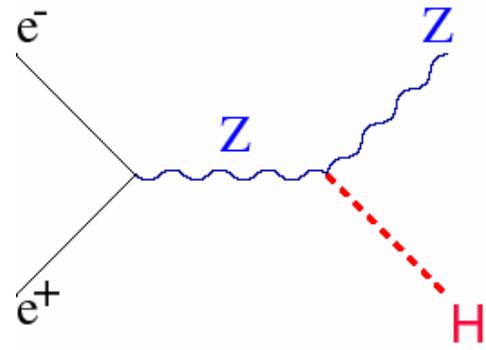
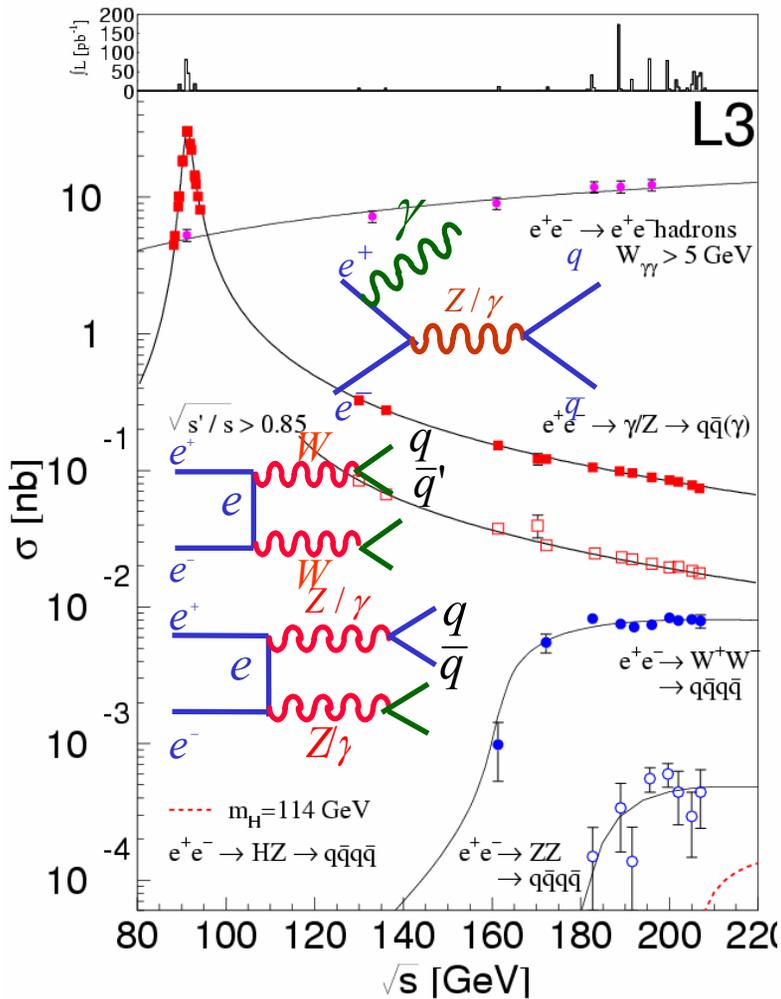
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Run 16249 Event 18898 2 Nov 2000 07:59:18

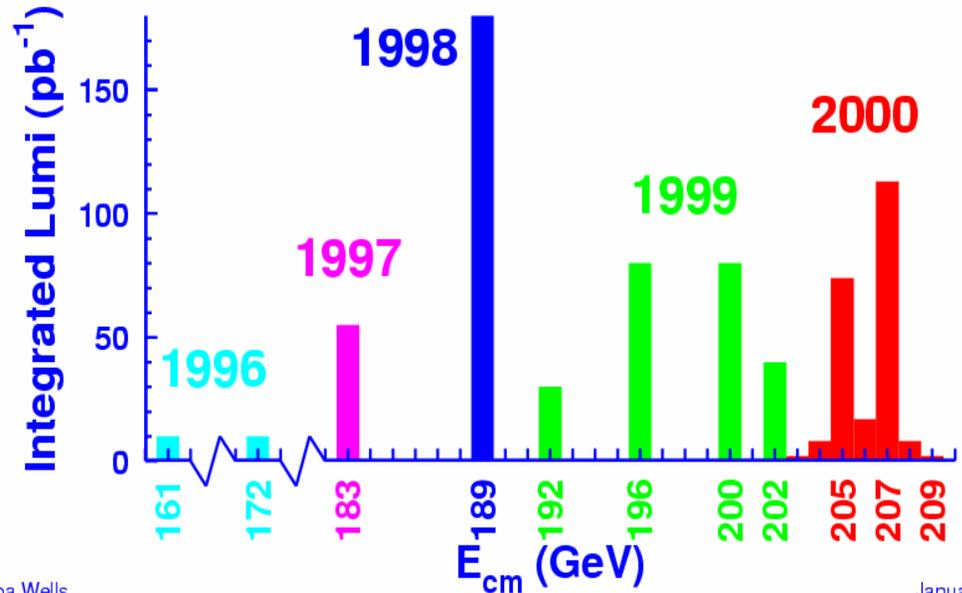




# LEP



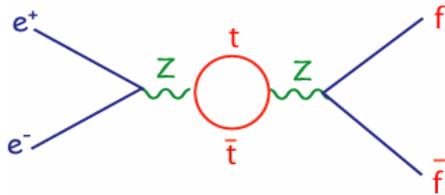
Total LEP I luminosity  $\sim 200 \text{ pb}^{-1}$ /experiment  
 LEP II luminosity  $\sim 750 \text{ pb}^{-1}$ /experiment



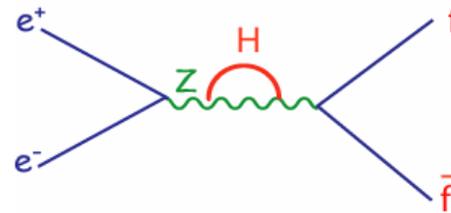
Pippa Wells

January 2001

# Precision Measurements and the Higgs Boson



$$\sim \frac{\alpha m_t^2}{\pi m_Z^2}$$



$$\sim \frac{\alpha}{4\pi} \log \frac{m_H^2}{m_Z^2}$$

From LEP Electroweak WG and the SLD Heavy Flavor Group, May 2002

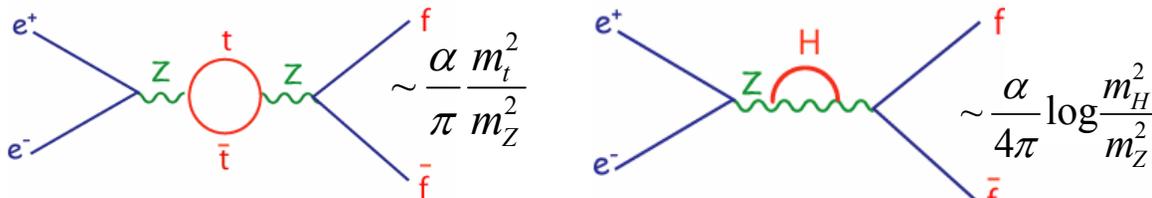
All=  
LEP I+II,  
SLD,  
UA2,  
CDF,  
DO,...

$$m_t = 174.3(5.1)$$

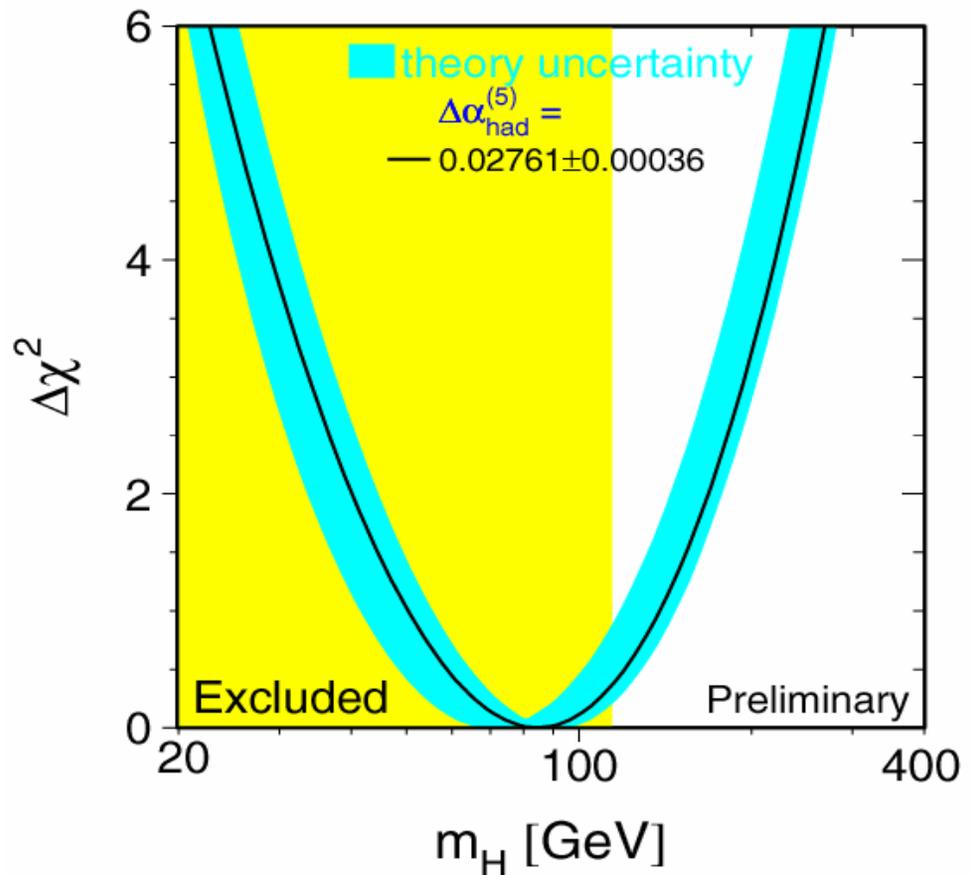
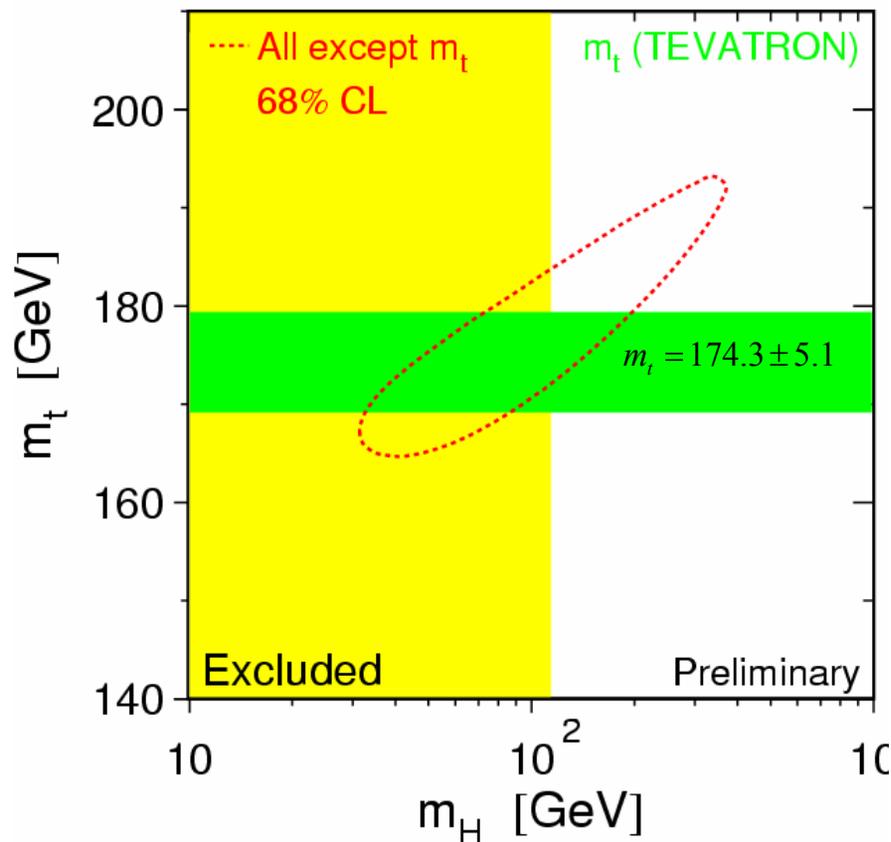
	LEP I+II (incl W)	All Z pole + $m_W, \Gamma_W$	All Data Excluding NuTeV	All Data Including NuTeV
$m_t$	185 +13,-11	181 +11,-9	175.8 +4.3,-4.2	174.7 +4.5,-4.3
$\log m_H$	2.38 +4.1,-.39	2.08 +.38,-.33	1.91 +.21,-.22	1.93 +.21,-.23
$m_H$	238 +371,-141	121 +166,-65	81 +49,-32	85 +54,-34
$\chi^2/\text{dof}$	14.3/9	18.5/12	19.6/14	28.8/15

Stability

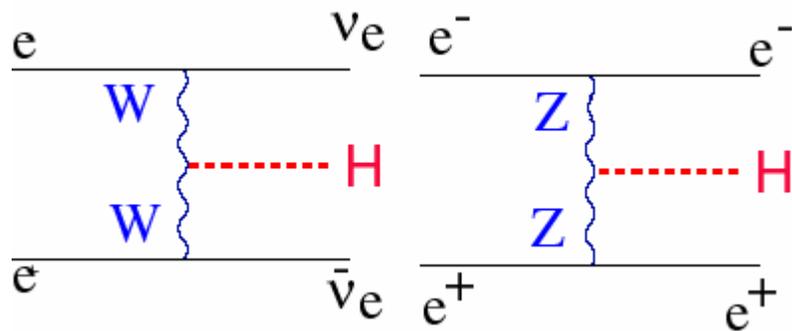
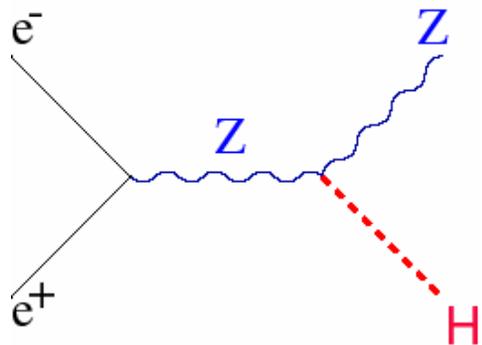
# Constraints on the Standard Model



$\log m_H = 1.93^{+0.21}_{-0.23}$   
 $m_H = 85^{+54}_{-34}$   
 $m_H < 196 \text{ GeV @ 95\% CL}$



# Higgs Production and the Wall

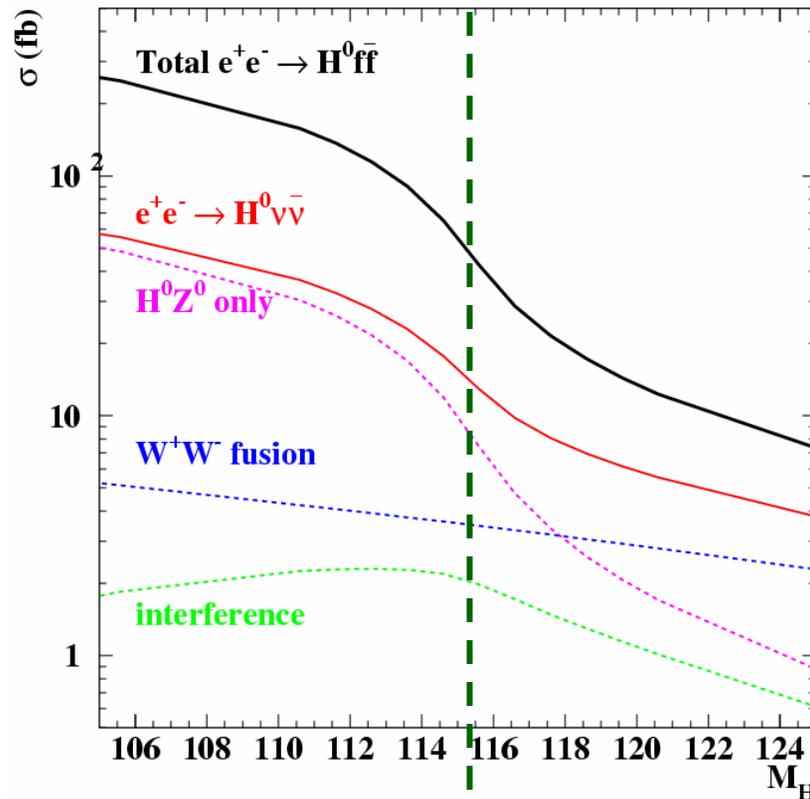


THE WALL

$E_{CM} = 206.6 \text{ GeV}$

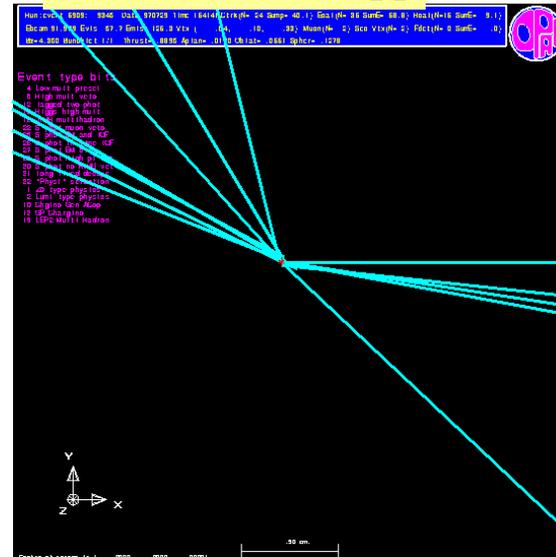
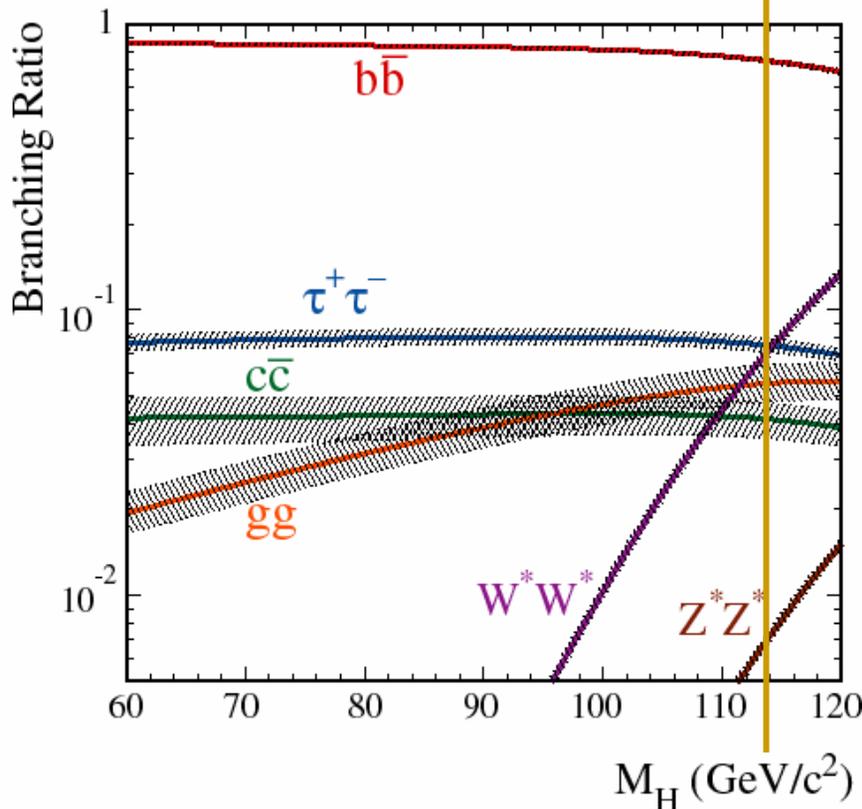
$= 206.6 - 91.2 = 115.4$

At the wall  $\sigma \sim 0.05 \text{ pb}$

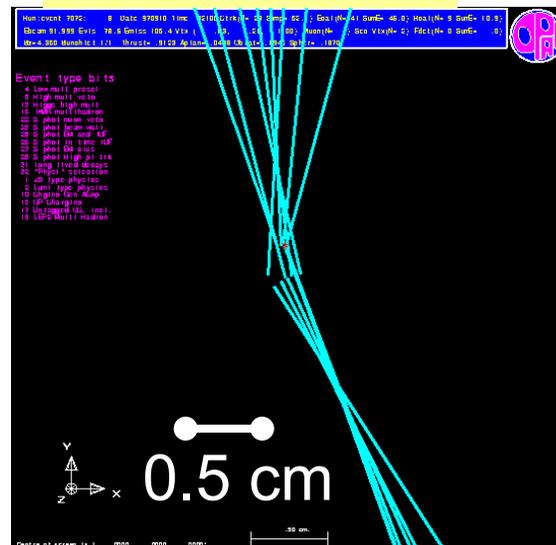


# SM Higgs Decay

$$e^+e^- \rightarrow ZZ \rightarrow \nu\nu q\bar{q}$$



$$e^+e^- \rightarrow ZH \rightarrow \nu\nu b\bar{b}$$



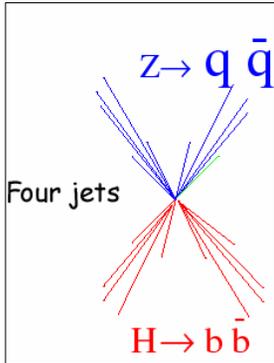
- B-tag is an essential ingredient in Higgs search

# Higgs Search Channels

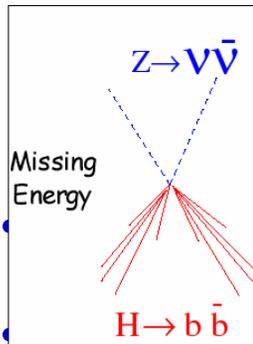
$H \rightarrow b\bar{b}$  ( $\sim 75 - 85\%$ ),  $\tau^+\tau^-$  ( $\sim 8\%$ )

$Z \rightarrow q\bar{q}$  (70%),  $\nu\bar{\nu}$  (20%),

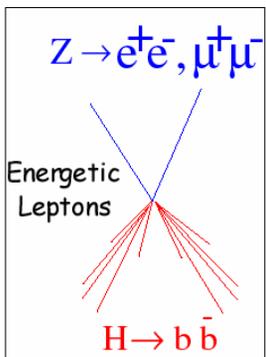
$e^+e^- + \mu^+\mu^-$  (6.6%),  $\tau^+\tau^-$  (3.3%)



- Energy-momentum conservation
- The 2 most probable b-tagged jets recoil against a di-jet compatible with a Z-boson

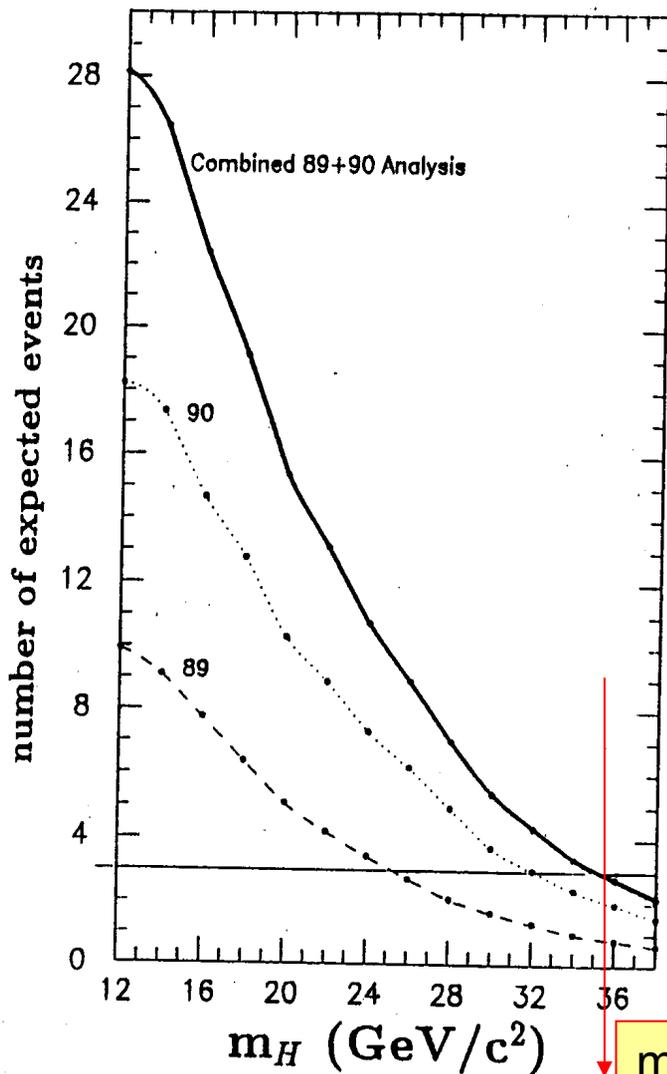


- The recoil mass of the 2 b-tagged jets is compatible with a Z boson



- 2 high energetic leptons with a mass compatible with a Z boson recoil against 2 jets.
- Clean channel

# First Higgs Limit Procedures

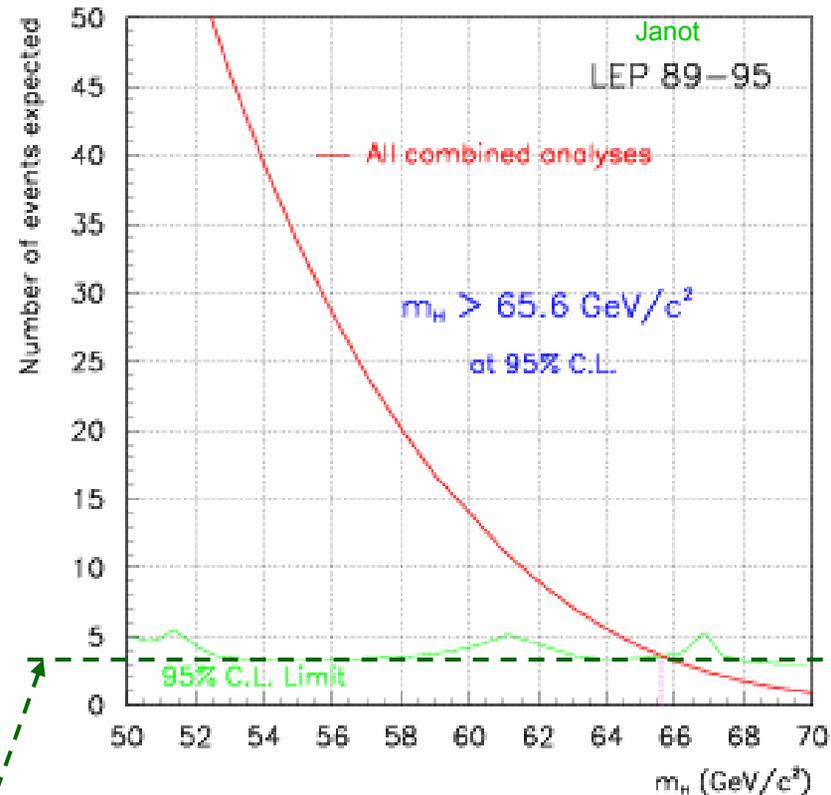
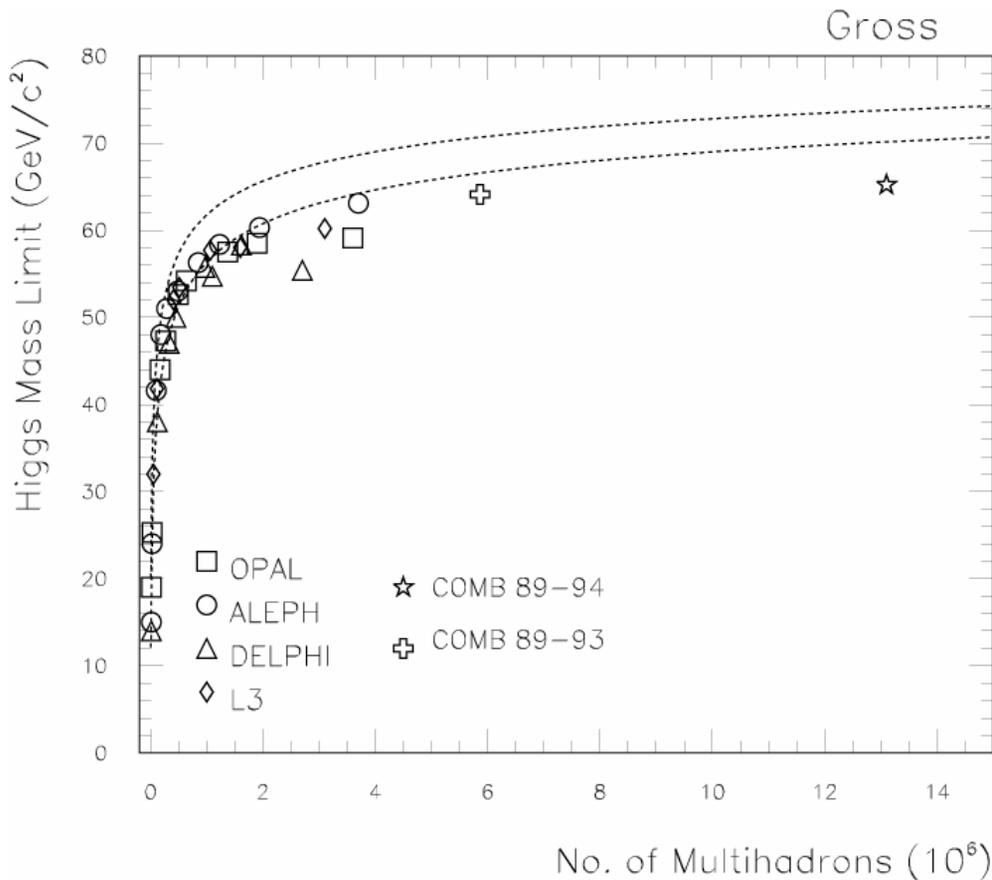


Statistical Procedure in a Background FREE environment

$$N_{\text{exp}} = Lum \cdot \sigma(ee \rightarrow hZ) \cdot eff$$

$$Pr ob(N_{\text{obs}} = 0 | N_{\text{exp}} = N_{95} = 3) = 5\%$$

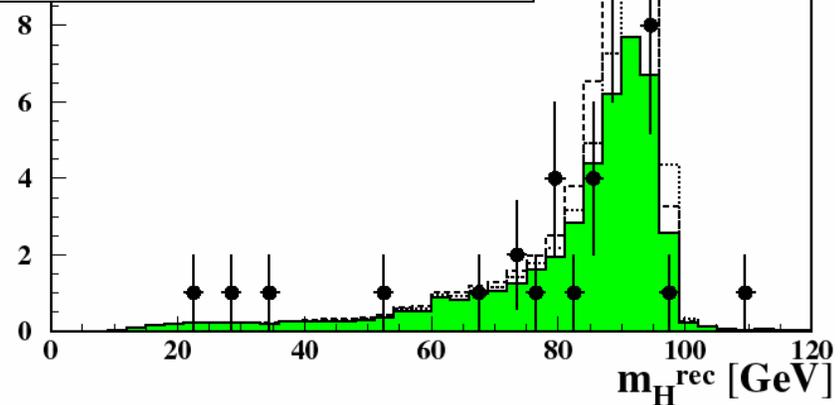
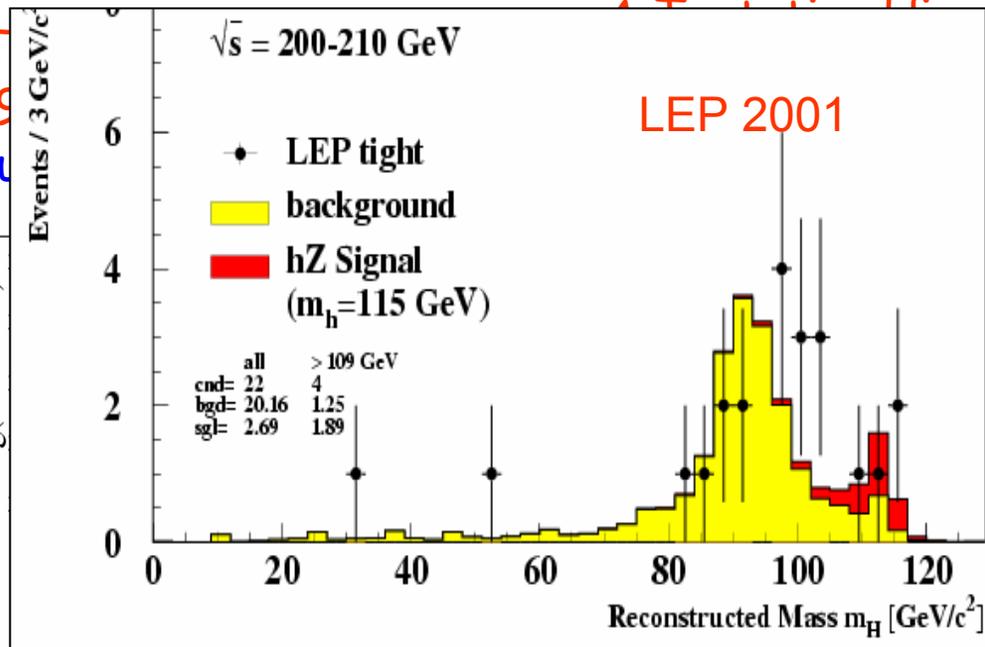
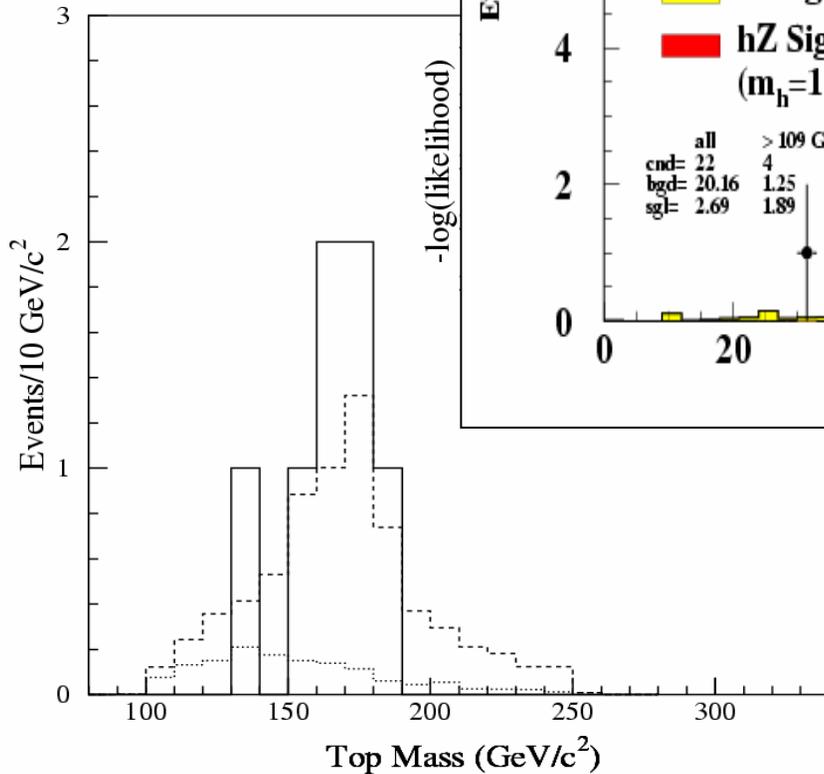
# LEP 1 Saturation and final Limit



- The final LEP I limit is based on  $N_{95} \sim 3$ , i.e. no background
- At the end of LEP I the need to develop a statistical method that can cope with non-vanishing background and events with finite mass resolution was emerged.

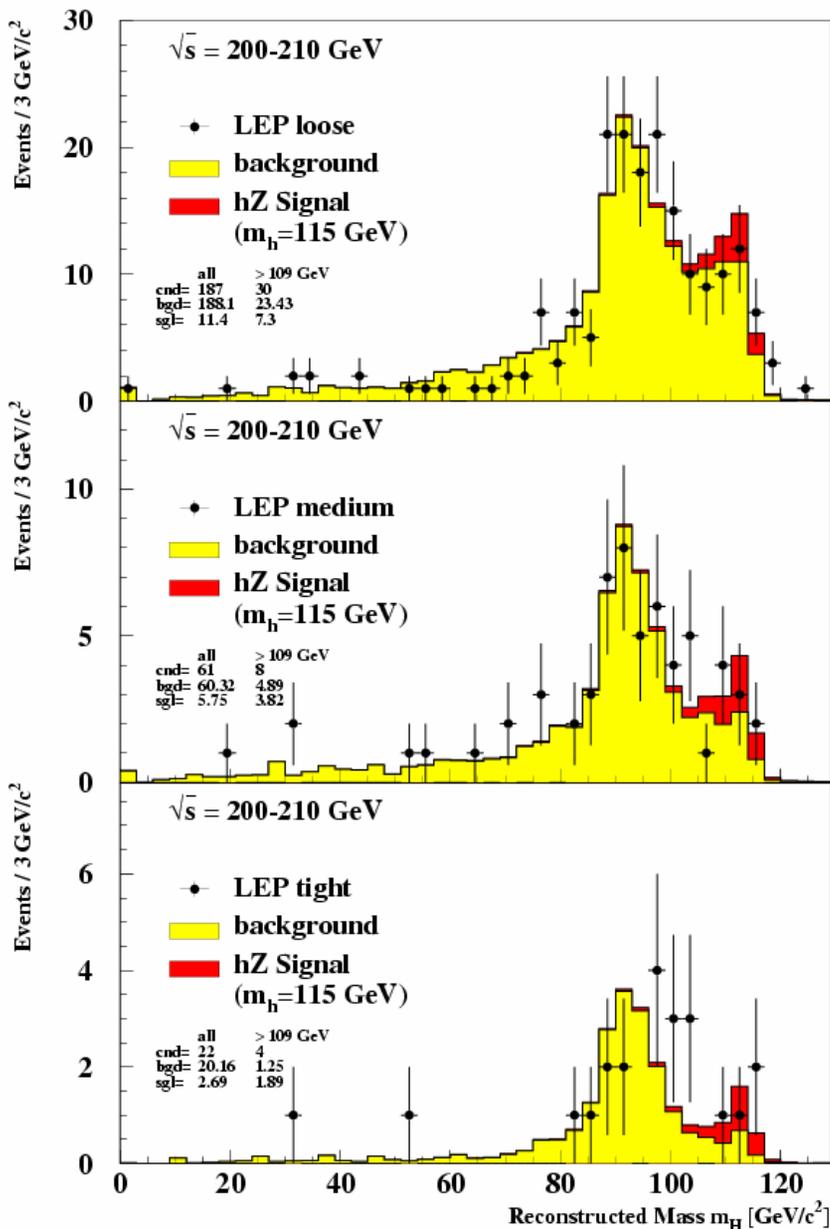
# Golden Signatures

Evidence for Top  
CDF June 13, 1995  
Prob for BG fluct



INARY

# Is that IT?



Now, go and convince people  
That mass histograms are  
"just for illustrative purposes"

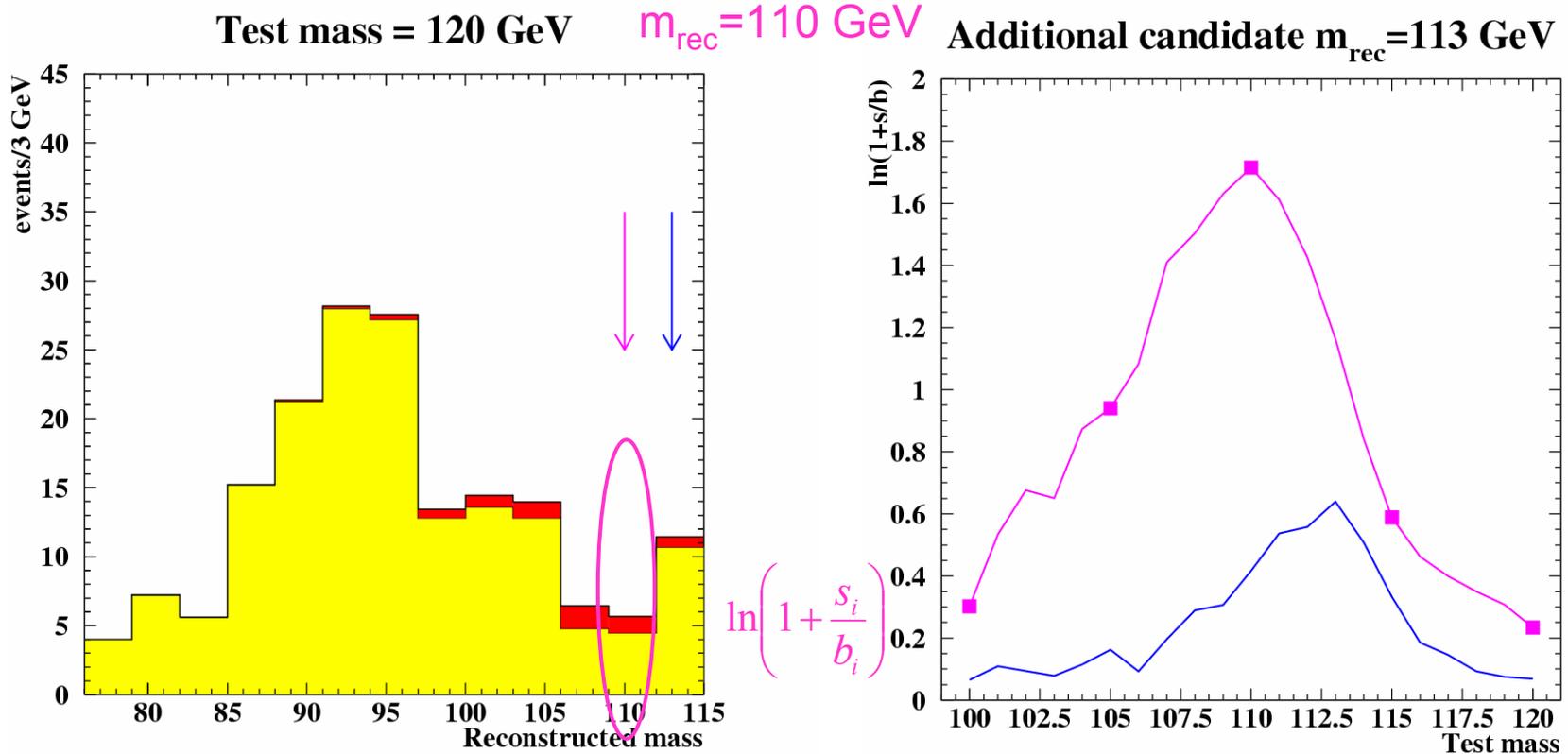
Is there a "hidden" variable behind  
the signal region events?

Perhaps their b-tag content is  
bigger than that of the other  
events?

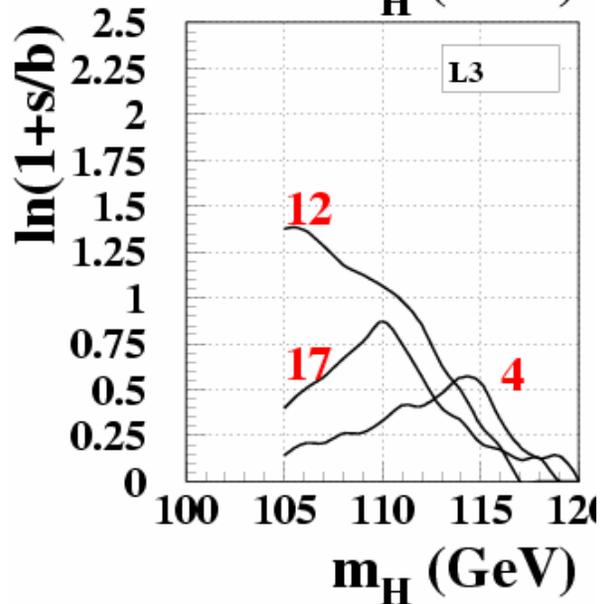
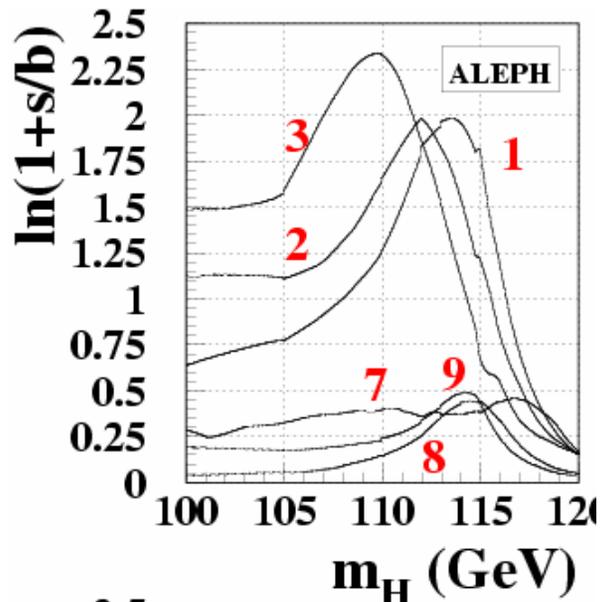
One has to FEEL the statistical  
procedure at his fingertips to  
really appreciate if such a  
signature could indicate a 115 GeV  
Higgs boson or not!

# Spaghetti Higgs Factory

- Q: What is a **High Ranked** ("top") **Higgs candidate**?
- A: A "top" Higgs candidate is an event with an observed reconstructed mass  $m_{rec} = 110$  GeV that for a given **hypothetic test Higgs mass**  $m_H$  has a high weight  $\ln\left(1 + \frac{s_i}{b_i}\right)$



# Most Significant Events

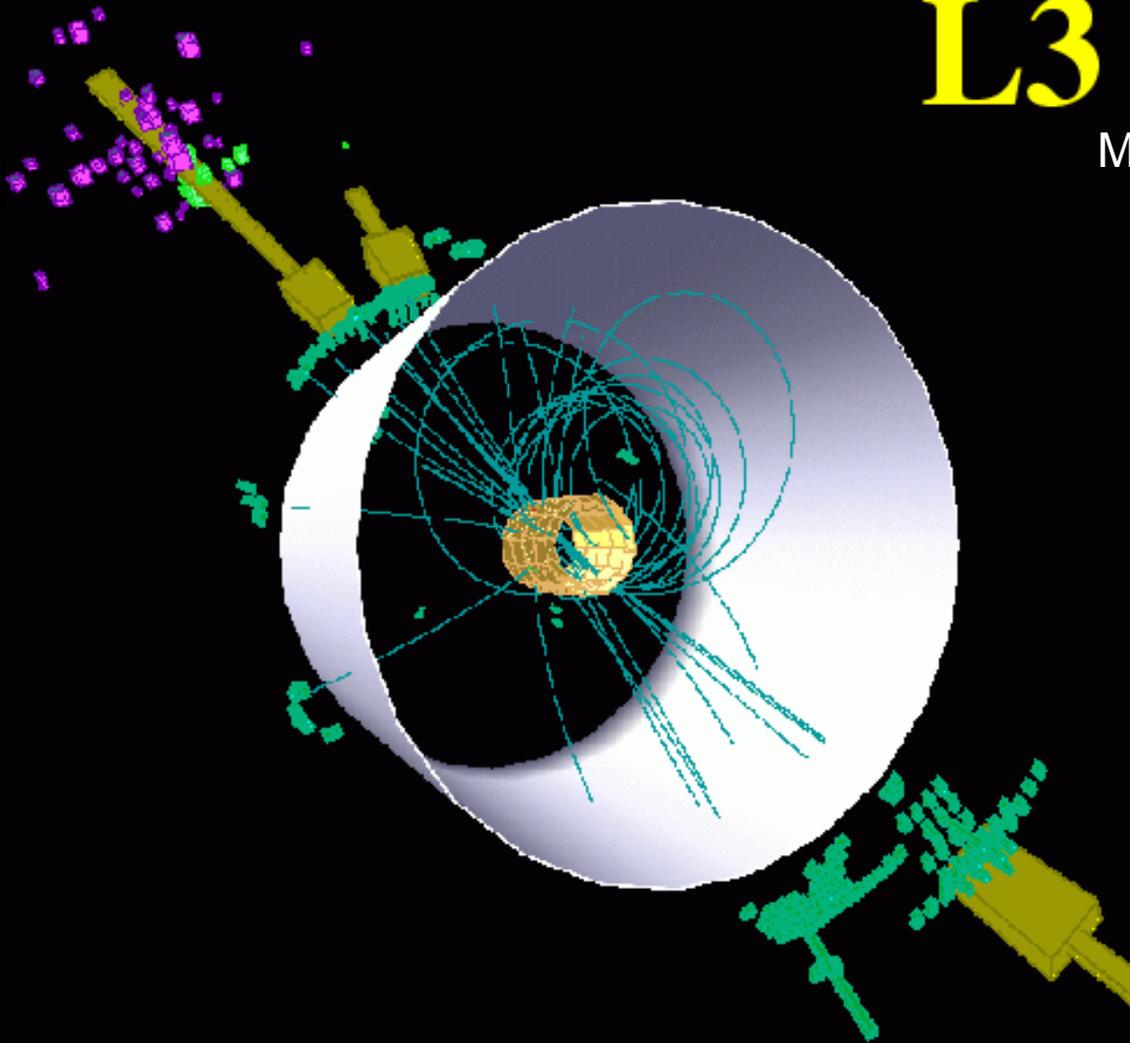


	Expt	$E_{cm}$	Decay channel	$M_H^{rec}$ (GeV)	$\ln(1 + s/b)$ @115 GeV
1	Aleph	206.7	$\pm$ jet	114.3	1.73
2	Aleph	206.7	$\pm$ jet	112.9	1.21
3	Aleph	206.5	$\pm$ jet	110.0	0.64
4	L3	206.4	E-miss	115.0	0.53
5	Opal	206.6	$\pm$ jet	110.7	0.53
6	Delphi	206.7	$\pm$ jet	114.3	0.49
7	Aleph	205.0	Lept	118.1	0.47
8	Aleph	208.1	Tau	115.4	0.41
9	Aleph	206.5	$\pm$ jet	114.5	0.40
10	Opal	205.4	$\pm$ jet	112.6	0.40
11	Delphi	206.7	$\pm$ jet	97.2	0.36
12	L3	206.4	$\pm$ jet	108.3	0.31
13	Aleph	206.5	$\pm$ jet	114.4	0.27
14	Aleph	207.6	$\pm$ jet	103.0	0.26
15	Opal	205.4	E-miss	104.0	0.25
16	Aleph	206.5	$\pm$ jet	110.2	0.22
17	L3	206.4	E-miss	110.1	0.21
18	Opal	206.4	E-miss	112.1	0.20
19	Delphi	206.7	$\pm$ jet	110.1	0.20
20	L3	206.4	E-miss	110.1	0.18



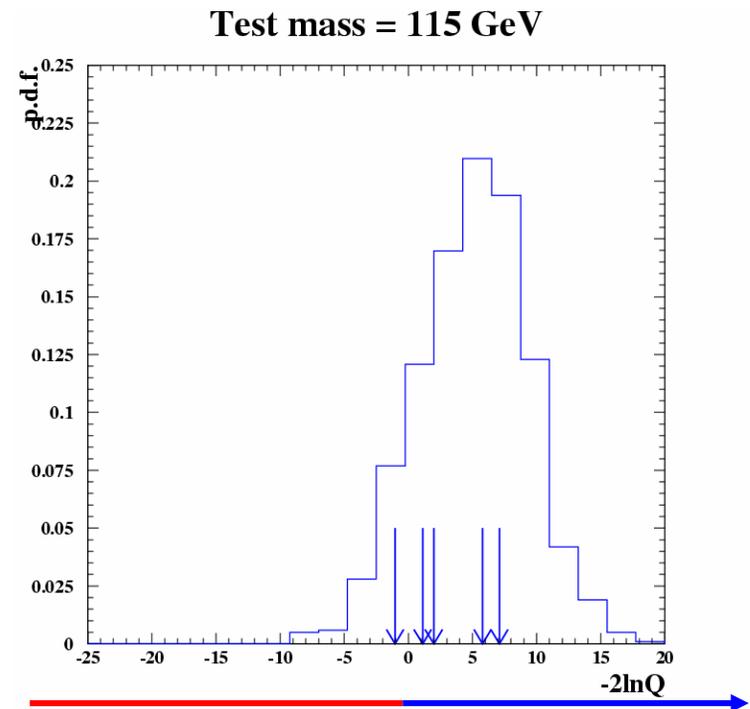
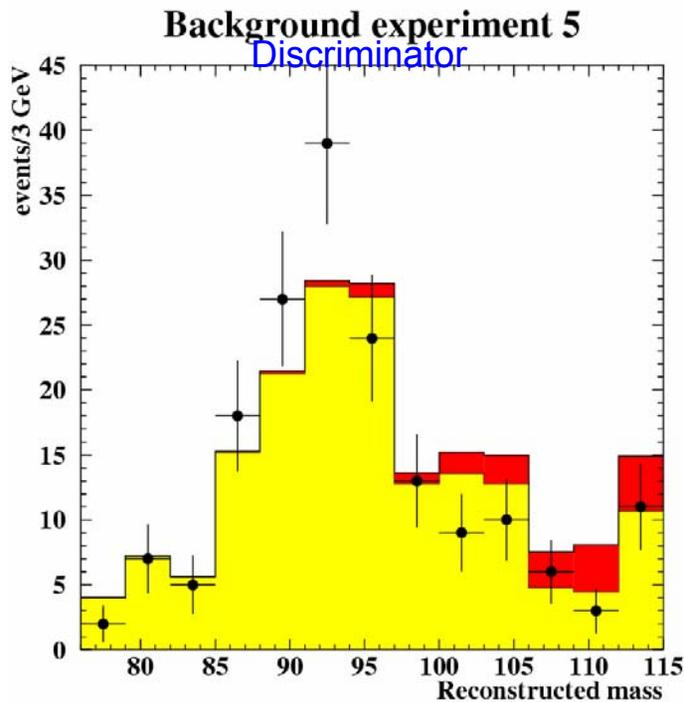
# L3 Missing Energy Candidate

**L3**  $E_{\text{CM}}=206.4$   
 $M_{\text{rec}}=115 \text{ GeV}$



# Simulating bg Experiments

- Construct a **Discriminator** (Not necessarily mass, could be 2-D)
- Divide the **discriminator** to bins  $i=1, \dots$   
There are  $N_i$  observed candidate events in each bin; we then calculate the **likelihood ratio  $-2\ln Q$**
- The likelihood ratio,  **$-2\ln Q(m_H)$**  tells us how much the outcome of an experiment is **signal-like**



NEXT

# The Statistical Procedure or Ranking Experiments

$$Q = \frac{P_{\text{poisson}}(\text{data}|s+b)}{P_{\text{poisson}}(\text{data}|b)} = \frac{L(s+b)}{L(b)} = \frac{e^{-(s_{TOT}+b_{TOT})}}{e^{-b_{TOT}}} \prod_{i=1}^{N_i} \frac{s_i + b_i}{b_i}$$

Each observed event is counted with a weight  $\ln\left(1 + \frac{s_i}{b_i}\right)$

$$-2 \ln Q = 2s_{TOT} - 2 \sum_{i=1}^{N_i} N_i \ln\left(1 + \frac{s_i}{b_i}\right)$$

s+b like

b-like  $-2\ln Q$

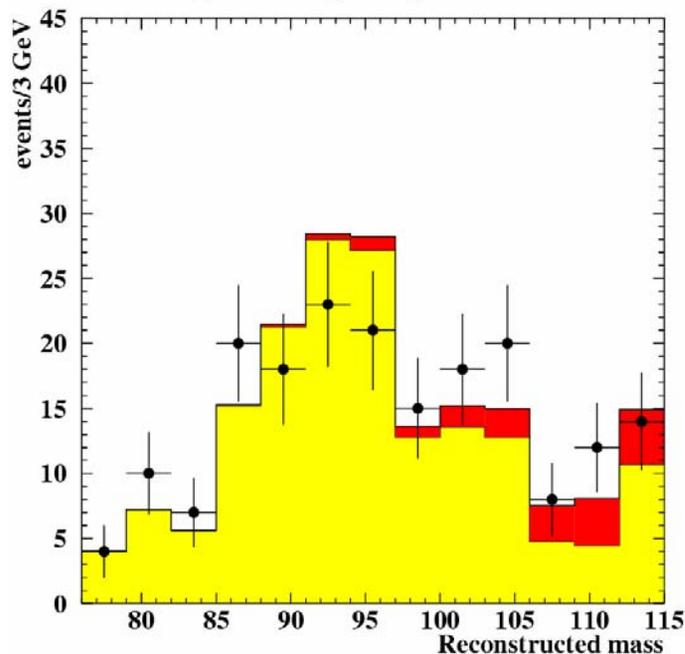
The likelihood ratio,  $-2\ln Q(m_H)$  ranks the experimental events configuration between two hypotheses: "s+b"-like and "b"-like,

# Simulating **s+b** Experiments ( $m_H=115$ )

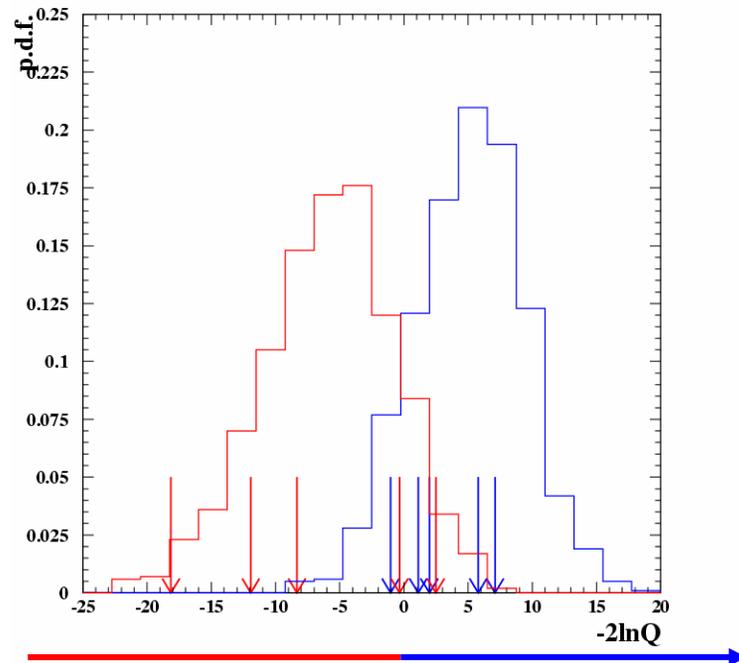
- Now we let's play the "game" from a 115 GeV Higgs point of view...

$$-2 \ln Q = 2S_{TOT} - 2 \sum_{i=1}^{N_i} \ln \left( 1 + \frac{S_i}{b_i} \right)$$

Signal+bkg. Experiment 5



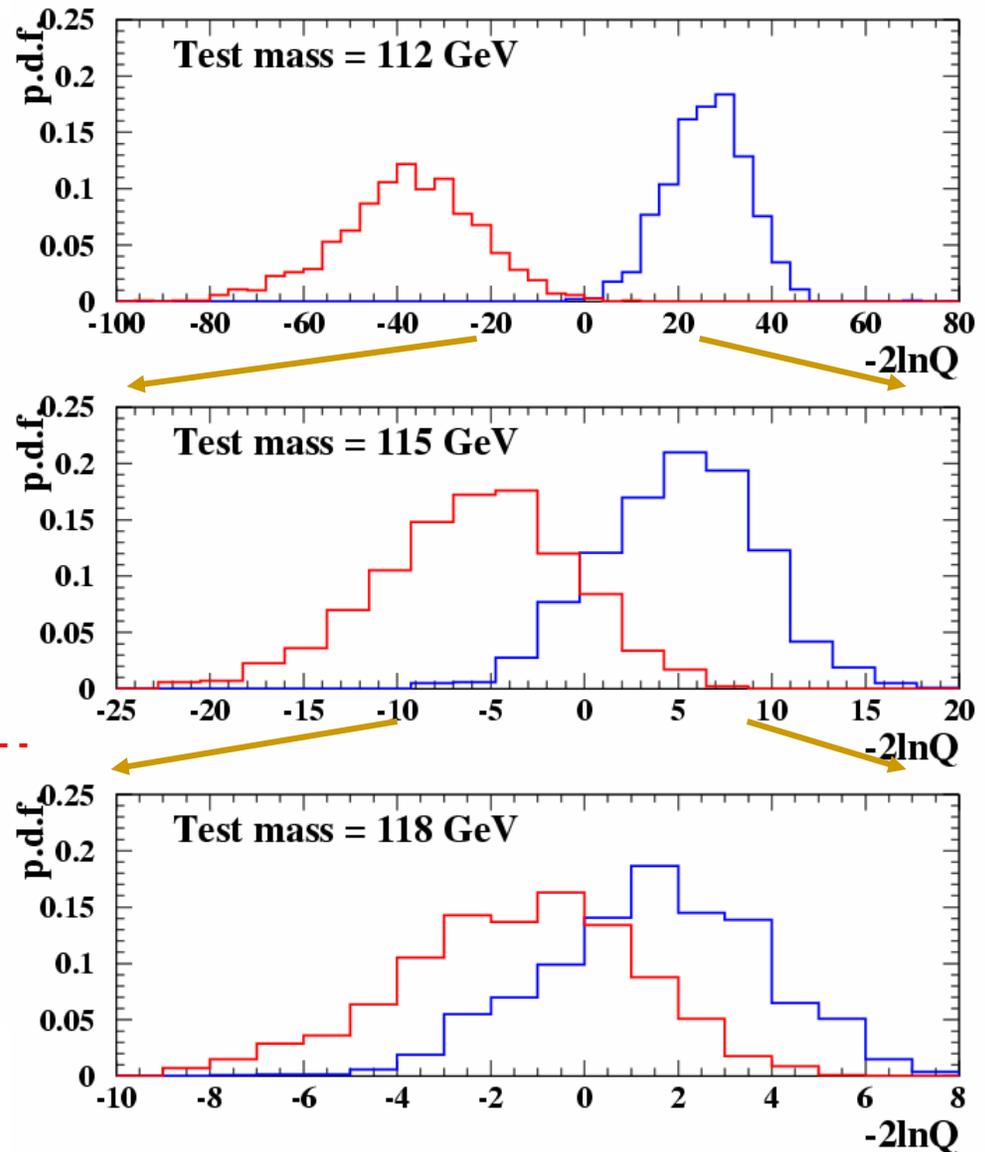
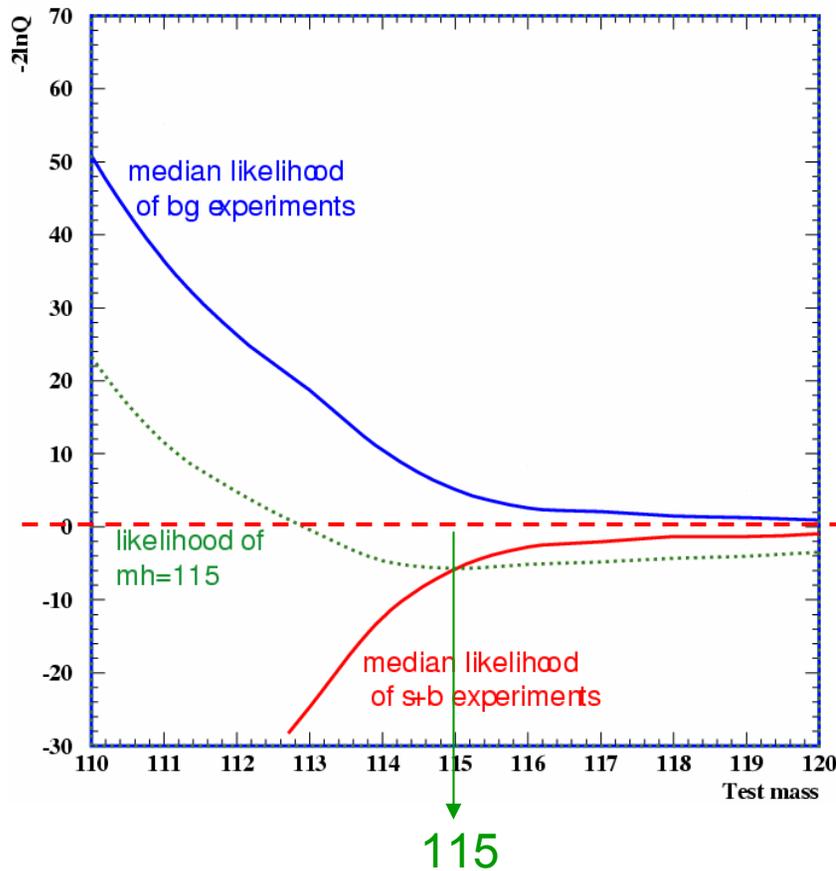
Test mass = 115 GeV



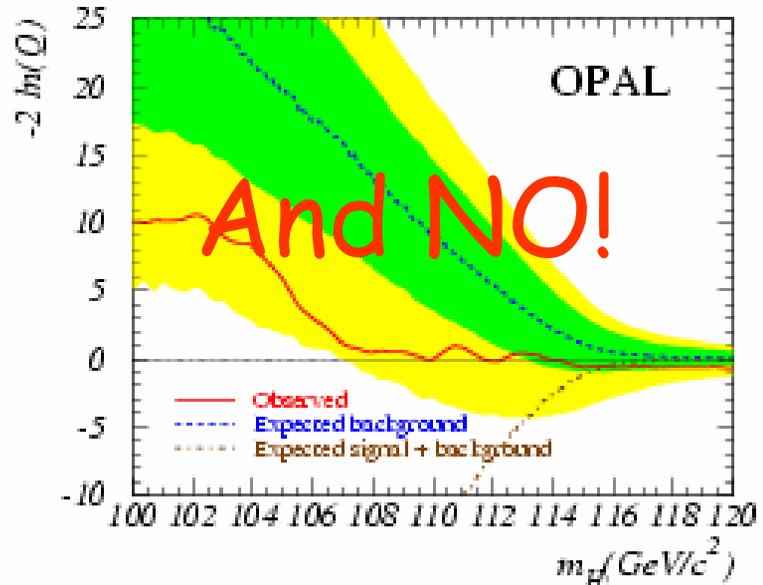
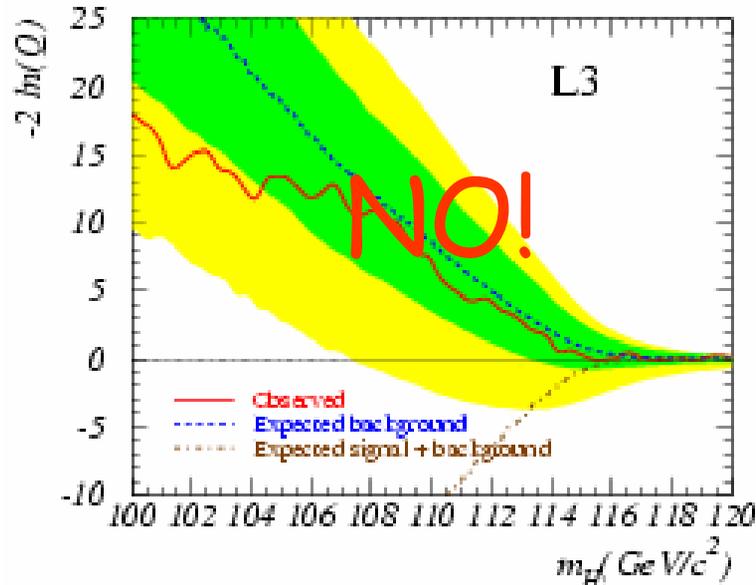
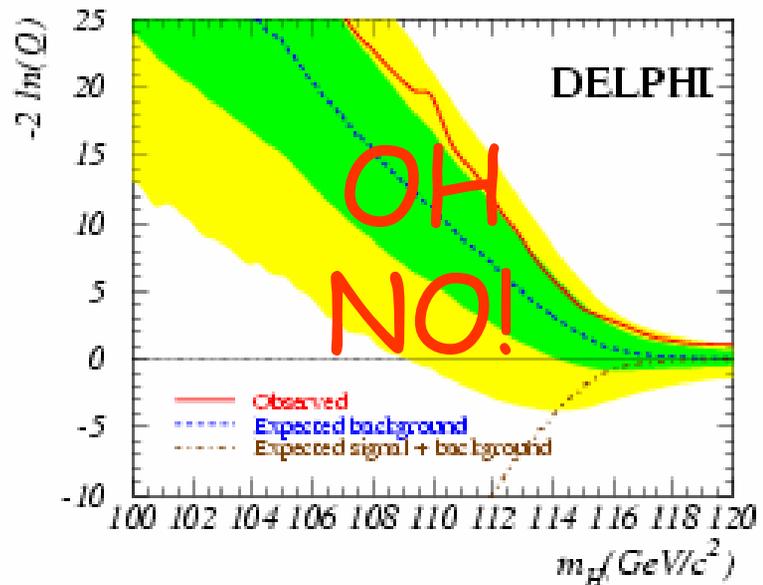
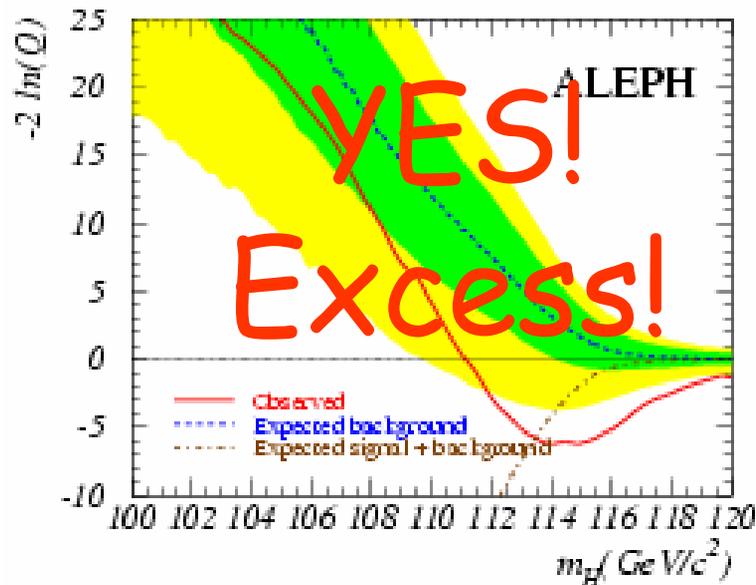
s+b like

b-like

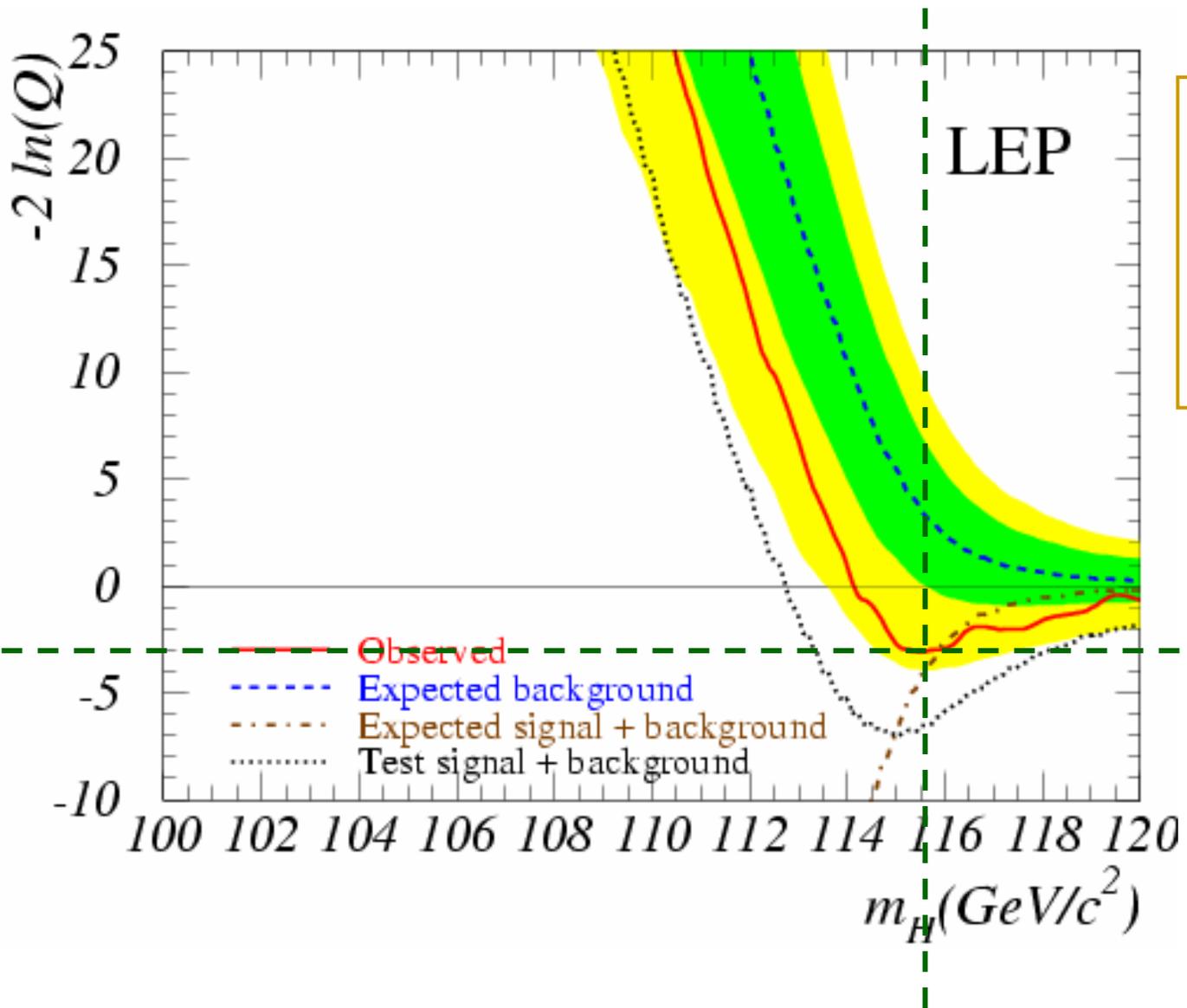
# Signal-Background Separation



# The Real Thing: 4 Experiments, 4 Likelihoods

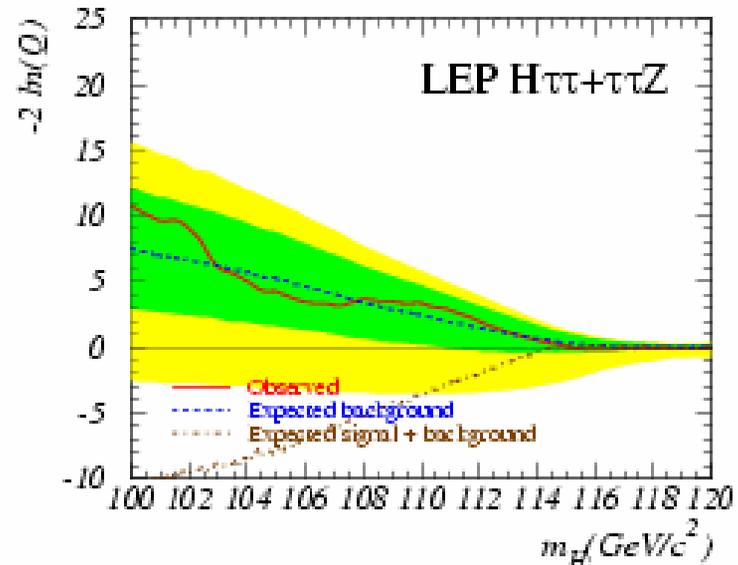
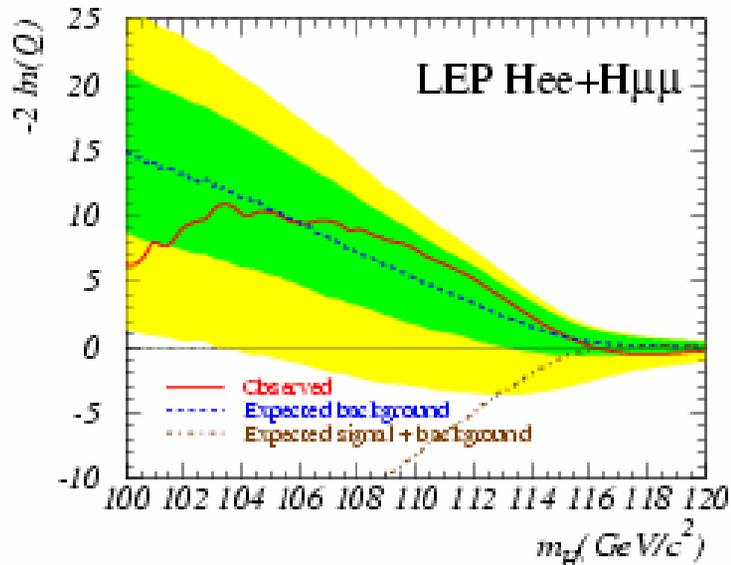
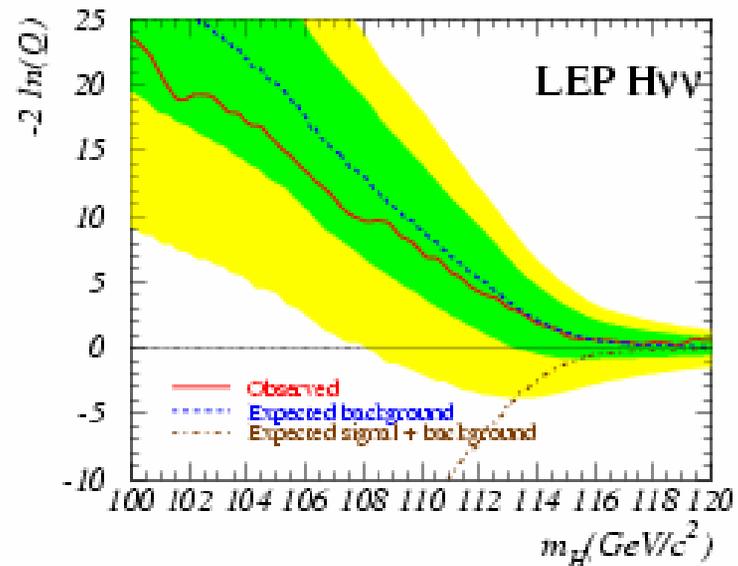
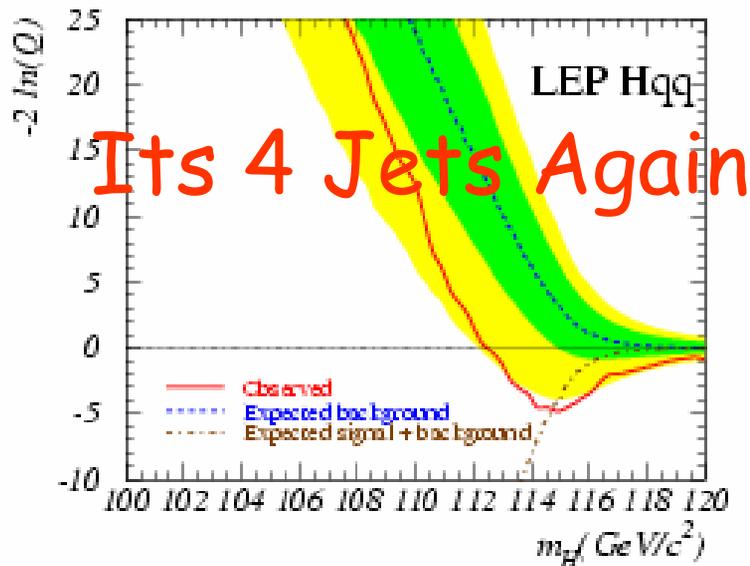


# All 4 Experiments Combined Into One: LHWG



Maximum Likelihood for  $m_H=115.6$   
Enormous sensitivity to test mass due to the kinematical wall!

# Channel By Channel



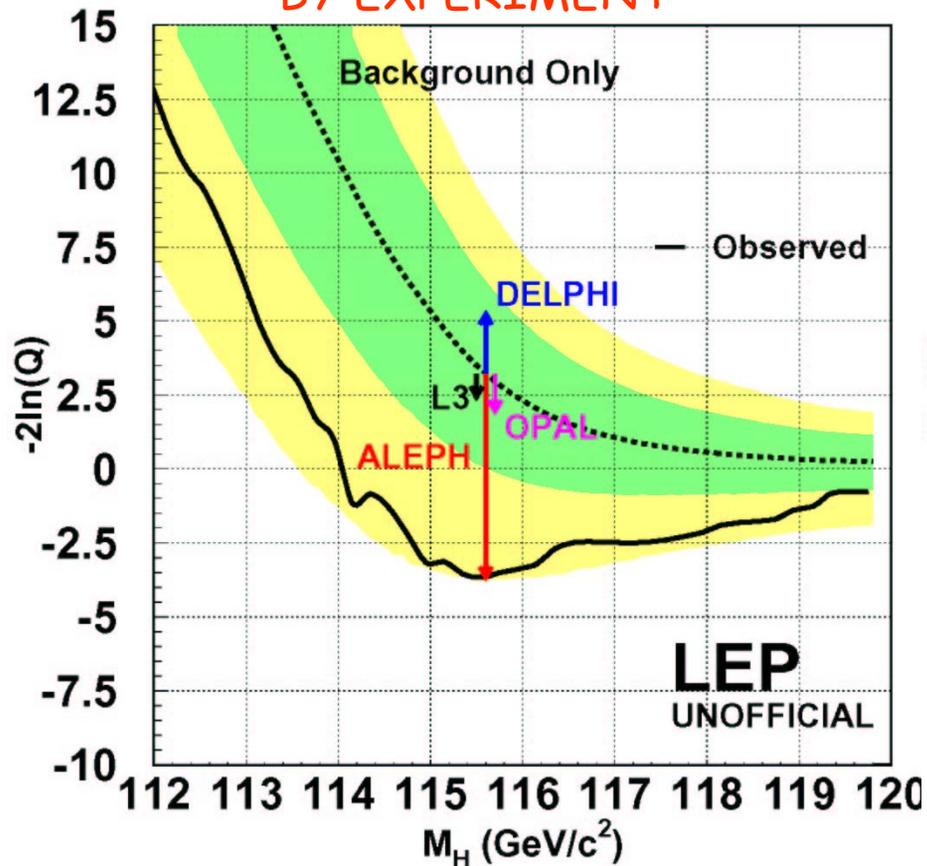
# Focus on Year 2000

Unofficial plots from C. Tully DPF 2002 BASED on 2000 data ONLY!

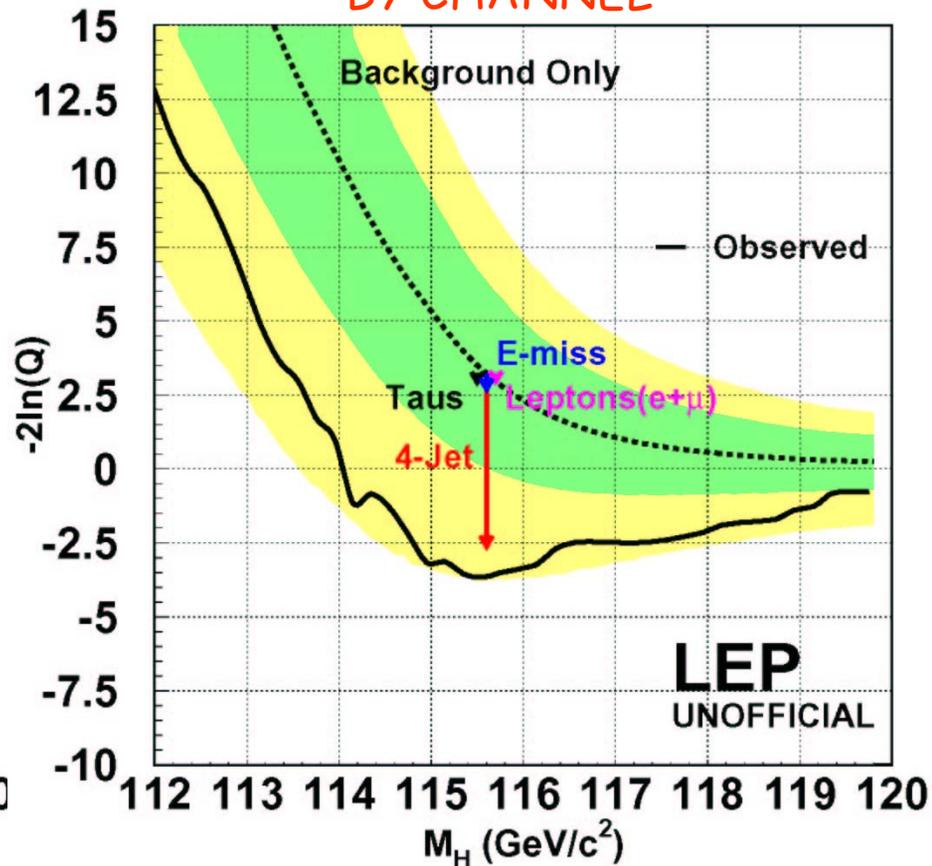
- Note that  $\ln Q$  is additive

-  completely dominate the fluctuation

BY EXPERIMENT

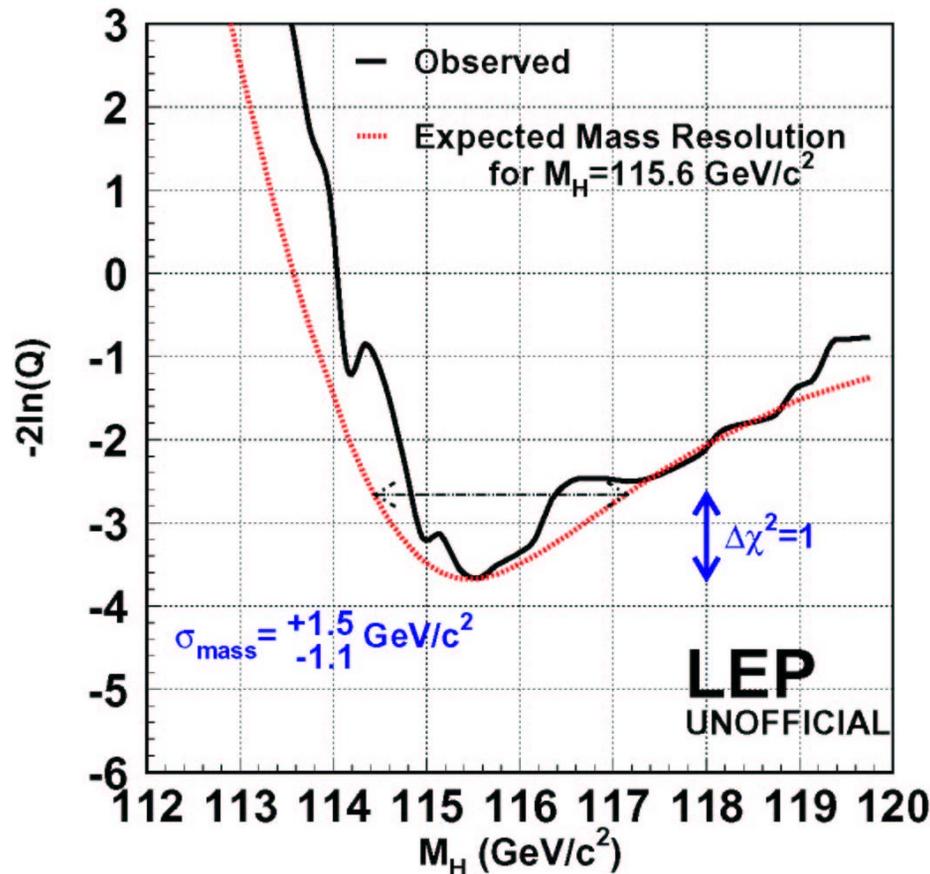


BY CHANNEL



# If there is a Higgs

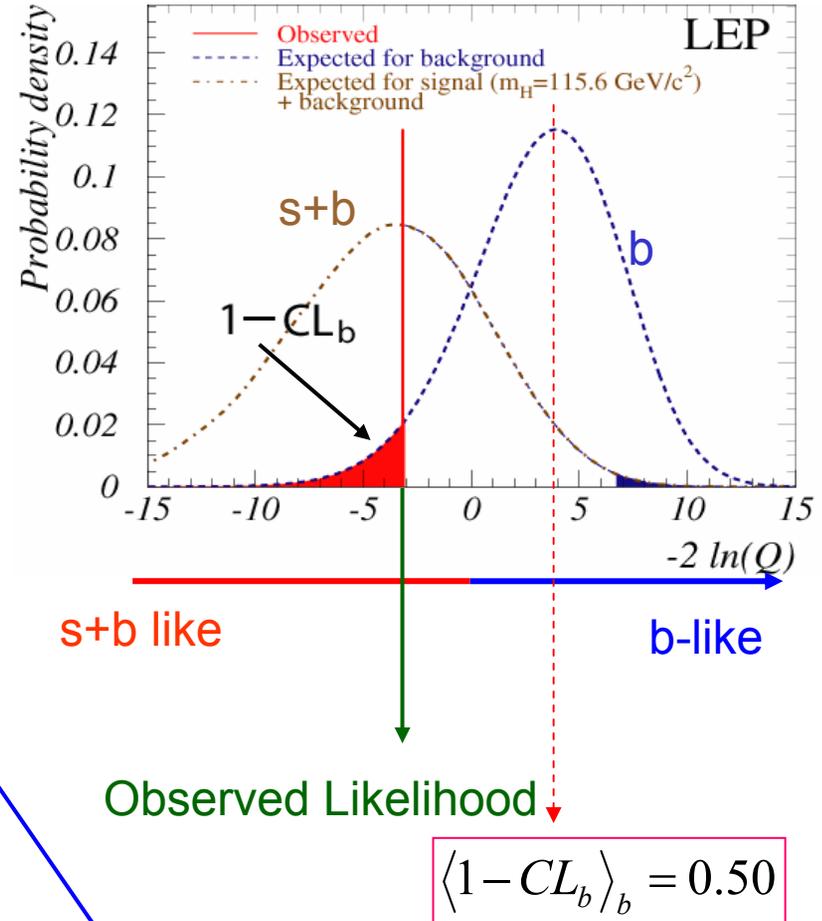
- If there is a Higgs in the year 2000 data its mass could be interpreted from the maximum likelihood  $m_H = 115.6^{+1.5}_{-1.1}$



C. Tully DPF 2002

# Confidence Levels

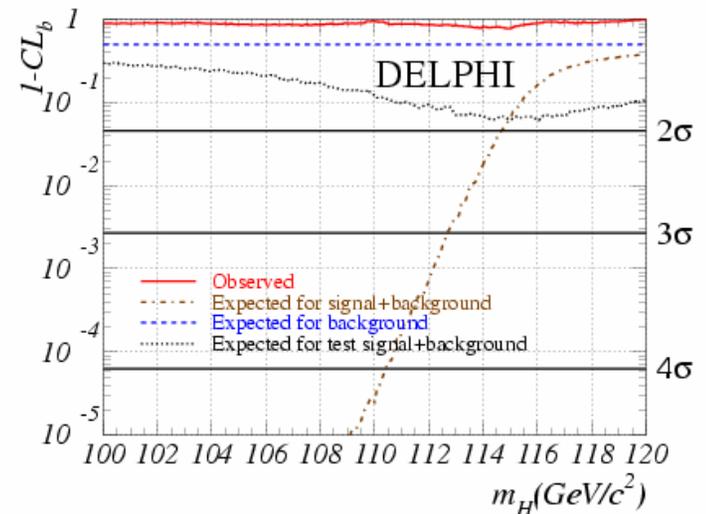
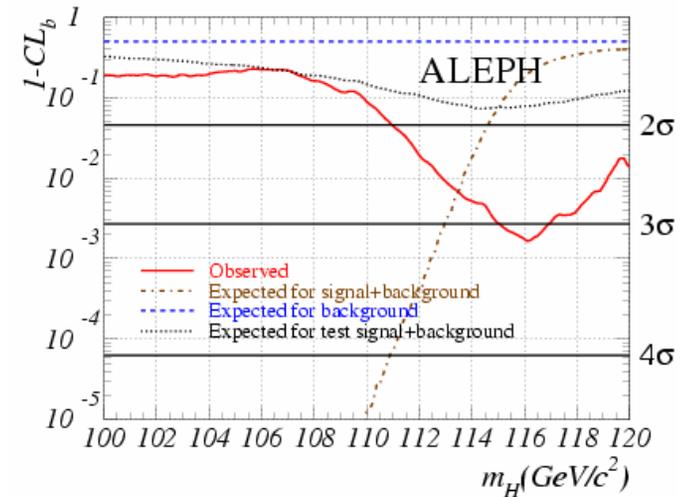
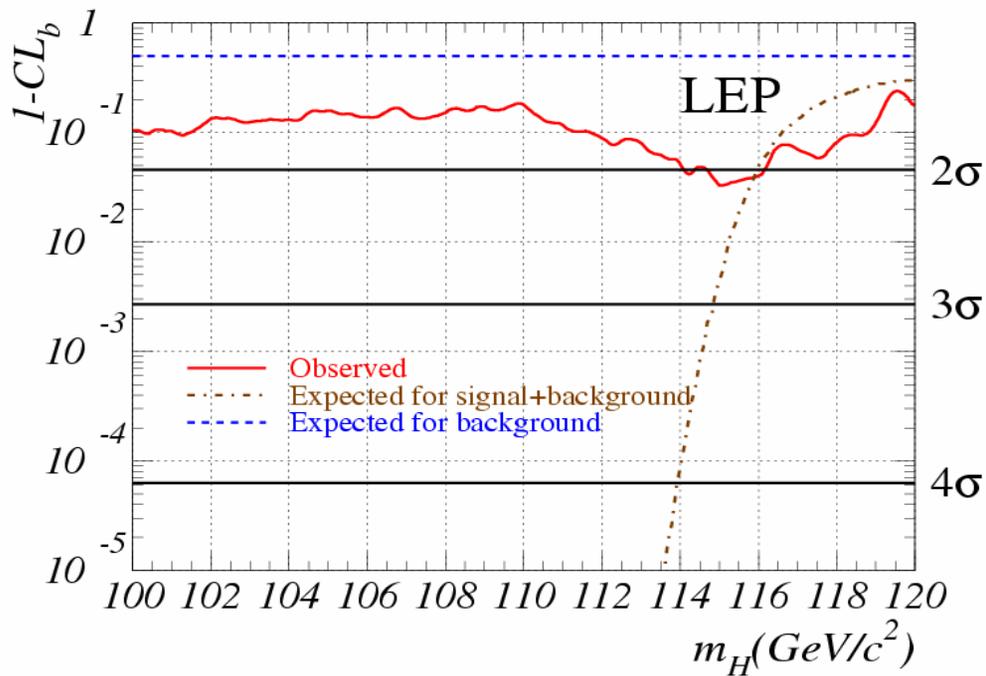
- How probable is a result of an experiment?
- The PDF of  $-2\ln Q$  was created from an ensemble of "b" or "s+b" experiments
- $1-CL_b$  is the probability for a background only experiment to give a more signal-like likelihood than the observed one!
- LEP Result:  
 **$1-CL_b=0.034$  ( $2.1 \sigma$ )**
- In 3.4% background experiments we expect to observe at least as signal-like result as we observe



Alph	$2.0 \times 10^{-3}$
DELPHI	0.87
L3	0.24
OPAL	0.22
DLO	0.49

$1-CL_b$	0.32	0.046	$2.7 \times 10^{-3}$	$6.3 \times 10^{-5}$	$5.7 \times 10^{-7}$
	$1\sigma$	$2\sigma$	$3\sigma$	$4\sigma$	$5\sigma$

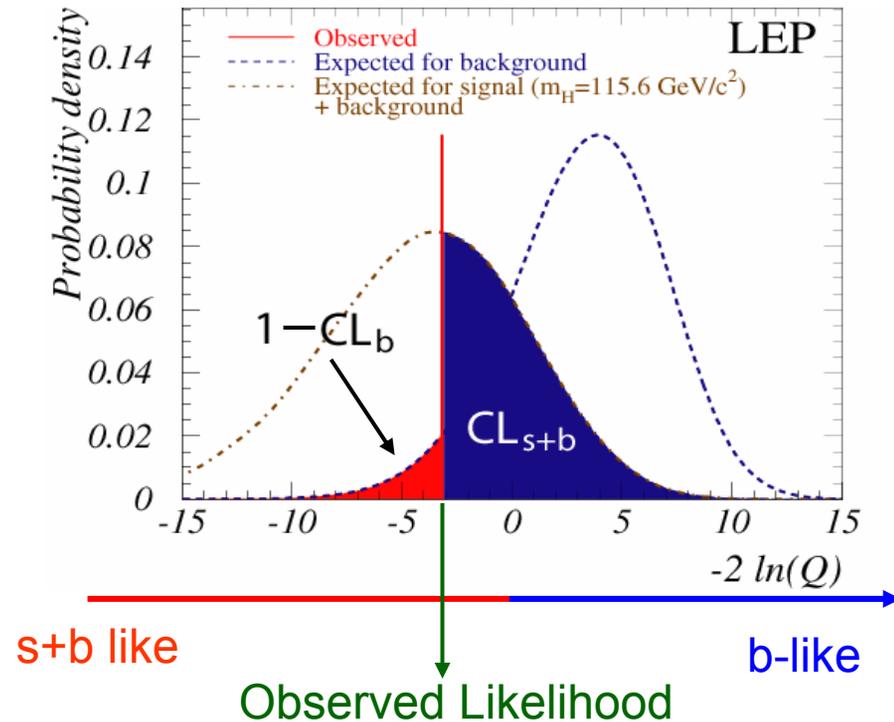
# A Higgs Discovery?



- Look for a minimum in  $1-CL_b$
- A Higgs Discovery?
- Not really....

# Signal CL

- $CL_{s+b}$  measures the compatibility of the experiment with "s+b" hypothesis.
- A bigger  $CL_{s+b}$  means the experimental result is more "s+b" like
- YOU CANNOT EXCLUDE AN "S+B" HYPOTHESIS WITH A LARGE  $CL_{s+b}$
- An "s( $m_H$ ) +b" hypothesis can be excluded at >95% CL if only in <5% of the hypothetical "s+b" experiments the result would be more "b" like



Looks like DELPHI could exclude the "s ( $m_H=115.6$ ) +b" hypothesis at the 98% CL

However, can they exclude a 115.6 "s" hypothesis?

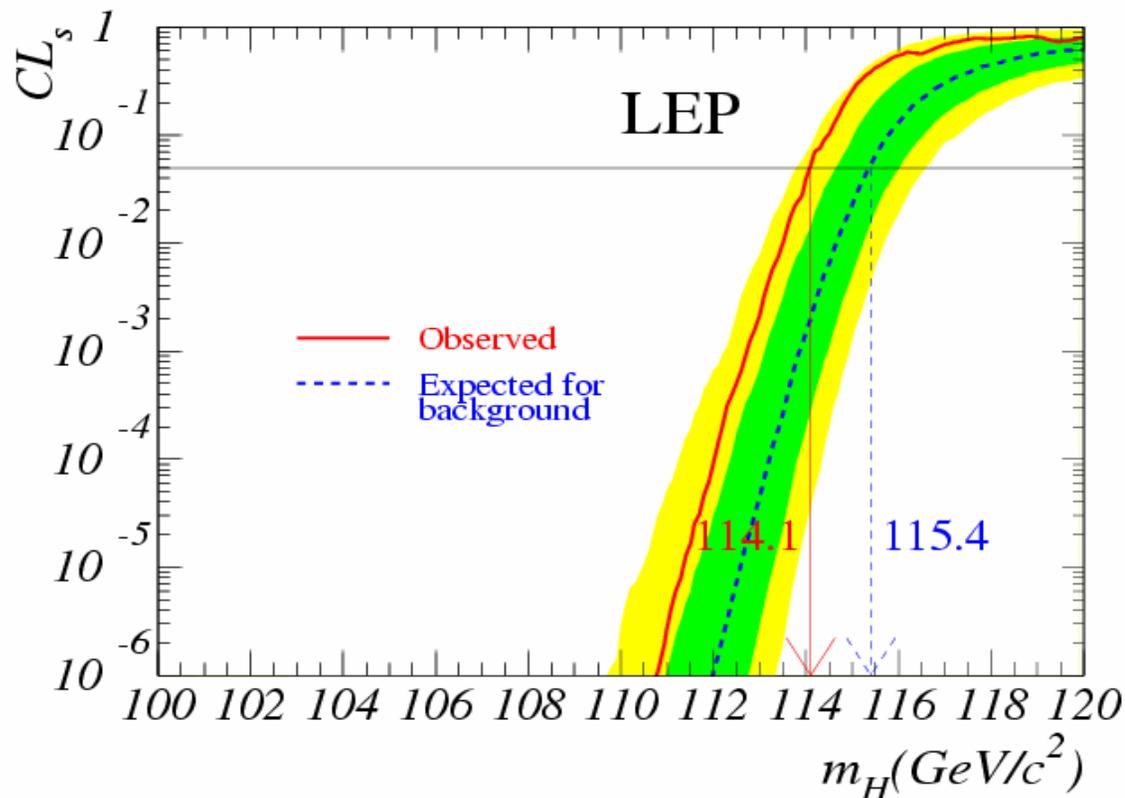
Define

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

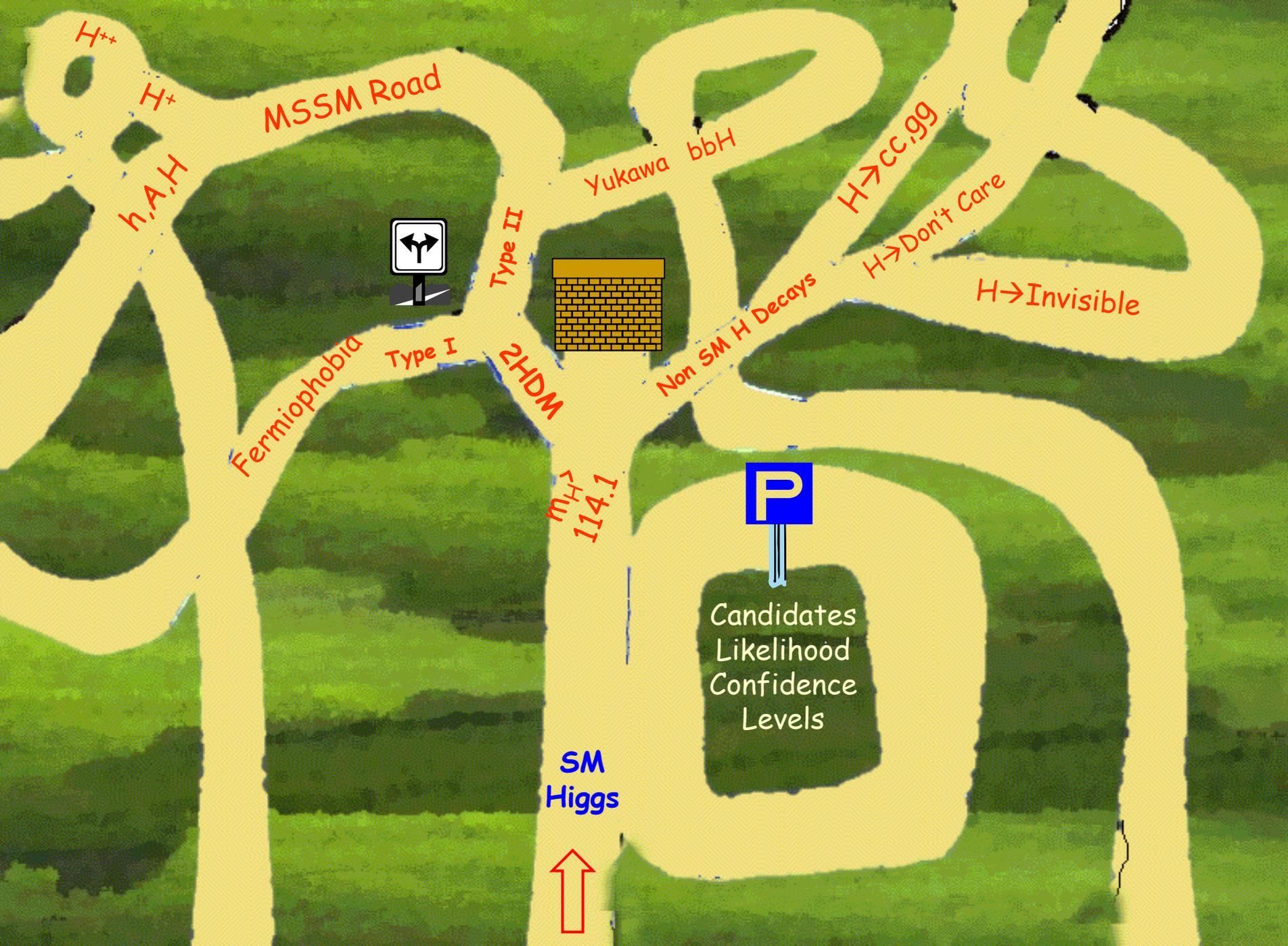
	$1 - CL_b$	$CL_{s+b}$
Aleph	$2.0 \times 10^{-3}$	0.94
DELPHI	0.87	0.02
L3	0.24	0.47
OPAL	0.22	0.47
DLO	0.49	0.07

# Higgs Mass Lower Bound

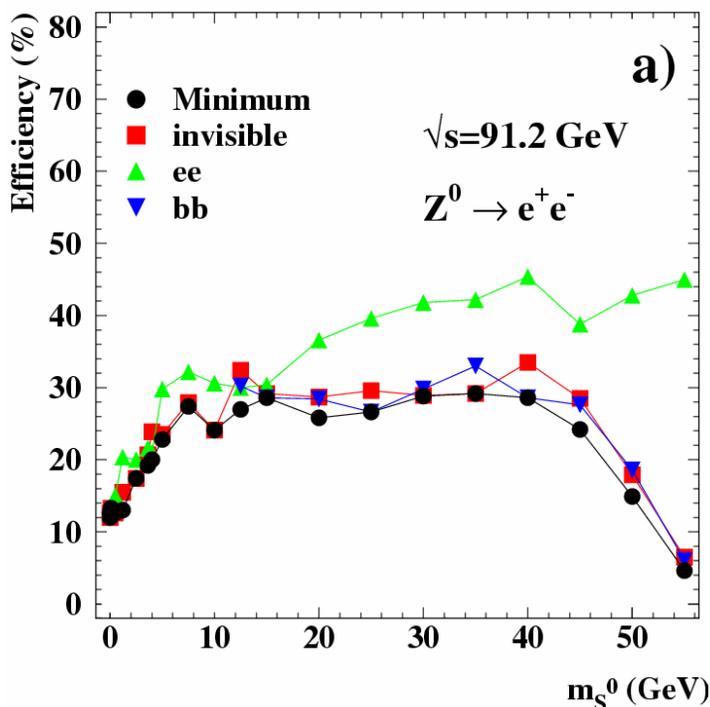
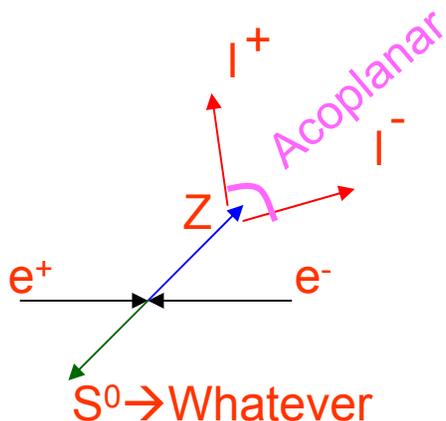
- When  $CL_s(m_H) < 5\%$  a Higgs boson with a mass  $m_H$  is excluded at  $>95\%$  CL!
- LEP Excludes a 114.1 GeV Higgs Boson (expected 115.4) at the 95% CL!



	Exp	Obs
ALEPH	113.8	111.5
DELPHI	113.5	114.3
DLO	114.9	114.8
LEP	115.4	114.1

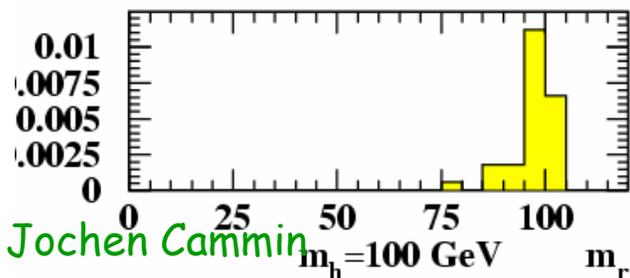
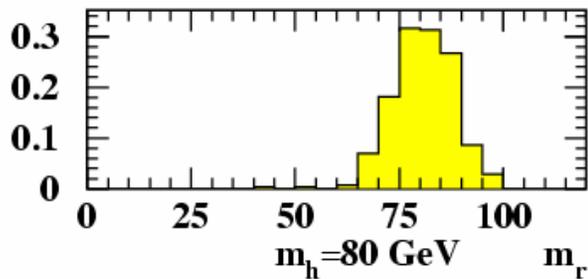
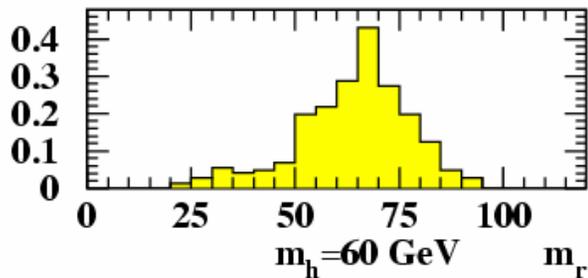
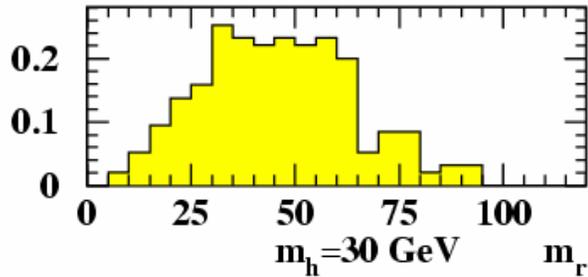


# Higgs Decay Mode Independent Searches



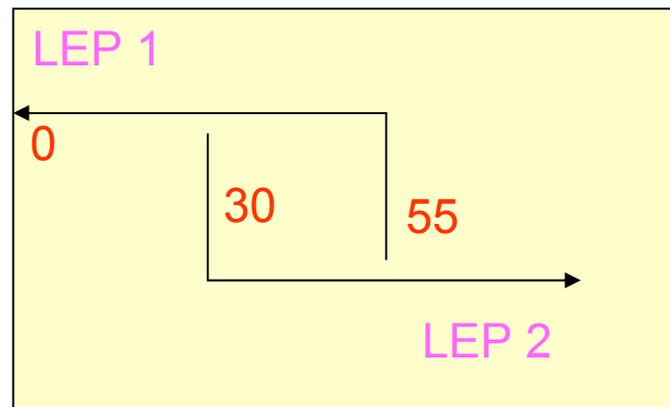
- Search for acoplanar leptons
- Look for a peak in the recoil mass, however, sensitivity is retained for continuous wide recoil mass
- LEP 1: Z is off shell
  - look for acoplanar leptons ( $\mu$ 's and  $e$ 's) with  $m_{ll} > 20 \text{ GeV}$
  - Use photon and conversions veto
  - For  $S^0 \rightarrow \gamma\gamma$  and  $S^0 \rightarrow ee$  (with  $m_{ee} < 0.5$ ) use  $ee \rightarrow Z^0 S^0 \rightarrow \nu\nu\gamma\gamma, \nu\nu ee$
- LEP 2: Z is on shell
  - Look for acoplanar leptons with  $m_{ll} \sim m_Z$
  - Veto radiative return photons

# Higgs Decay Mode Independent Searches



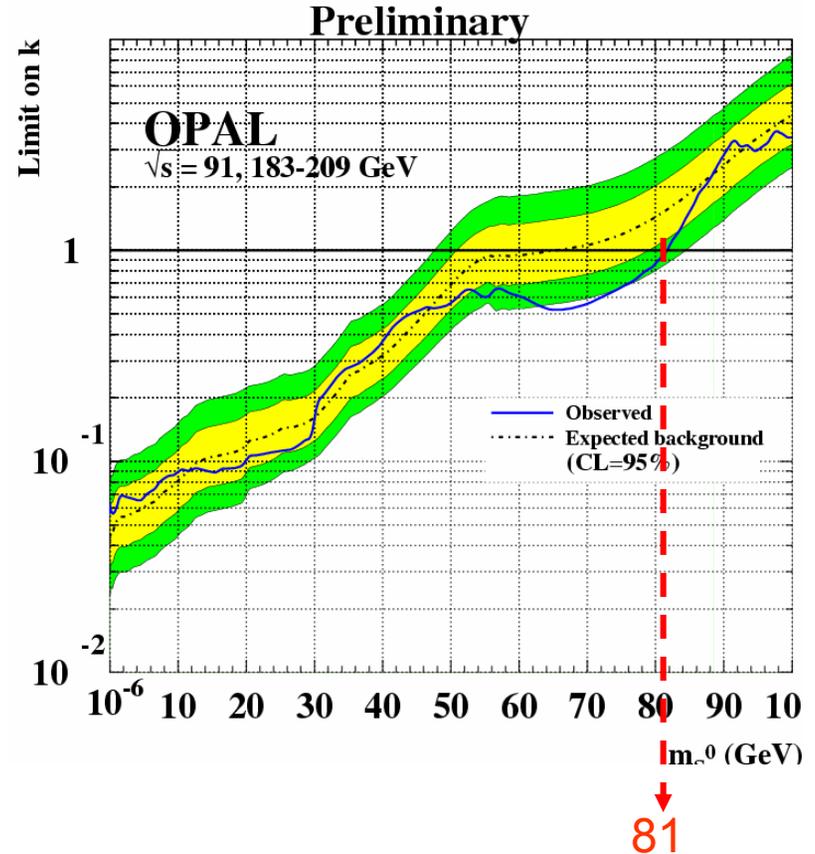
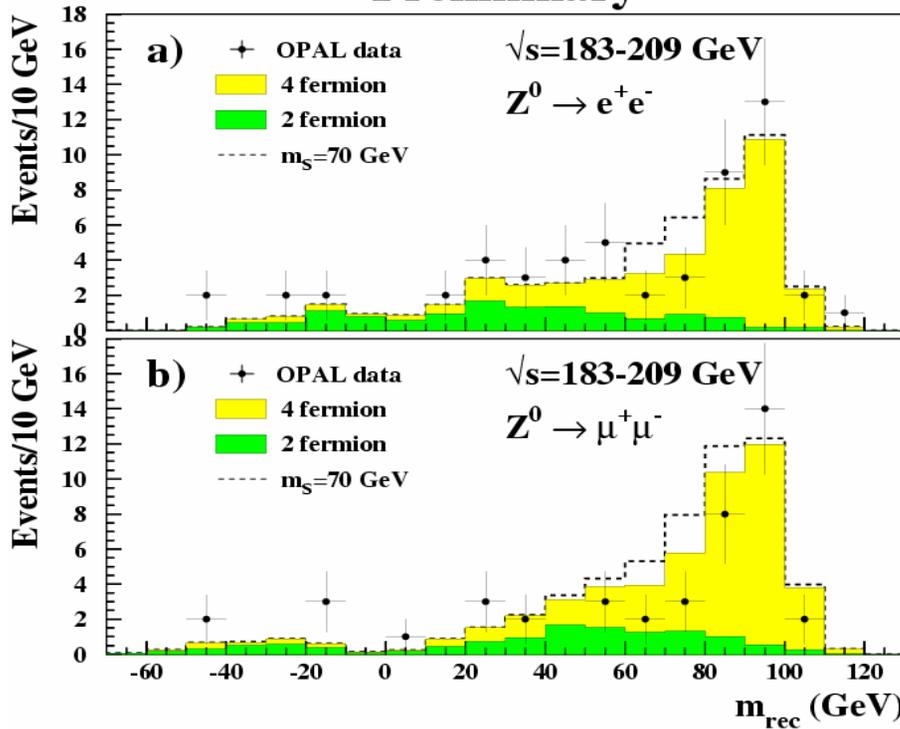
Jochen Cammin

- At LEP II, as the Higgs boson becomes lighter the Z boson is boosted and the leptons tend to be more energetic and collinear.
- This results in
  - Worse recoil mass resolution
  - Worse signal/bg separation



# Higgs Decay Mode Independent Searches

Preliminary

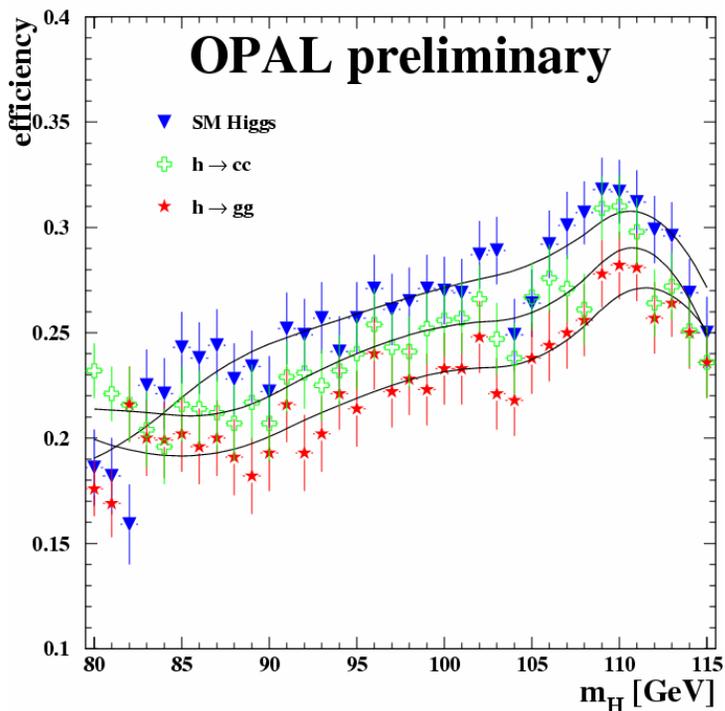


- Set limits on  $k = \frac{\sigma(ee \rightarrow s^0 z)}{\sigma(ee \rightarrow H_{SM}^0 z)}$
- SM Higgs is excluded up to 81 GeV irrespective of its decay mode

For more details see talk by Jochen Cammin

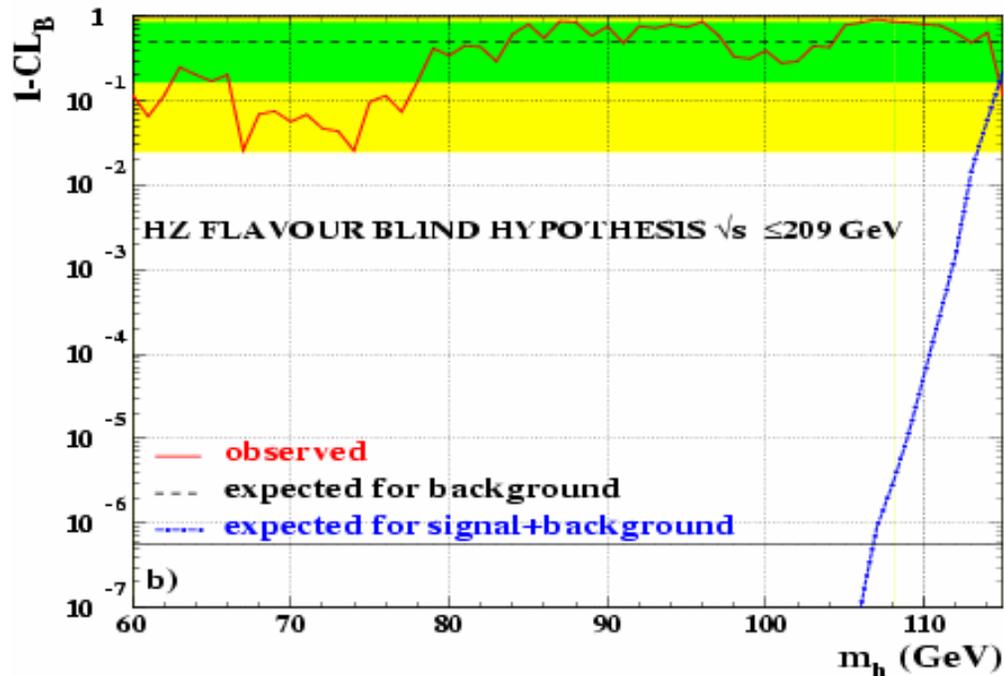
# Flavour Independent Higgs Decay Modes

- In various Models  $H \rightarrow bb$  suppressed
- Search for  $ee \rightarrow hZ \rightarrow qq\bar{q}\bar{q}, qq\nu\nu, qqll$
- Optimize event selection for each test mass
- Take lowest efficiency

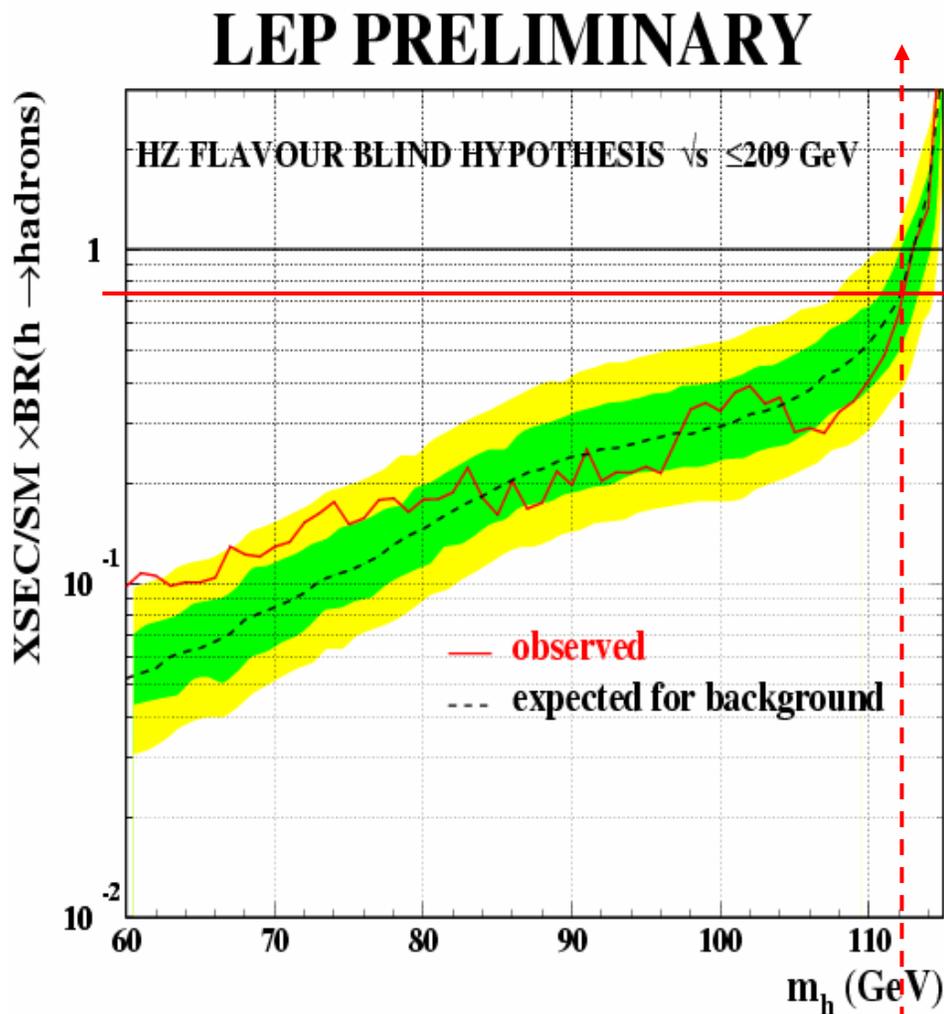


Compatibility with Background

**LEP PRELIMINARY**



# Flavour Independent Higgs Decay Modes

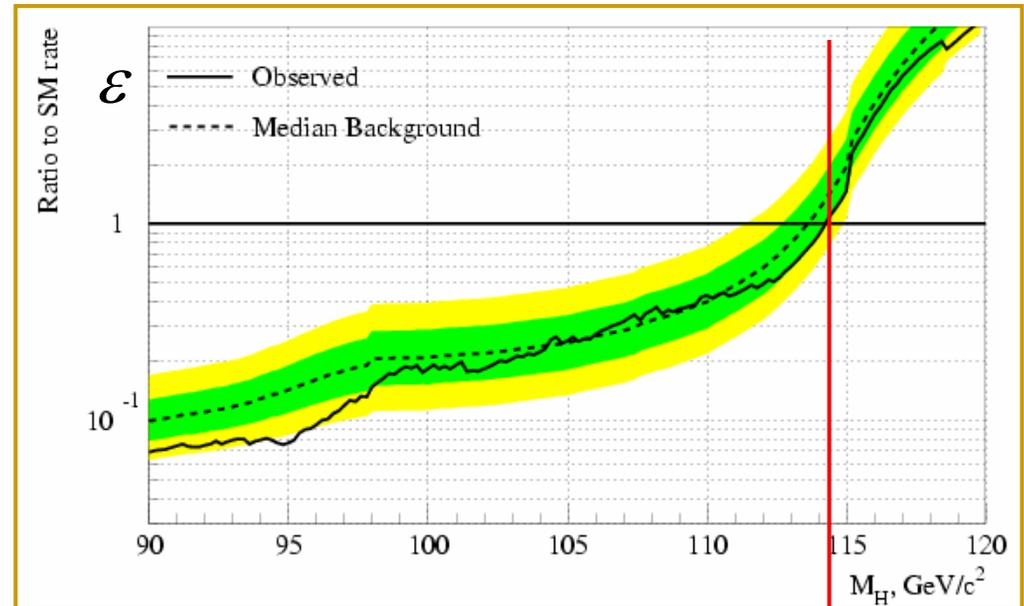
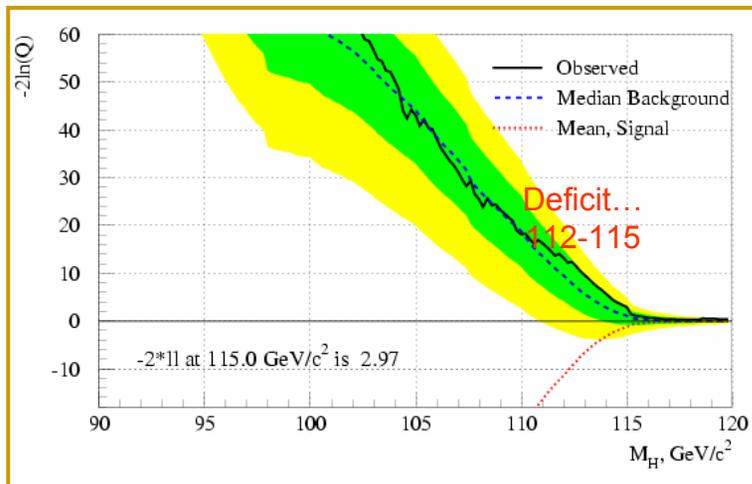


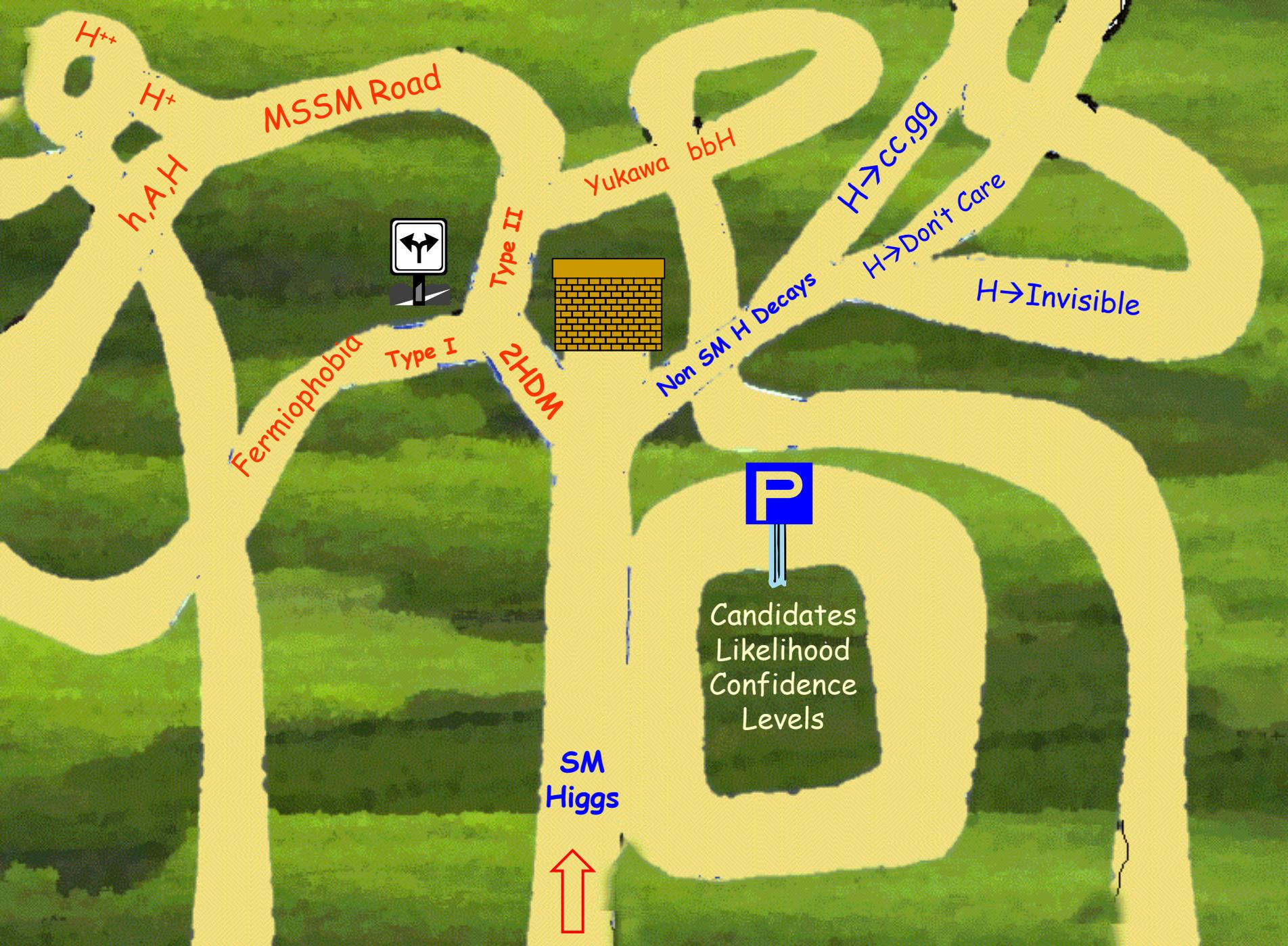
- 95% Upper Limit on the Production Cross-Section  $\times$  BR(hadrons)
- For SM-like BR of  $\sim 75\%$  (typical for  $m_H \sim 115$  GeV) a Higgs boson with mass below 112 GeV is excluded, this is almost as strong as the SM Higgs Boson limit (114.1 GeV)
- $m_H > 112.9$  (113.0) GeV With  $BR(H \rightarrow \text{hads}) = 1.0$

For Exotic Higgs Searches see talk by Marcel Stanitzki

# Search for Invisible Decaying Higgs Boson

- In SUSY models the Higgs boson might decay to neutralinos  $H \rightarrow \chi_0 \chi_0$
- Search for acoplanar jets or leptons ( $\mu, e$  and  $\tau$  for Delphi)
- Results are given in terms of upper limit on  $\varepsilon = \frac{\sigma_{HZ}}{\sigma_{HZ}^{SM}} BR(H \rightarrow invisible)$
- For  $BR=100\%$  invisibly decaying, a SM-like Higgs is excluded up to 114.2 (113.6) GeV at the 95% CL





# 2 Higgs Doublets Models (2HDM)

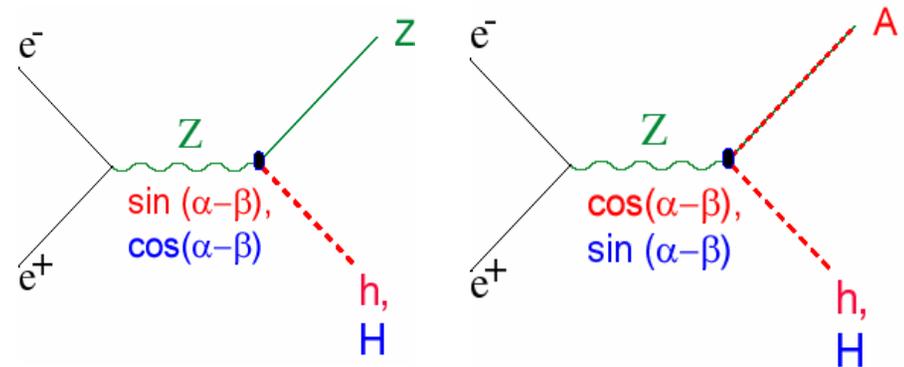
- Addition of doublets to the SM keeps the parameter  $\rho_{tree} = \frac{m_W}{m_Z \cos \mathcal{G}_w} = 1$

$$H_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \quad H_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

- Real parts mix with an angle  $\alpha$  to give the two neutral scalars  $h, H$
- Imaginary part (not eaten by Z) is the pseudo scalar  $A$
- In total **6 parameters** characterize the model:

$$m_{H^\pm}, m_h, m_H, m_A, \quad \text{tg}\beta = \frac{v_2}{v_1}, \quad \alpha$$

## Complementarity



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

$$\sigma_{hA} = \sigma_{HZ}^{SM} \lambda \cos^2(\alpha - \beta)$$

Couples to	Type I	Type II
d-type leptons	$H_2$	$H_1$
u-type quarks	$H_2$	$H_2$
d-type quarks	$H_2$	$H_2$
	$g_{hff} \sim \cos \alpha$ For $\alpha = \pi/2$ fermiophobic	e.g. MSSM

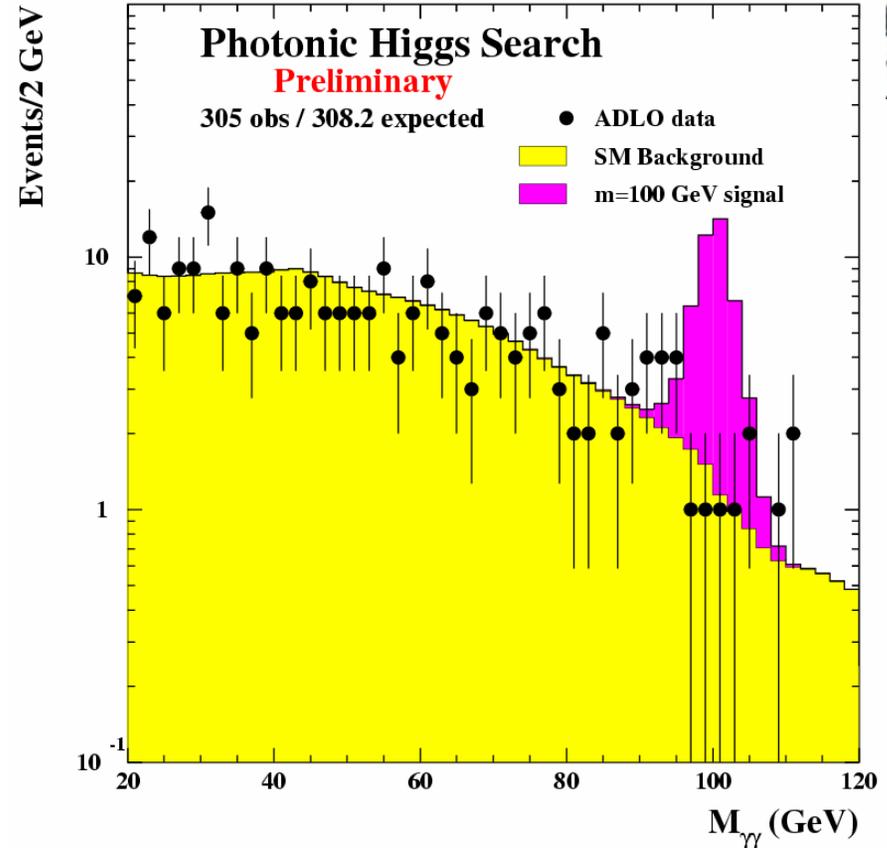
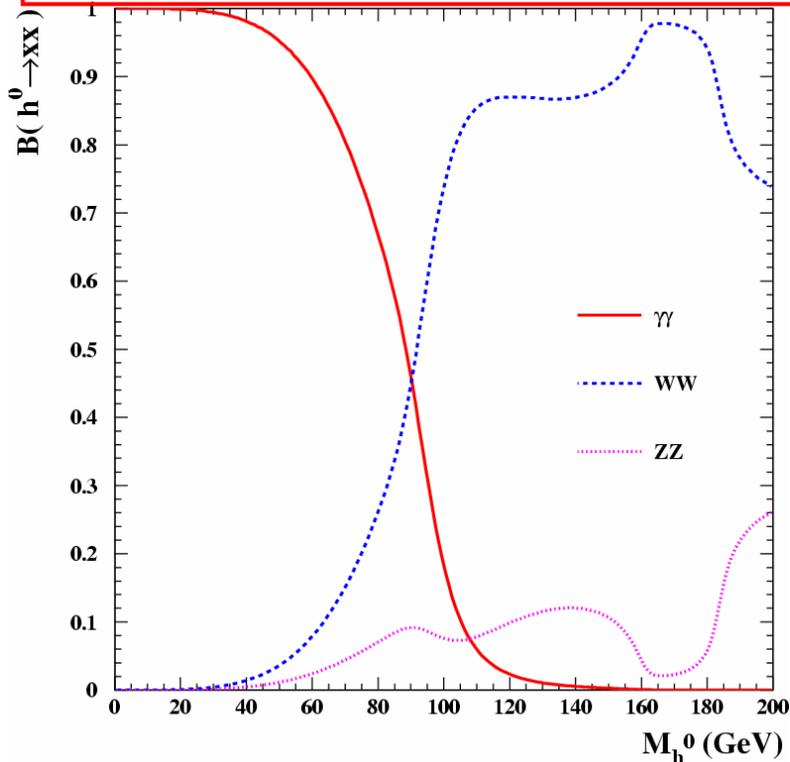
# 2HDM(I): One Higgs Over the Cuckoos Nest

- In 2HDM (type I) and other models  $H \rightarrow \gamma\gamma, WW$  dominantly.
- All experiments searched for the two-photons final state. L3 also searched for the WW decay mode.

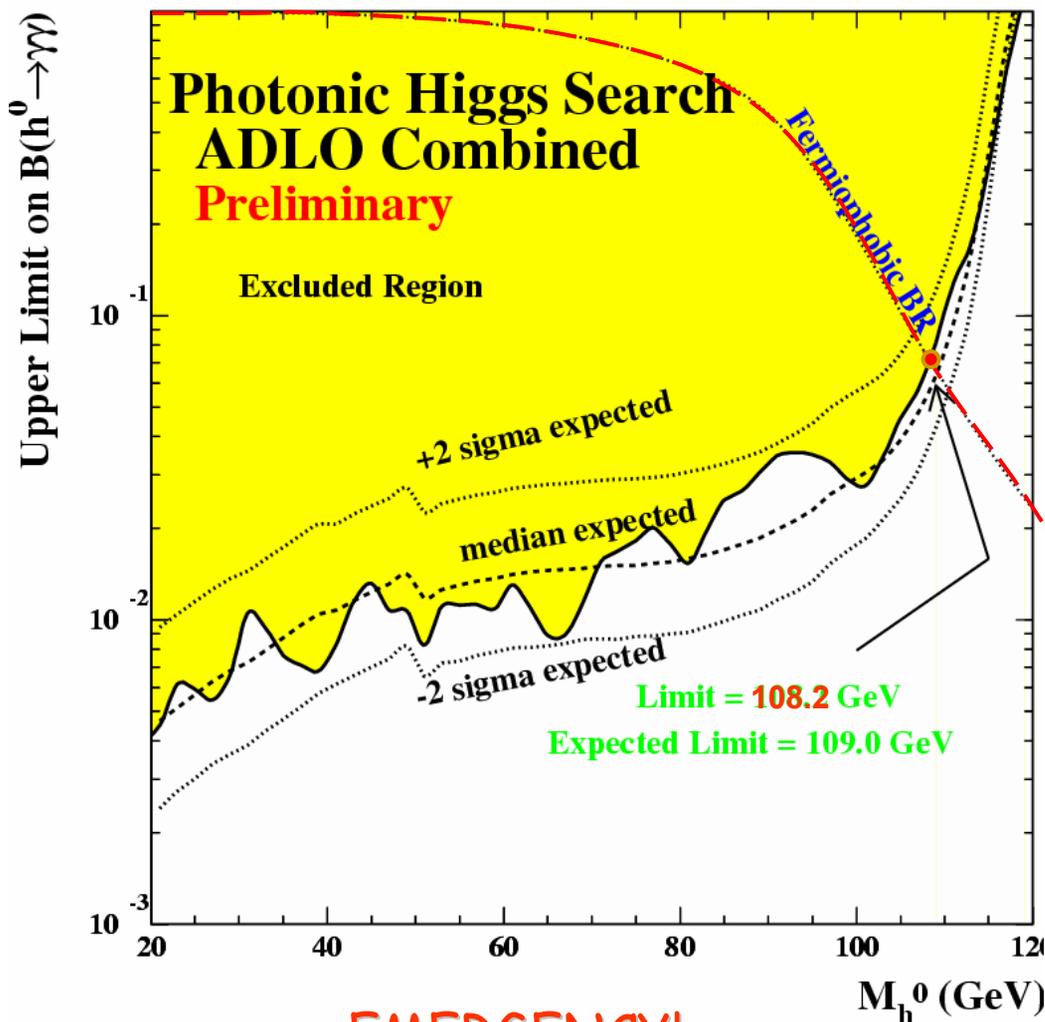
Fermiophobic  
Higgs



SM BRs with fermionic modes turned off



# One Higgs Over the Cuckoos Nest - Fermiophobic

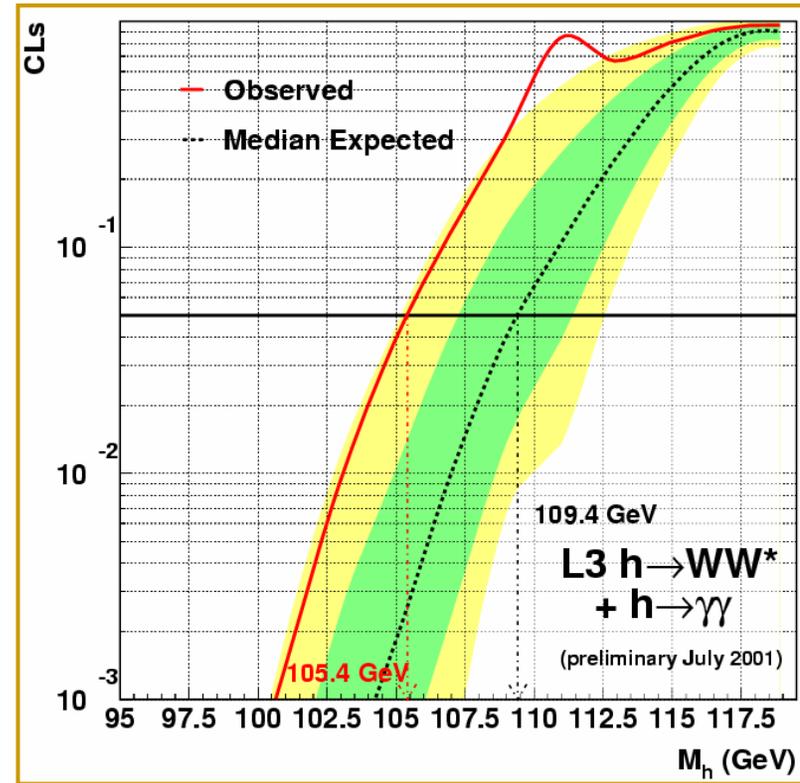
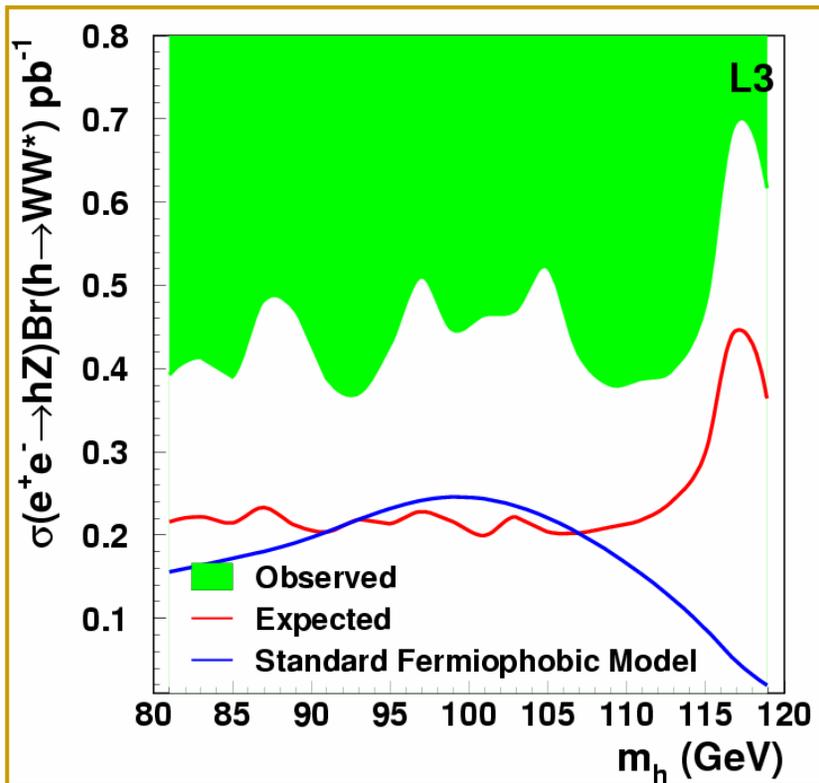


**EMERGENCY!**  
See Marcel Stanitzki Talk

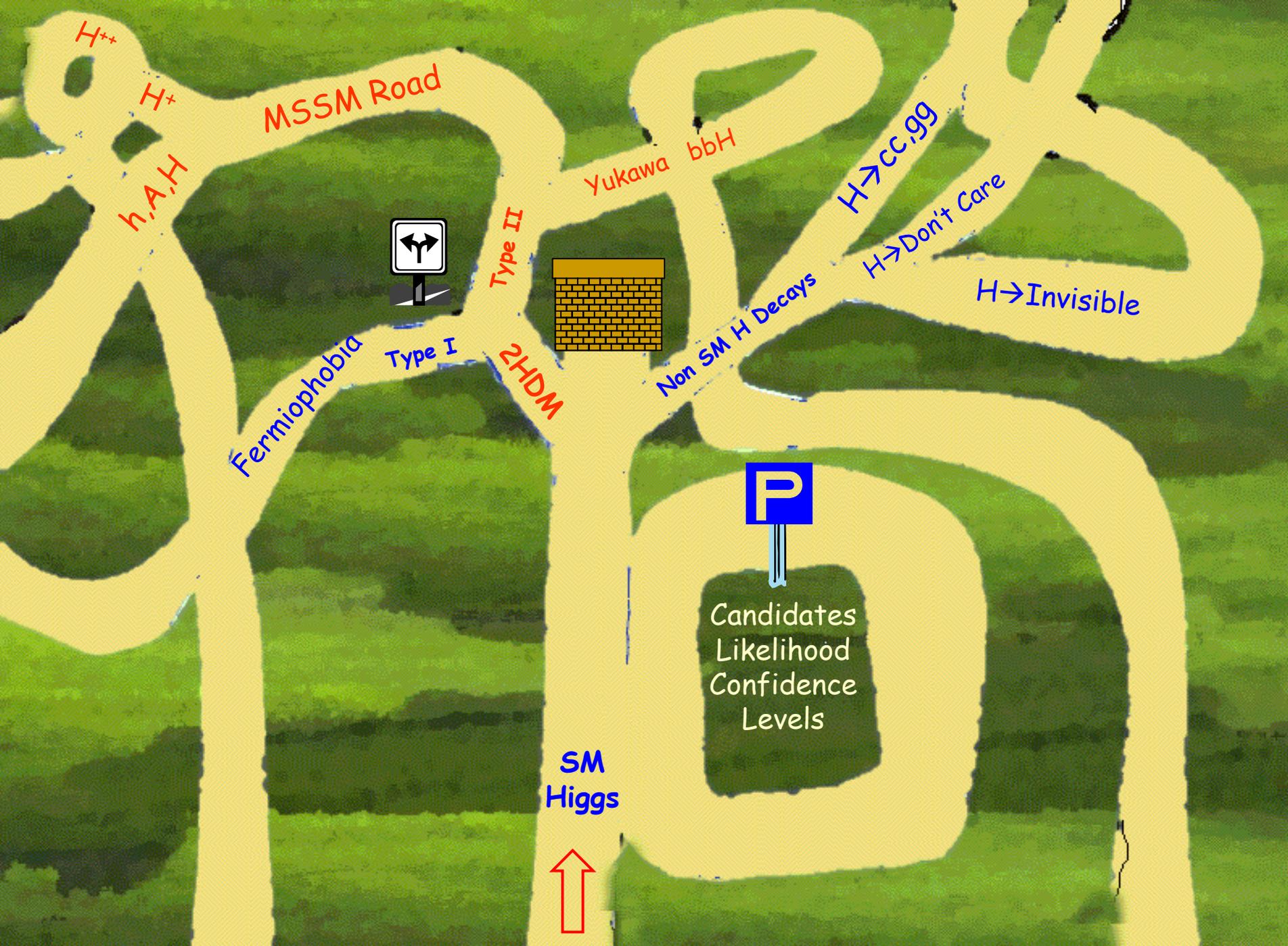
- Higher expected  $\sigma \times BR$  are easier to exclude
- LEP published a combined upper limit on the  $H \rightarrow \gamma\gamma$  BR
- Assuming a Fermiophobic Higgs one gets  $m_H > 108.2$  (109.0) GeV lower limit on the Higgs mass
- A 115 GeV Fermiophobic Higgs has a  $BR(H \rightarrow gg) < 0.3$  and is therefore NOT excluded
- Individual experiments limits based on  $H \rightarrow \gamma\gamma$ : 106.4 (Alep), 105.4 (L3)...

# Fermiophobic Higgs: $h \rightarrow WW$ Decay Mode

- $h \rightarrow WW^*$  ,
  - $hZ \rightarrow qqqq(nn), qqln(nn), qqln(qq)$  [Missing Energy Channels]     $hZ \rightarrow qqqq(qq)$  [6 jets]
- Small but consistent excess in observed events , e.g. in year 2000, in  $qqlv$  channel, except 57.4 events, observe 73 with an expected signal of 2.5 for  $m_h=115$  GeV. **Due to excess  $h \rightarrow WW$  alone cannot set a limit!**
- However, when combined with  $h \rightarrow \gamma\gamma$ , L3  $WW+\gamma\gamma$  has a sensitivity equivalent to the combined  $h \rightarrow \gamma\gamma$  LEP sensitivity, 109.4 GeV (expected) with 105.4 GeV observed



For more details see talk by Marcel Stanitzki



# Two Higgs Double Models (2HDM) type II

- $$hc\bar{c} : \frac{\cos \alpha}{\sin \beta}; \quad hb\bar{b} : -\frac{\sin \alpha}{\cos \beta};$$

$$Ac\bar{c} : \cot \beta; \quad Ab\bar{b} : \tan \beta$$

- Parameter Scan in General 2HDM(type II)

$$1 \leq m_h \leq 120 \text{ GeV}$$

$$3 \leq m_A \leq 2000 \text{ GeV}$$

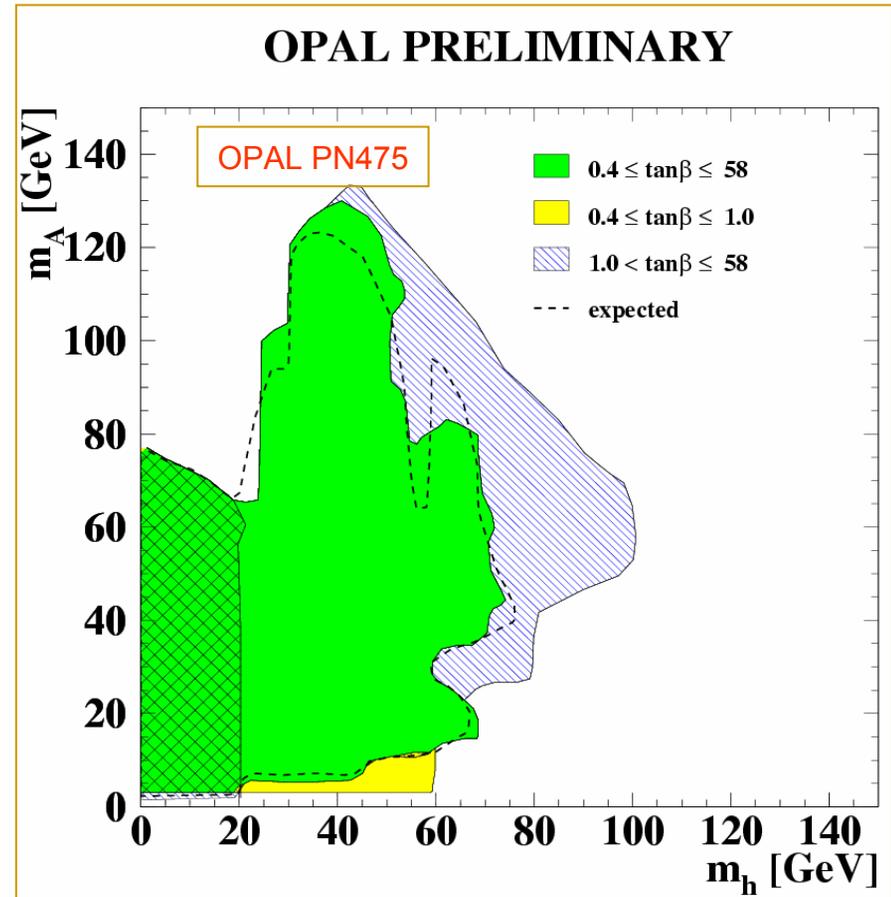
$$0.4 \leq \tan \beta \leq 58.0$$

$$\alpha = \pi/2, \pi/4, -\pi/4, -\pi/2$$

$m_{H^\pm}$  and  $m_H$

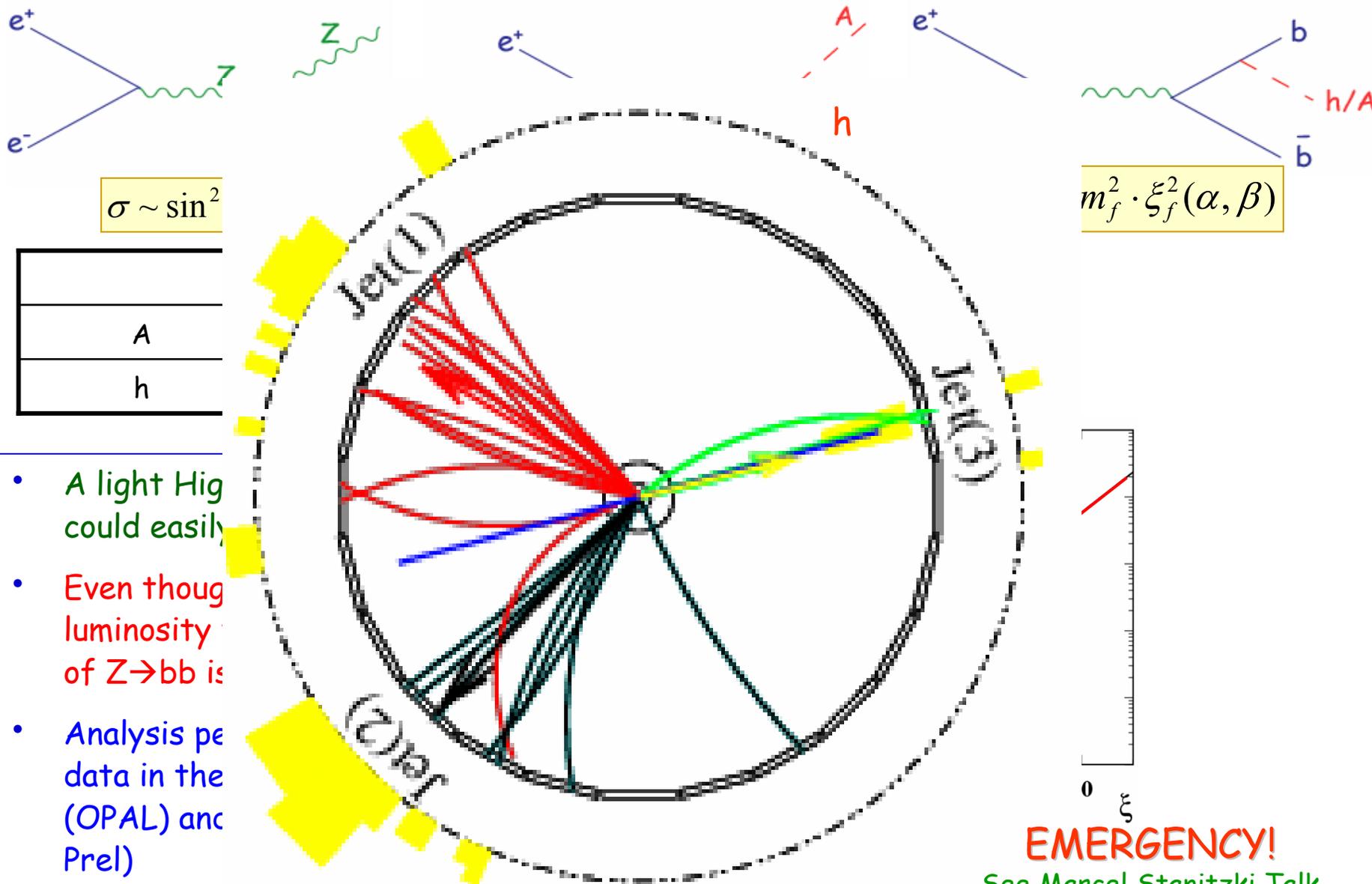
*beyond kinematic reach*

- Below  $\tan\beta=0.4$   $m_A$  and  $m_h$  not well defines, below  $m_A \sim 3$  radiative corrections unstable



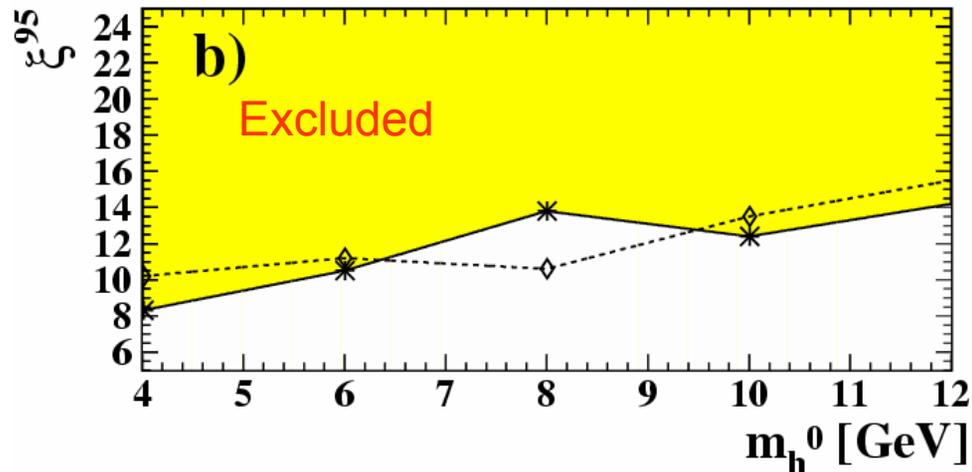
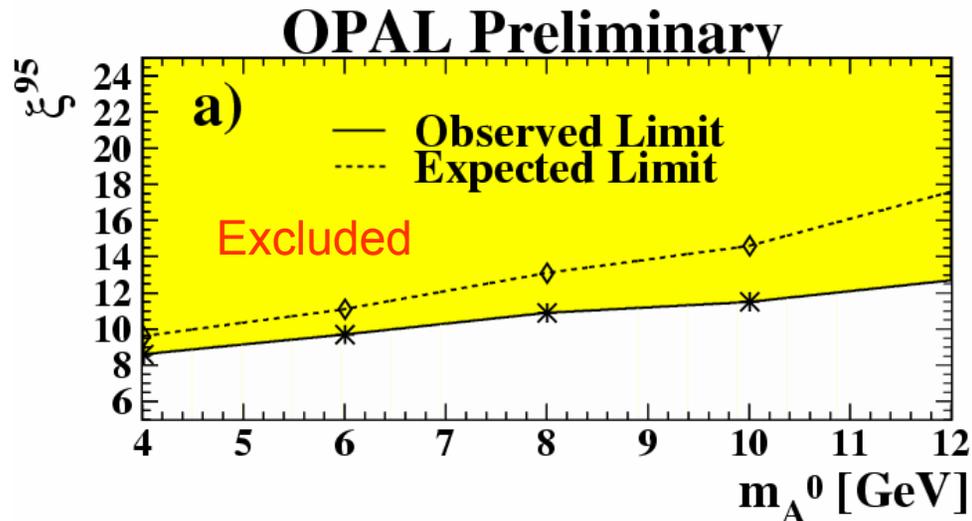
The lower you allow  $\tan\beta$  the exclusion is weaker

# Yukawa Production of Light Higgs



# Yukawa Production of Light Higgs

- With  $\text{BR}(h \rightarrow \tau\tau) = 100\%$  one finds limits on
  - $\xi_{S_A}^b \sim 8.6-11.6$  and
  - $\xi_{S_h}^b \sim 8.3-13.8$



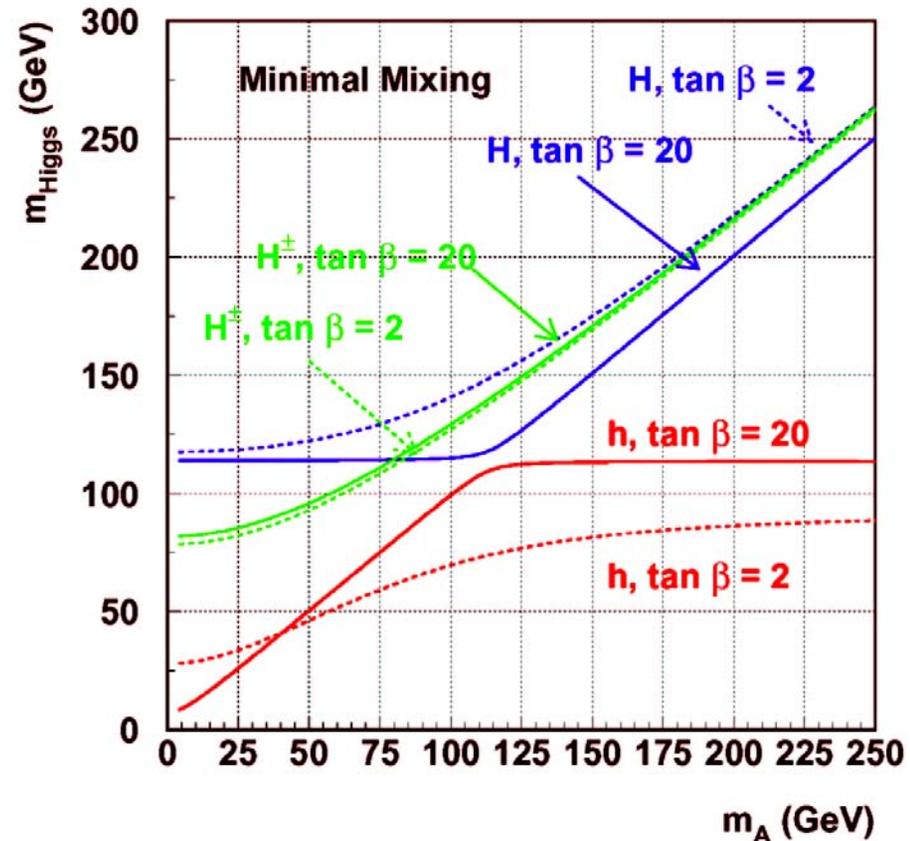
# MSSM

- MSSM is a 2HDM type II Supersymmetric Model
- Tree level: 2 pars ( $m_h, m_A$ ) or  $(\tan\beta, m_h)$  or  $(\tan\beta, m_A)$  determines  $\alpha$  and the mass spectrum

$$m_h = m_Z |\cos 2\beta| \leq m_Z$$

$$m_{H^+} < m_W$$

- “LEP 2 must discover the light Higgs boson or MSSM is out”, but ALLAS MSSM is saved by radiative corrections that shift the Higgs mass upward



As  $\tan\beta$  gets bigger  $m_h \sim m_A$  till it saturates at  $m_{h_{\max}}$

For low  $m_A$  there might also be sensitivity to the heavier H

# MSSM - Radiative Corrections

- $$m_h^2 = m_Z^2 \cos^2 2\beta \left[ f_1 \left( \frac{m_t^2}{v^2} \log \frac{m_s^2}{m_t^2} \right) + \frac{m_t^4}{v^2} f_2 \left( \tilde{A}_t, \log \frac{m_s^2}{m_t^2} \right) \right]$$

$$m_s = \sqrt{\frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{2}}$$

- $A_t$  The trilinear Higgs-stop coupling  $A_t g_{h\tilde{t}\tilde{t}^*} \varepsilon_{ij} H_2^j \tilde{Q}^i \tilde{t}_R^*$

- $A_t$  controls the mixing in the stop sector

$$\tilde{A}_t = A_t - \mu \operatorname{ctg} \beta$$

$$\begin{pmatrix} m_{\tilde{t}_L}^2 & m_t \tilde{A}_t \\ m_t \tilde{A}_t & m_{\tilde{t}_R}^2 \end{pmatrix} \Rightarrow m_{\tilde{t}_1}, m_{\tilde{t}_2}$$

- $\mu$  Higgs mixing parameter  $\mu \varepsilon_{ij} \hat{H}_1^i \hat{H}_2^j$

- Charged Higgs mass can go Below the W mass for small A mass

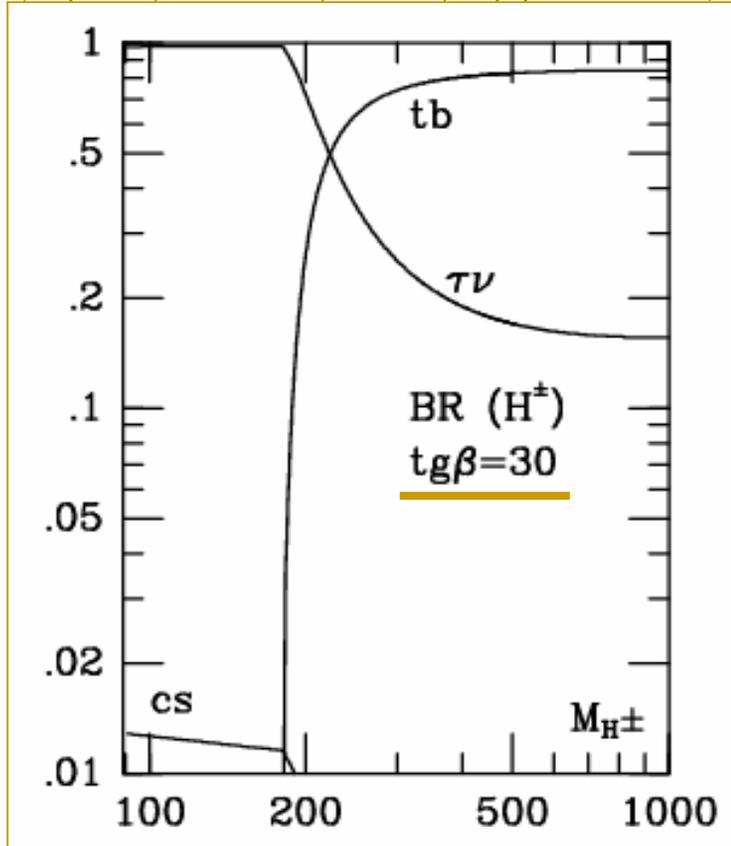
$$m_{H^\pm} \approx m_A^2 + m_W^2 + \frac{\mu^2 m_t^4}{\sin^2 \beta} f(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2)$$

# L3 Charged Higgs Anomaly

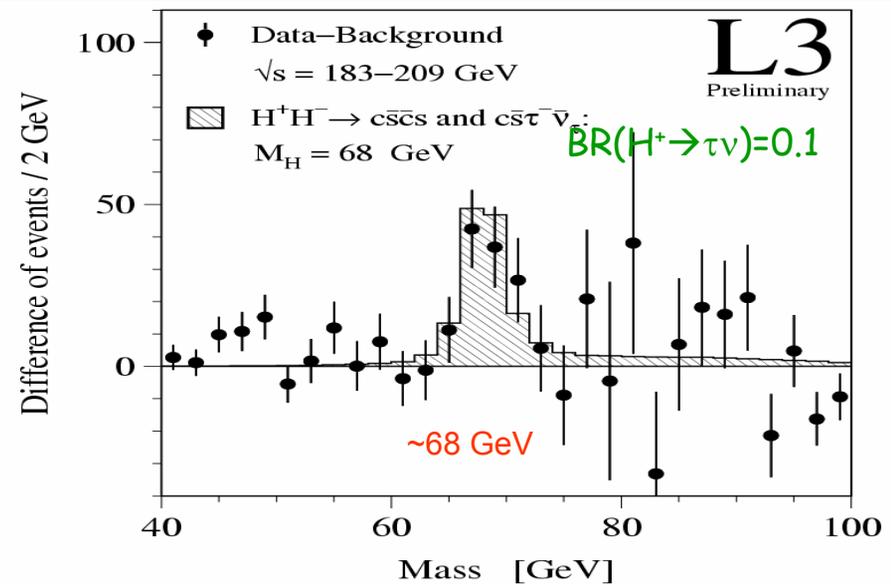
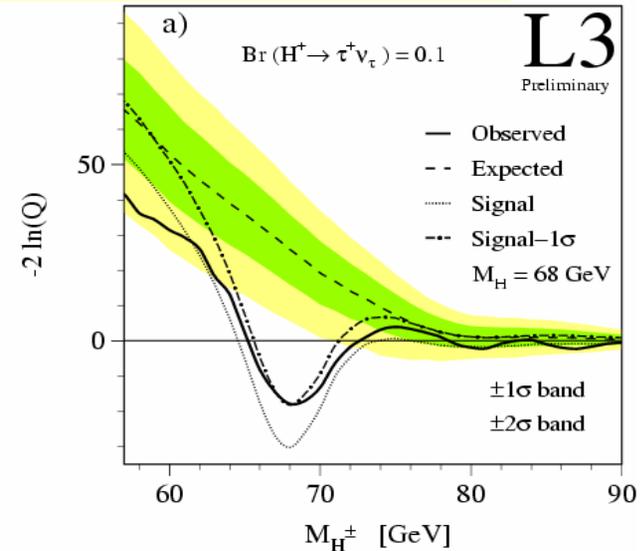
WORKING ASSUMPTION

$$BR(H^+ \rightarrow \tau^+ \nu) + BR(H^+ \rightarrow c\bar{s}) = 1$$

Djouadi, Kalinowski, Zerwas, hep-ph/9511342



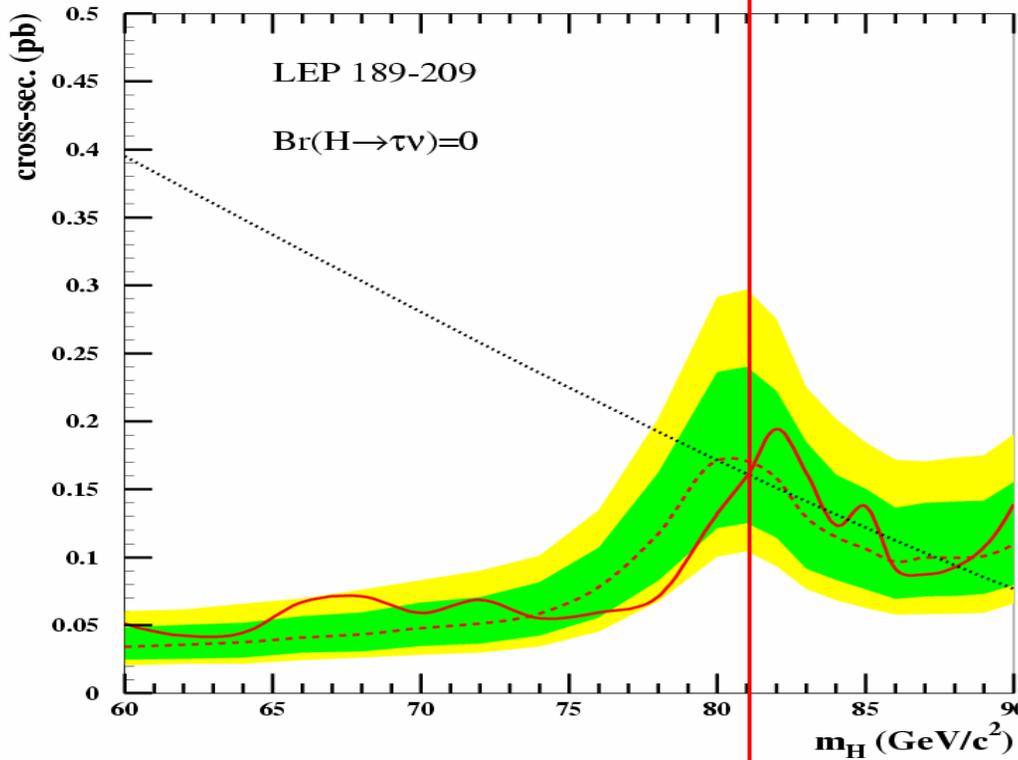
- This  $4.2\sigma$  anomaly has not been seen by any other experiment!



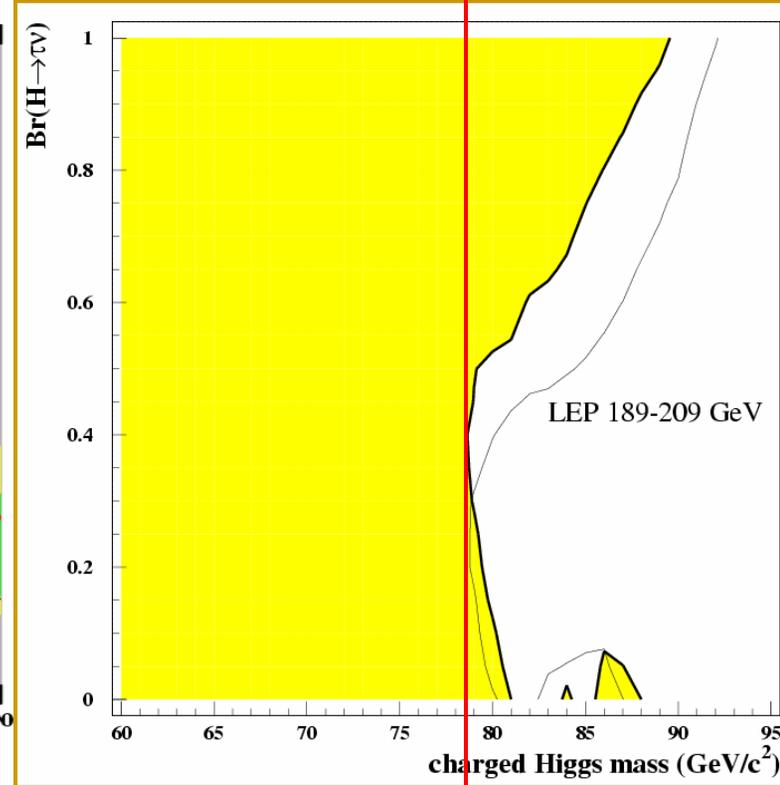
# Charged Higgs

WORKING ASSUMPTION

$$BR(H^+ \rightarrow \tau^+ \nu) + BR(H^+ \rightarrow c\bar{s}) = 1$$



81



78.6

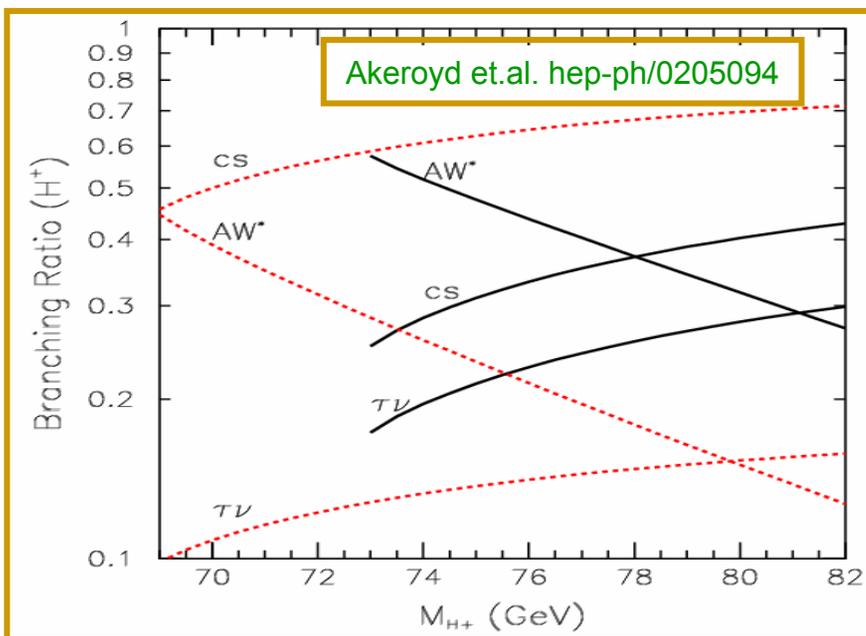
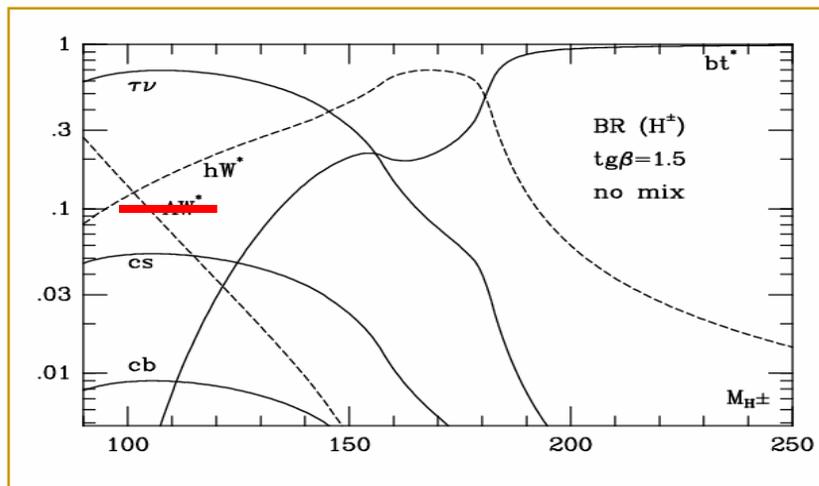
- There is loss of sensitivity near  $m_W$
- LEP combined limit

$$m_{H^+} > 81 \text{ GeV for } BR(H^+ \rightarrow \tau\nu) = 0$$

$$m_{H^+} > 78.6 \text{ GeV for any } BR(H^+ \rightarrow \tau\nu)$$

# Charged Higgs At Low $\tan\beta$

Djouadi, Kalinowski, Zerwas, hep-ph/9511342



- As  $\tan\beta$  gets lower the  $BR(H^+ \rightarrow AW^{*+})$  becomes dominant and the assumption of

$$BR(H^+ \rightarrow \tau^+ \nu) + BR(H^+ \rightarrow c\bar{s}) = 1$$

**BREAKS!**

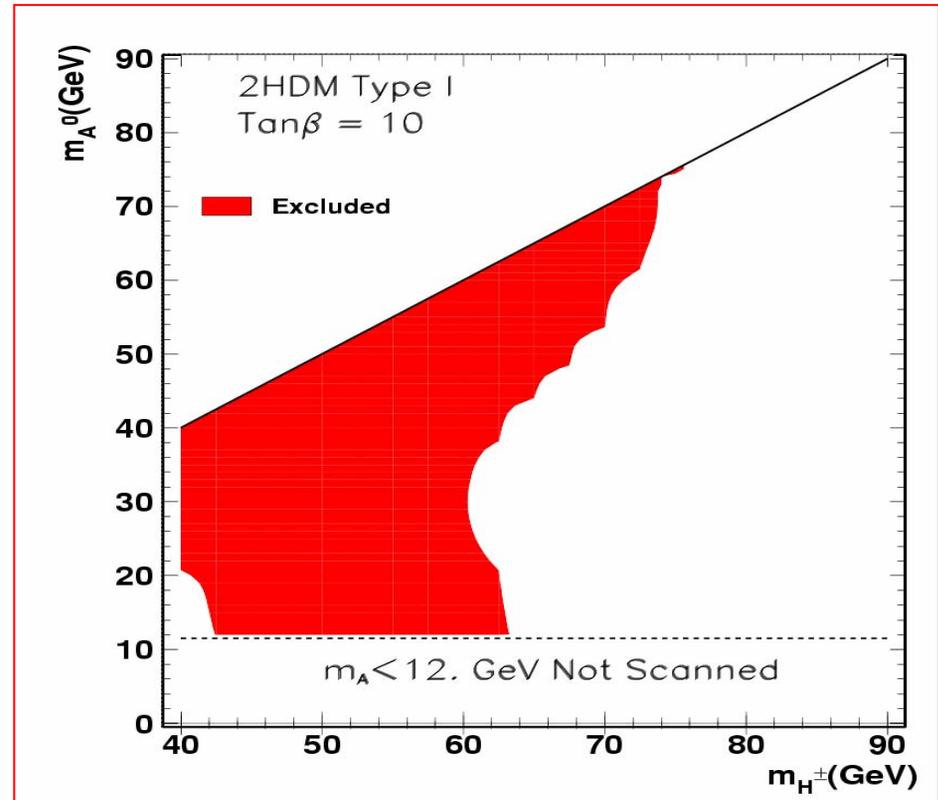
- The  $H^+ \rightarrow AW^{*+}$  decay mode must be taken into account!
- LEP has just now started to look into that (in the framework of 2HDM (II))
- However... next

**EMERGENCY!**

See Marcel Stanitzki Talk

$$H^+ \rightarrow AW^{+*}$$

- In type I 2HDM the  $H^+ \rightarrow AW^{+*}$  decay mode might be dominant for  $\tan\beta > 1$
- $A$  is assumed to decay for  $bb$ , so no scan was done for  $m_A < 12$  GeV
- OPAL searched for  $H^+H^- \rightarrow \tau\nu qqbb$ ,  $H^+H^- \rightarrow qqbb$ ,  $H^+H^- \rightarrow l\nu bb$



**EMERGENCY!**

See Marcel Stanitzki Talk

# Search for Doubly Charged Higgs Boson

- Doubly charged Higgs bosons,  $H^{\pm\pm}$  exist in LR symmetric models
- In LR symmetric models  $\sigma(ee \rightarrow H_L^{++} H_L^{--}) \neq \sigma(ee \rightarrow H_R^{++} H_R^{--})$
- $H^{++} \rightarrow e^+e^+, \mu^+\mu^+, \tau^+\tau^+, e^+\mu^+, \dots$
- $\Gamma(H^{++} \rightarrow \tilde{l}^+ l^+) \sim h_{H\tilde{l}^+ l^+}^2 \cdot m_{H^{++}}$
- Indirect constraints
 

$\mu^- \rightarrow e^- e^+ e^- \Rightarrow h_{He\mu} h_{Hee} < 4.7 \cdot 10^{-11} \text{ GeV} \cdot m_{H^{++}}^2$	Huitu-Maalampi Hep-ph/9410342
Bhabha $\Rightarrow h_{Hee}^2 < 9.7 \cdot 10^{-6} \text{ GeV} \cdot m_{H^{++}}^2$	
$\mu^+ e^- \rightarrow \mu^- e^+ \Rightarrow h_{Hee} \cdot h_{H\mu\mu} < 5.8 \cdot 10^{-5} \text{ GeV} \cdot m_{H^{++}}^2$	
- $h_{H\tau\tau} > 10^{-7} \rightarrow$  Decay at Interaction Point,  
smaller couplings  $\rightarrow$  long lived doubly charged (large impact parameter, kinked tracks, stable long lived).
- DELPHI searched only for  $\tau\tau$  decays but all possible lifetimes,  
OPAL for all possible decay channels assuming decay at IP

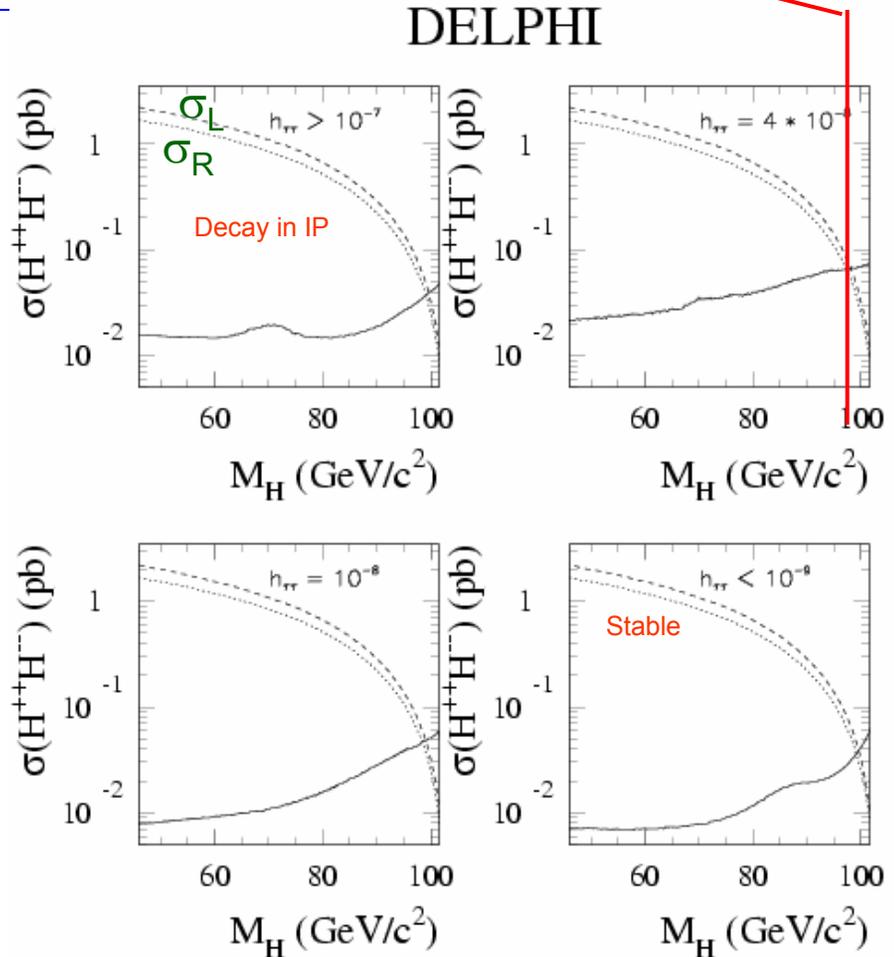
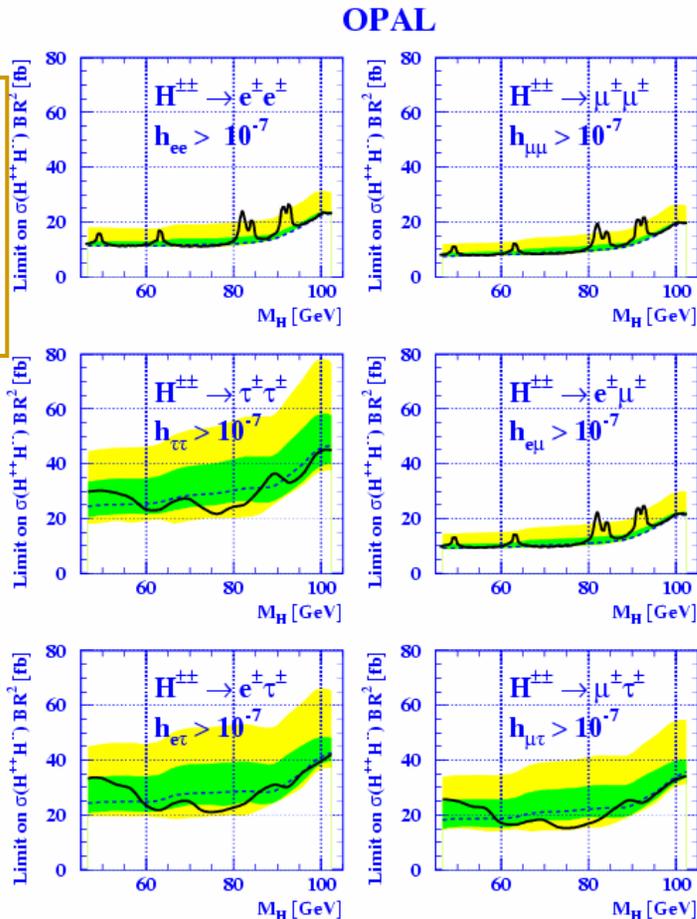
**EMERGENCY!**

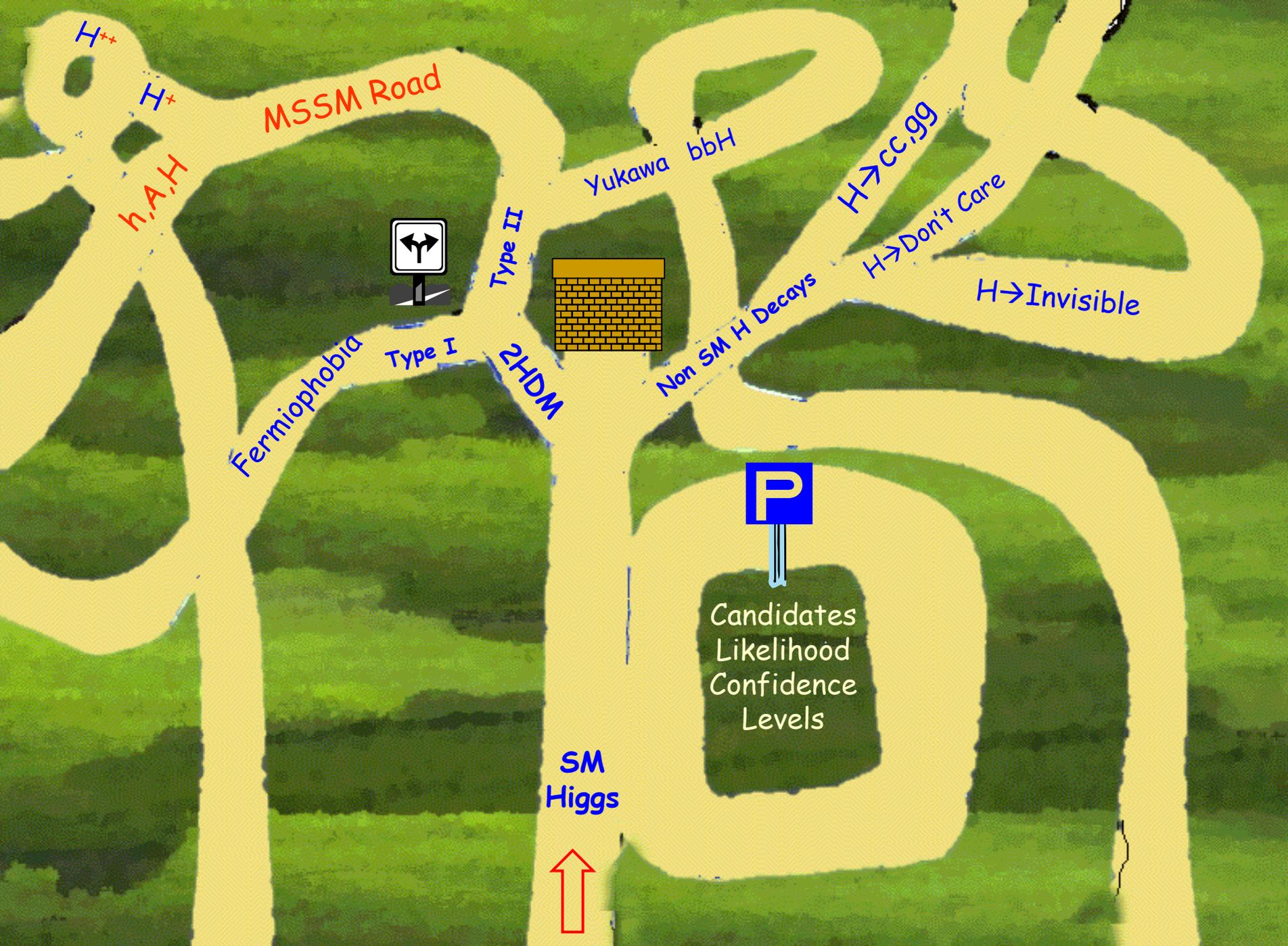
See Marcel Stanitzki Talk

# Search for Doubly Charged Higgs Boson

- For  $h_{H\tau\tau} > 10^{-7}$  OPAL/DELPHI set limits  $m(H_L^{++}) > 99.0/99.6$  GeV  
 $m(H_R^{++}) > 98.5/99.1$  GeV
- For all possible lifetimes DELPHI sets a limit  $m(H^{++}) > 97.3$  GeV

OPAL sets limits on production cross sections  
 All Decays in IP





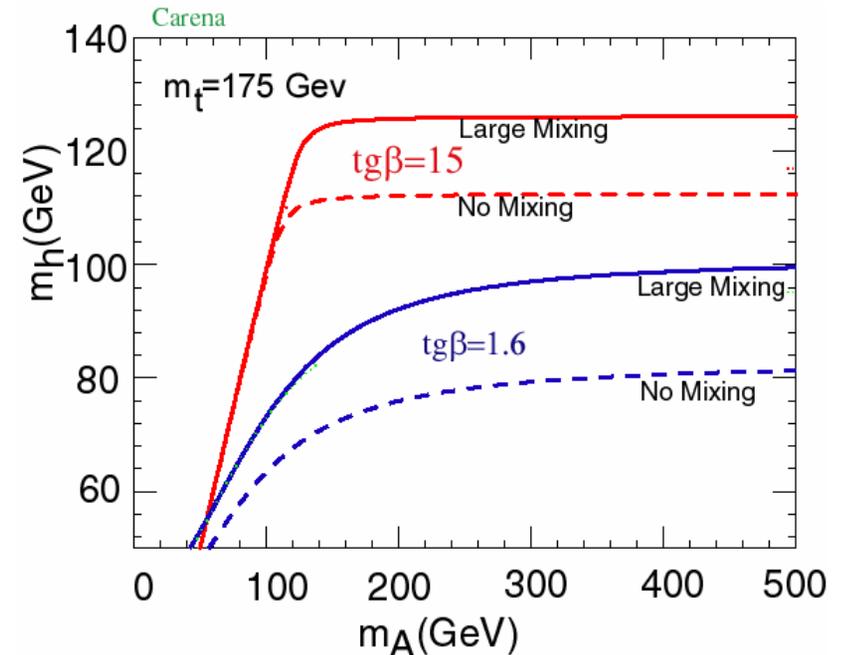
# Benchmarks

Carena, Heinemeyer, Wagner and Weiglein, hep-ph/9912223

Benchmark	Mass $\mu$	Parameters $X_t = A_t - \mu / \tan \beta$	$A_b$	$M_{SUSY}$	$M_{gluino}$	$M_h^{\max}$
No - Mixing	- 200	0	$A_t$	1000	800	~ 118
$m_h$ Max	- 200	2000	$A_t$	1000	800	~ 130
Large $\mu$	1000	- 300	$A_t$	400	200	~ 108

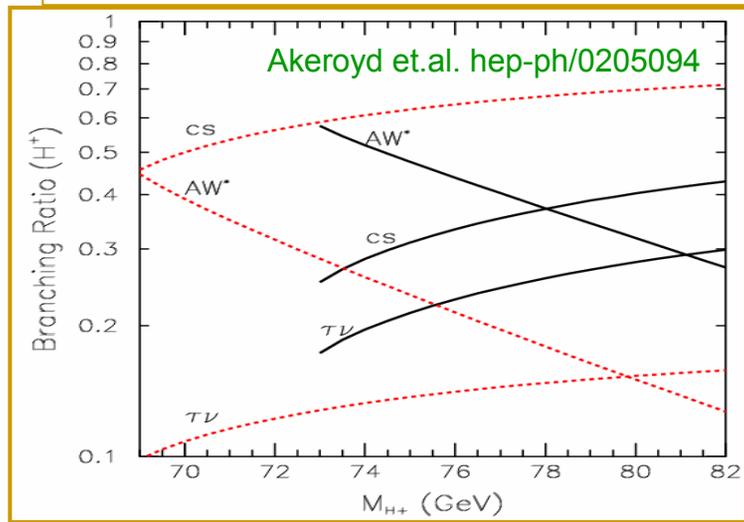
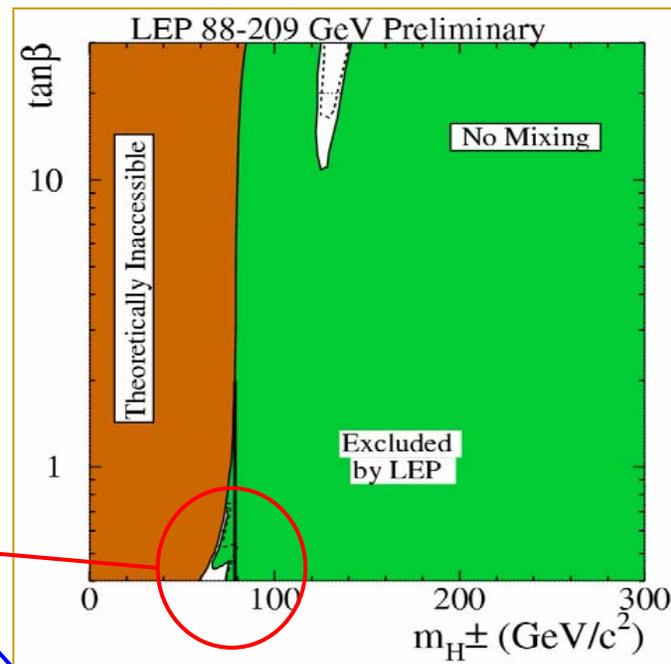
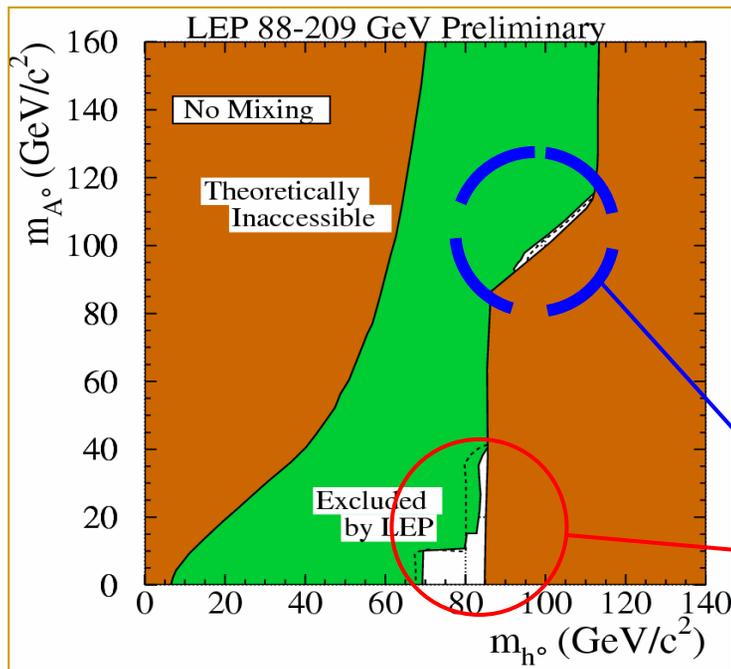
The Max  $m_h$  scenario was designed to yield the maximal value of the higgs mass

The Large  $\mu$  scenario is designed to produce suppressed Higgs to bb decays, yet either the h or the H are kinematically accessible at LEP 2.



Analysis is done using FeynHiggsDecay (Heinemeyer, Hollik, Weiglein '98)  
Incorporating HDecay (Djouadi, Kalinowski, Spira), [www.feynhiggs.de](http://www.feynhiggs.de)

# Minimal Mixing

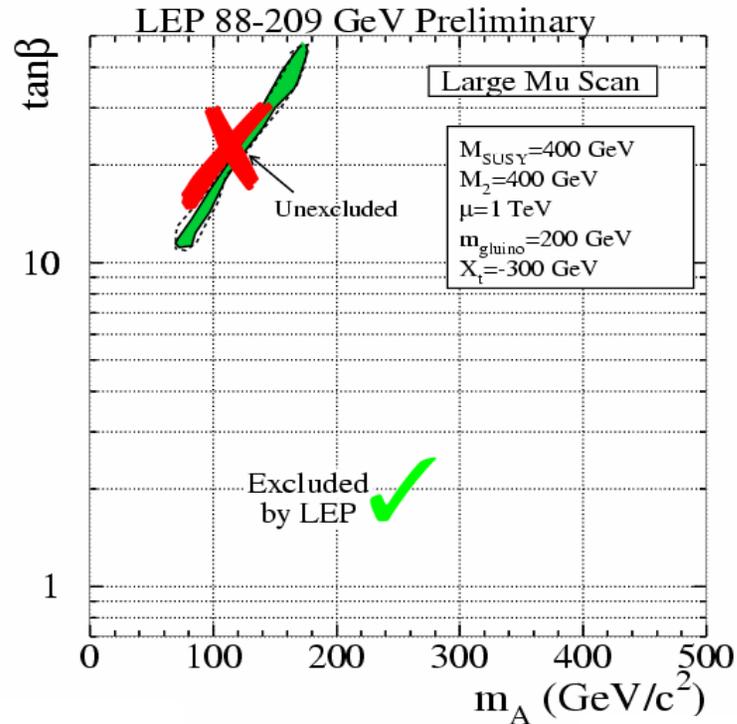
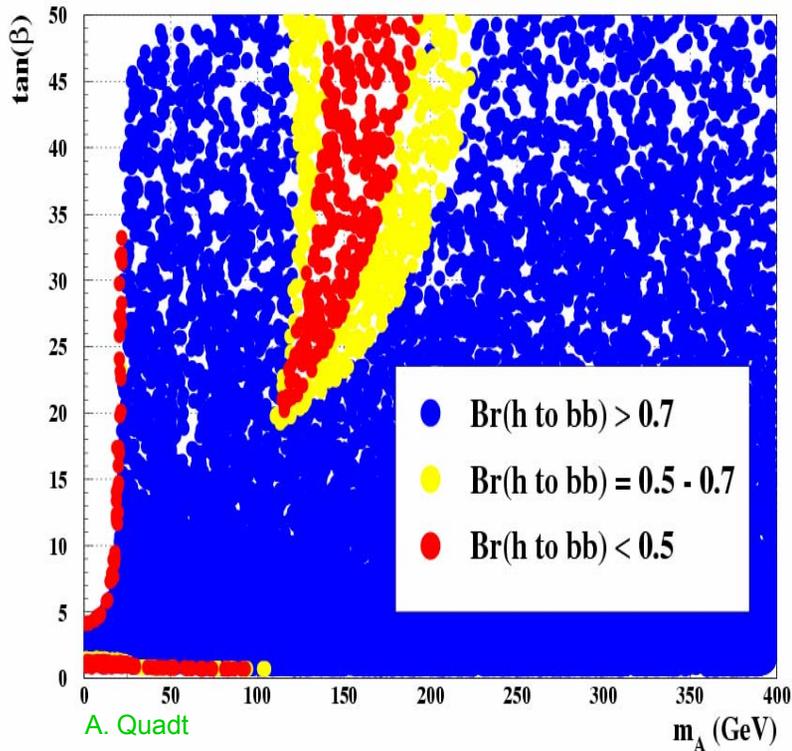


In this region  $\tan\beta \sim 0.4$  and  $m_{H^\pm} \sim 74$  GeV. Dedicated searches to  $H^\pm \rightarrow AW^*$  and flavour independent searches can help. An kinematical reach.

This would have probably been covered with a mild update of LEP energy. Part of this region is already covered by DELPHI flavour independent searches. This region will probably be completely covered in the next LEP iteration.

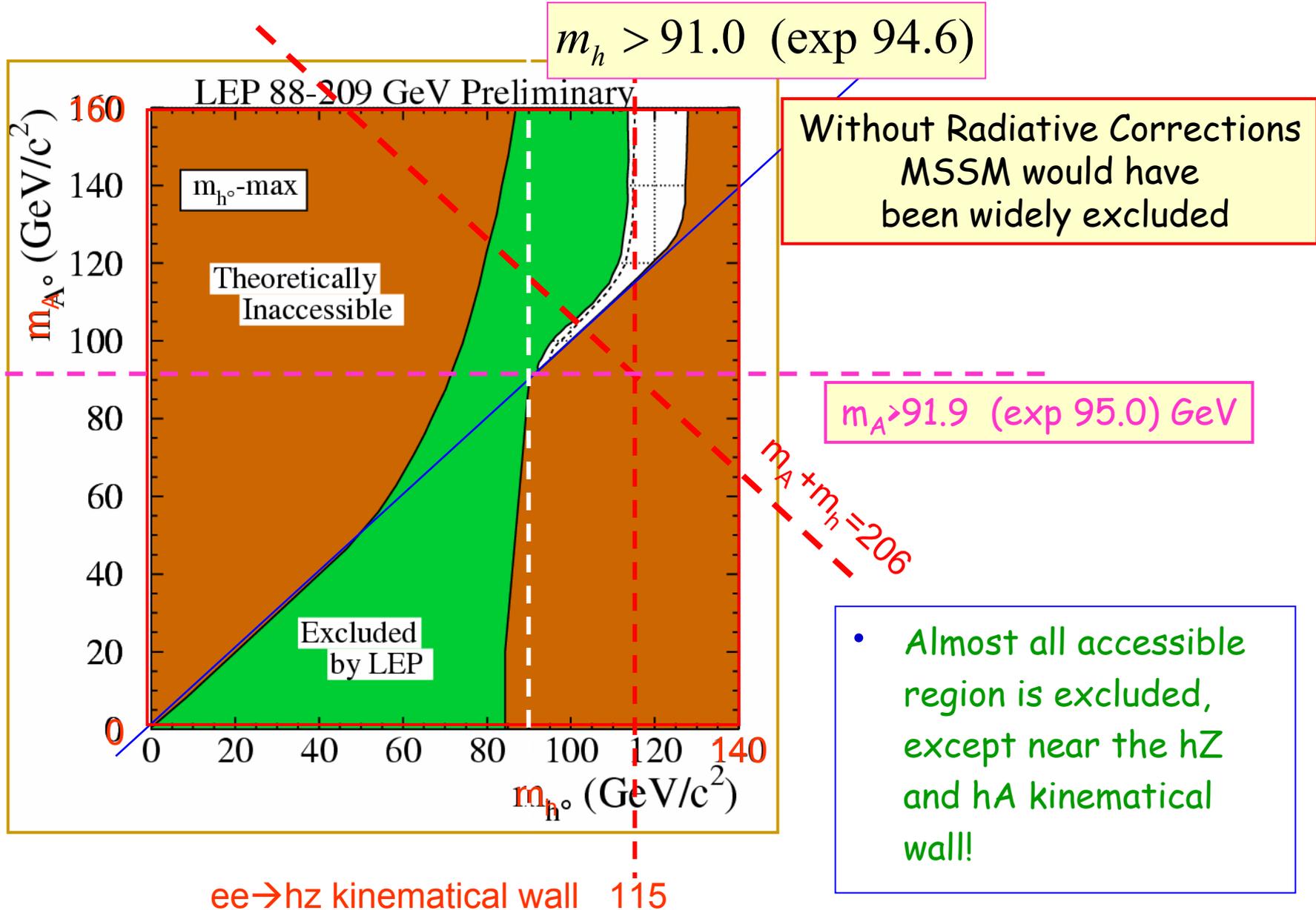
# Large $\mu$ Scenario

March 2001  $\rightarrow$  July 2001

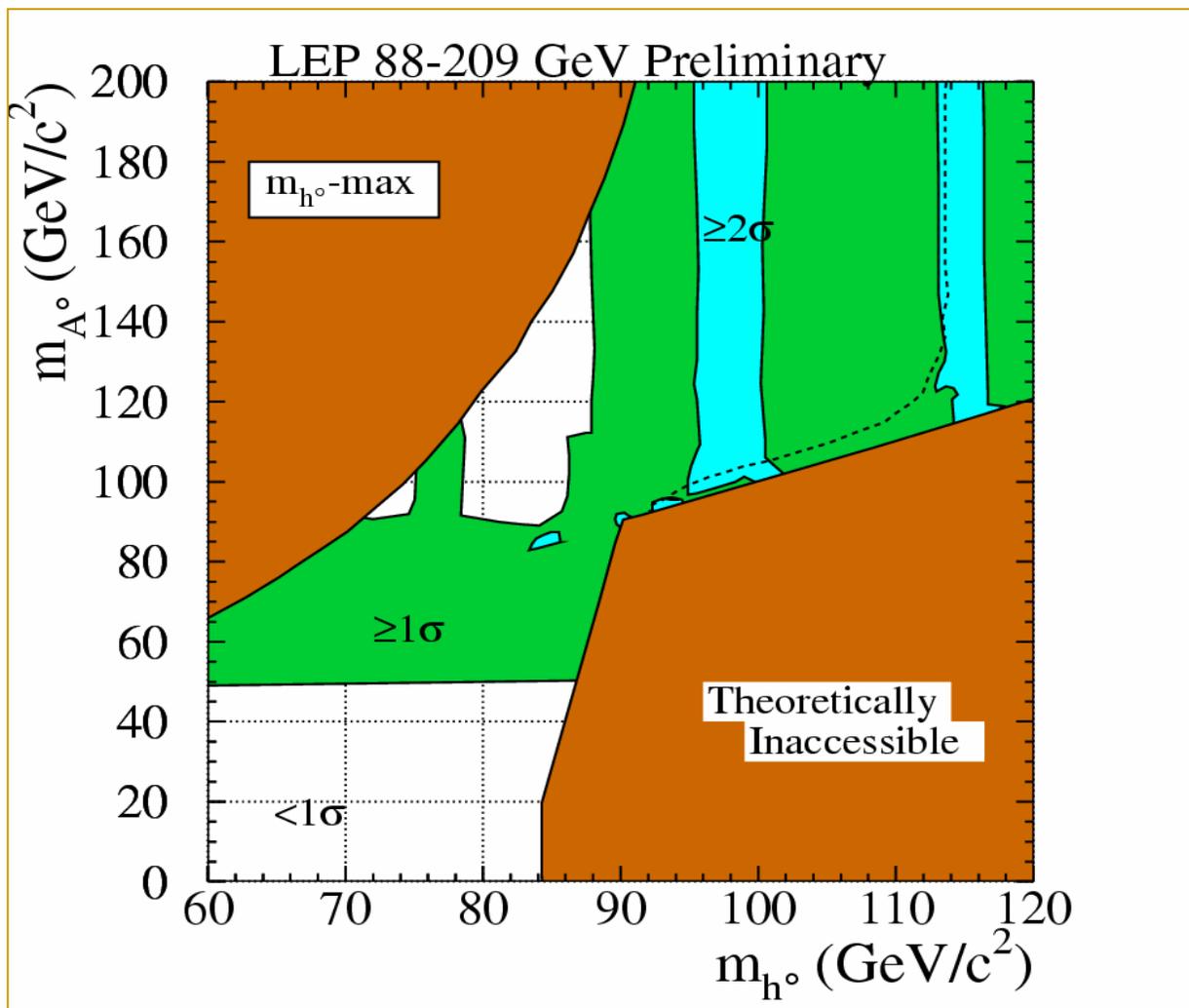


- With the flavour independent searches the all pre-LEP II defined region is now excluded!

# Maximal $m_h$

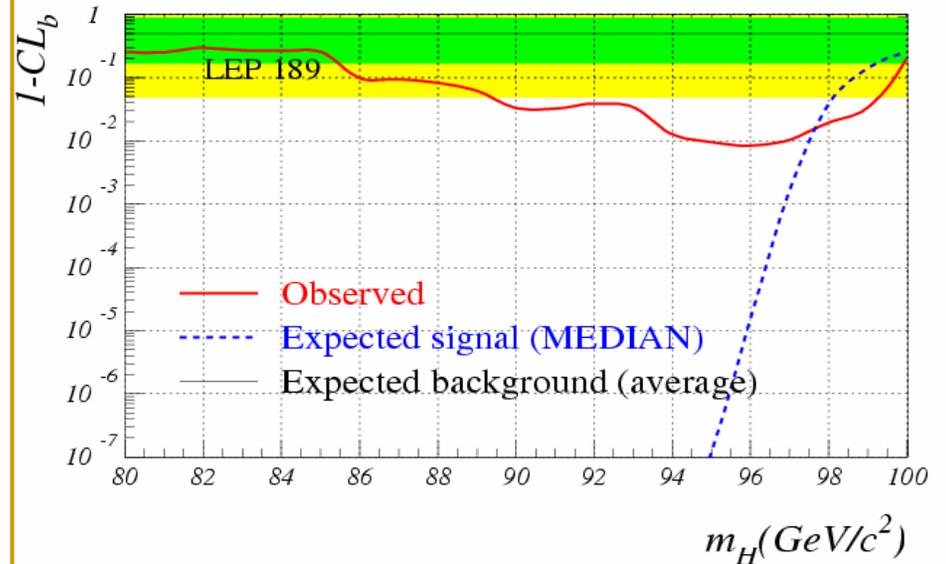
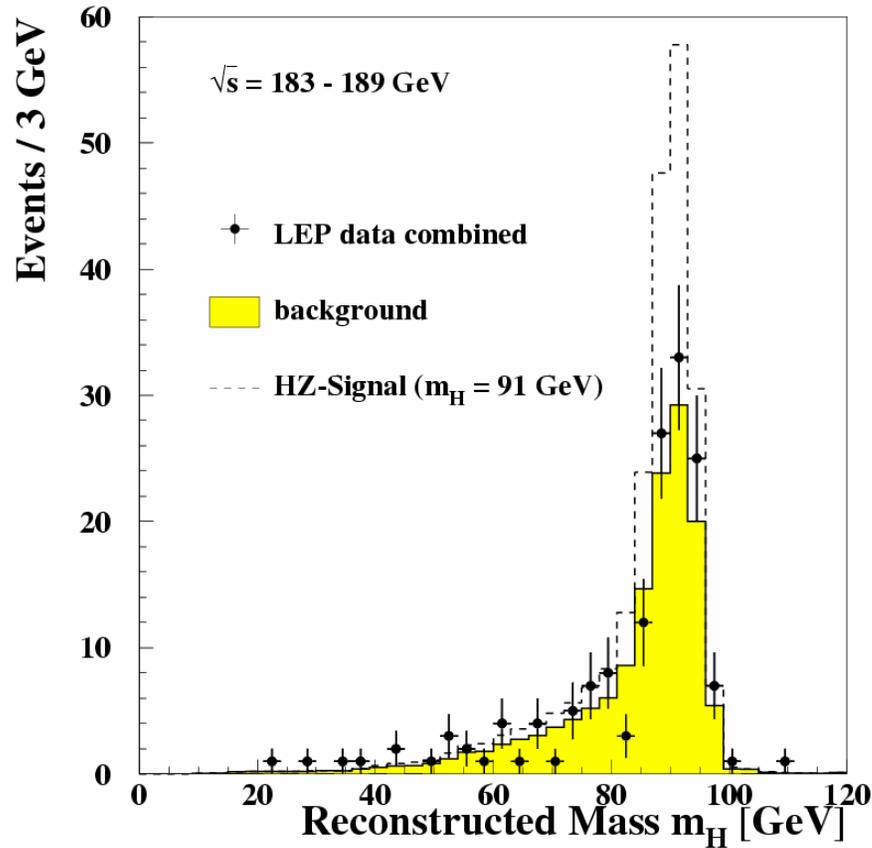


# Mh-Max Scenario - A Closer Look

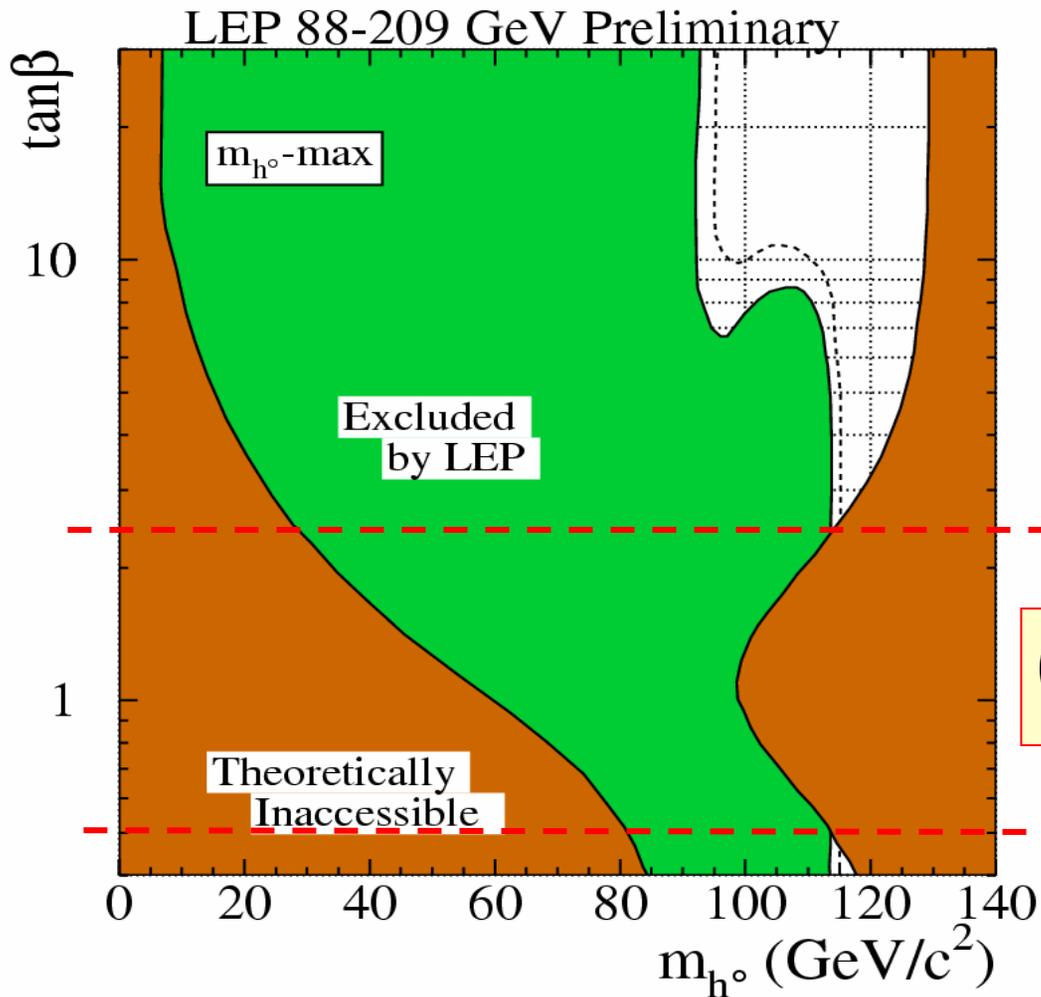


- Exclusion at the  $2\sigma$  level does not mean there cannot be an excess at the  $2\sigma$  level!
- You see something but its not what you exccpect from your model!
- Excess in LEP 189 (at  $\sim 97$  GeV) and LEP 206 ( $\sim 115$ ) is seen

# Excess 189



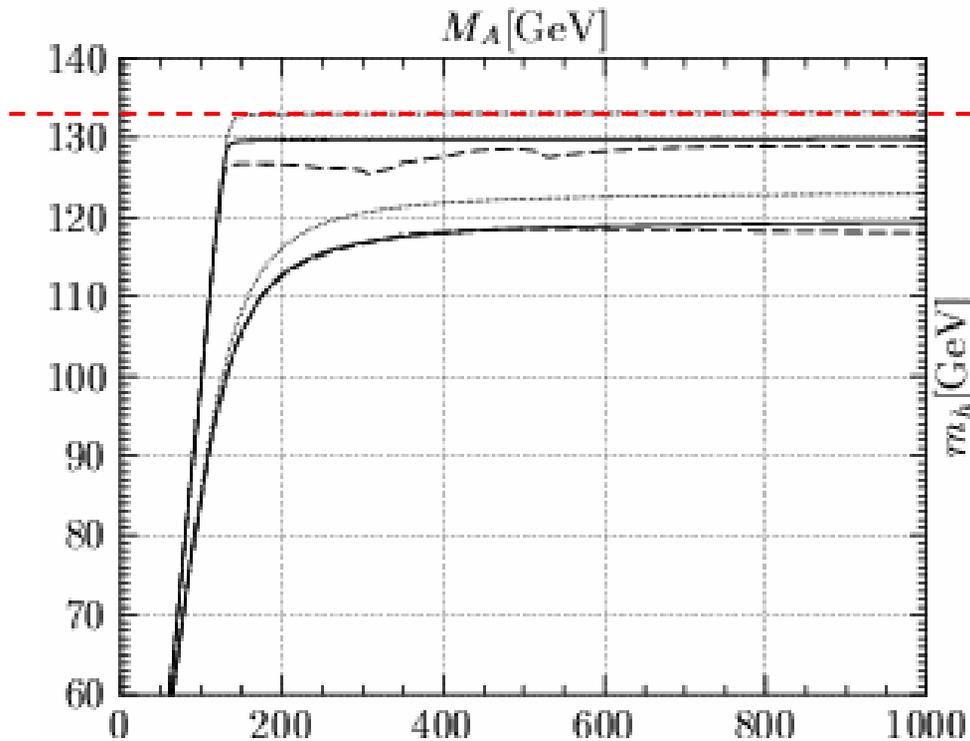
# Maximal $m_h$



For more details on  
MSSM searches and  
individual experiments  
results including final  
results from Aleph see  
talk by Elizabetha Locci

$$0.5 < \text{tg}\beta < 2.4$$

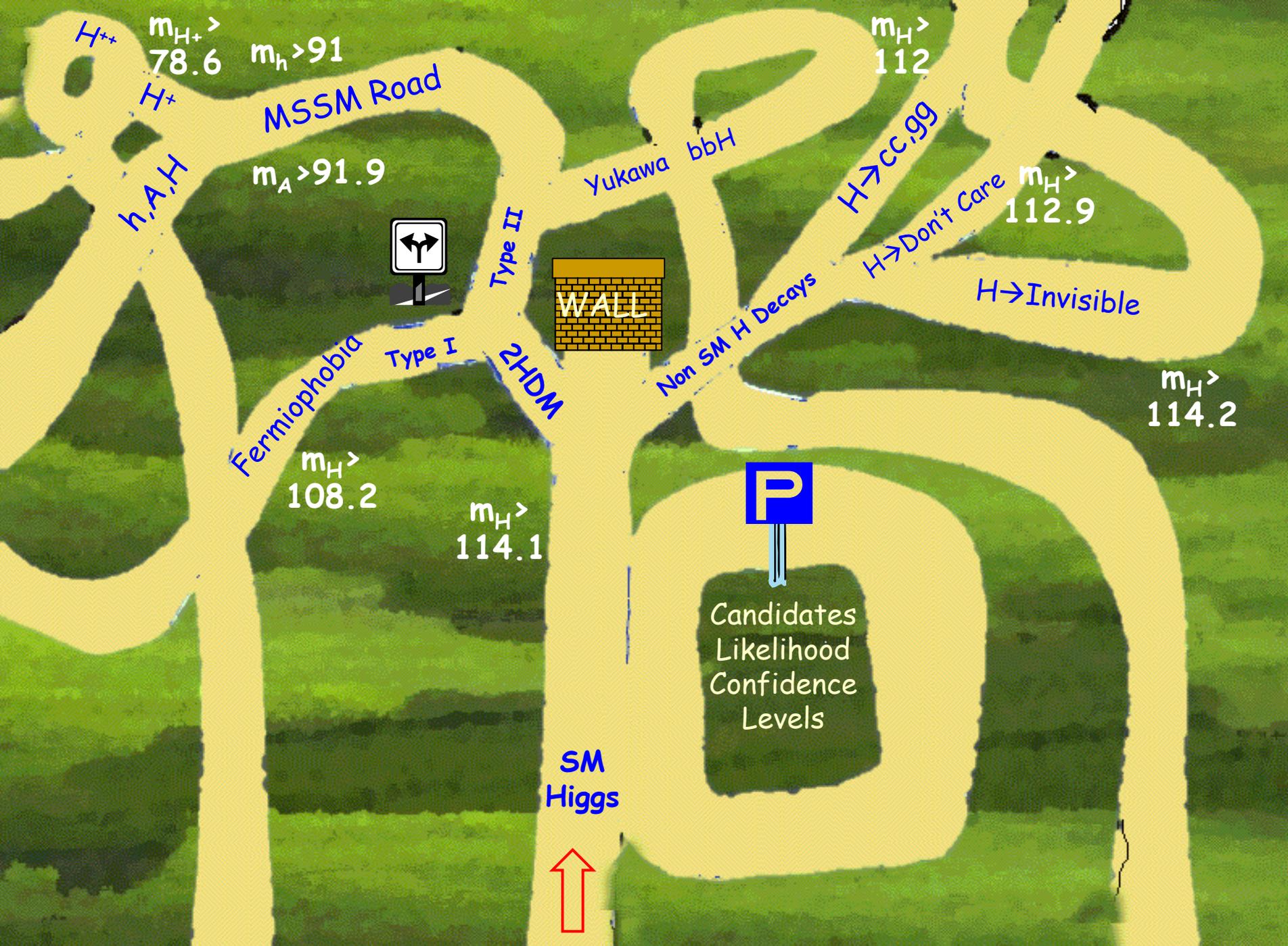
# Casting Doubts!



A new version of Feynhiggs including  $O(\alpha_s^2)$  two loop corrections to the neutral CP even Higgs boson mass (Brignole et. Al. HEP-PH 0112177) and incorporating a modified and more stable renormalization scheme might weaken existing sensitivities (see talk by S. Heynemeyer)

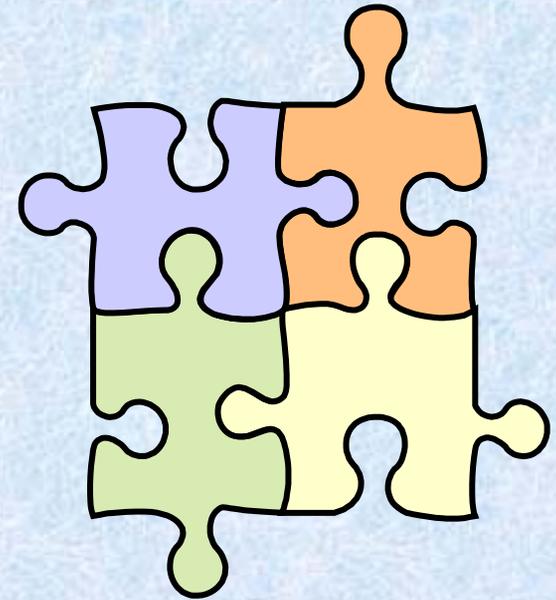
For example, in the mh-max scheme the max Higgs mass was shifted from 128 to  $\sim 134$  GeV, which weaken LEP limits on  $\tan\beta$ !

LEP will soon introduce modified benchmarks to accommodate the recent theoretical and experimental developments (e.g. the large  $m$  scenario has exhausted itself)



# Conclusions

- The LEP puzzle is still alive and kicking (and so is the puzzle of mass generation)
- Still lots of pieces to fit in (CP Violating Higgs, General Scan MSSM....)
- Unfortunately, so far, none of the pieces in this puzzle seems to be a Higgs boson but there is lots of space for exotic physics to be explored by the After-LEP TEVATRON, LHC and LC!



# Acknowledgements

- Chris Tully
- Amit Klier
  - Tom Junk
  - Alex Read
    - Arnulf Quadt
    - Jochen Cammin
- & to Peter Zerwas for giving me the opportunity and pleasure of preparing this talk



If the conclusions are not clear by the end of this talk, you have probably not been listening