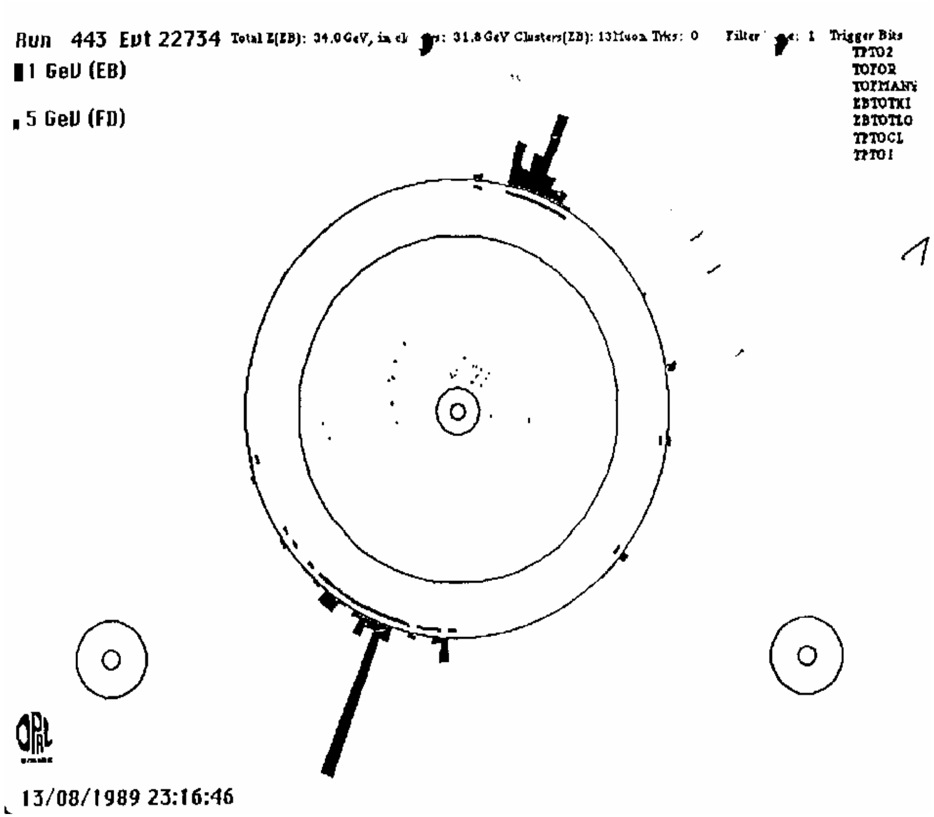
12 Years of Higgs Hunt at LEP or…

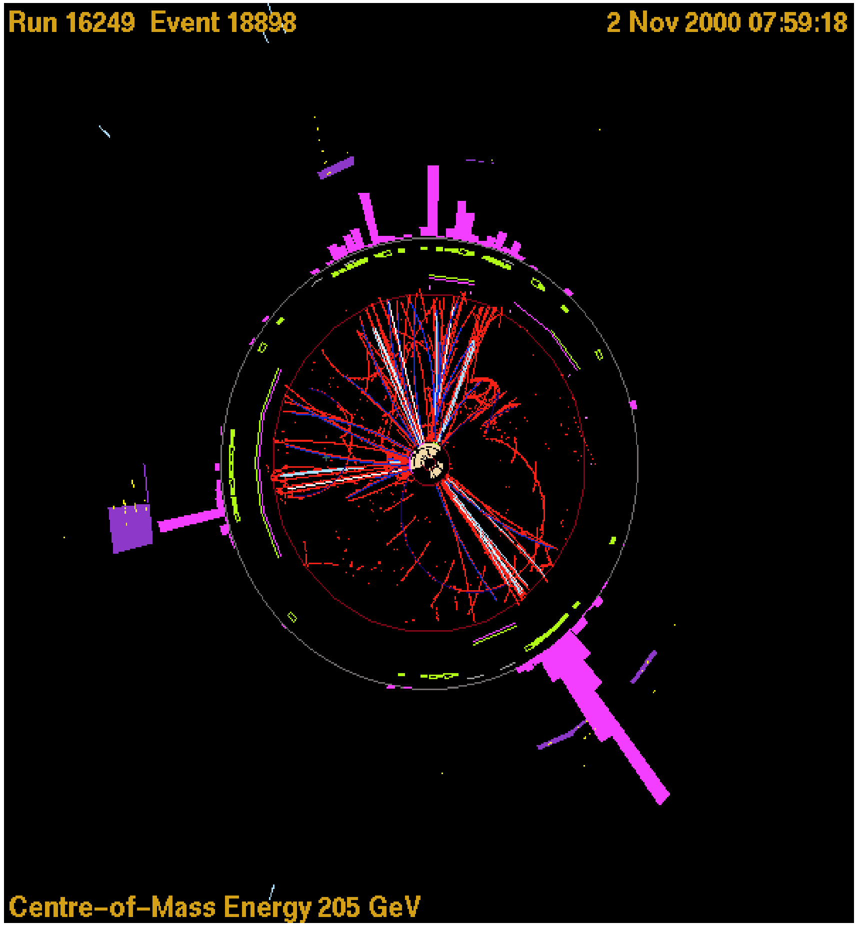
1989	1995
1990	1996
1991	1997
1992	1998
1993	1999
1994	2000

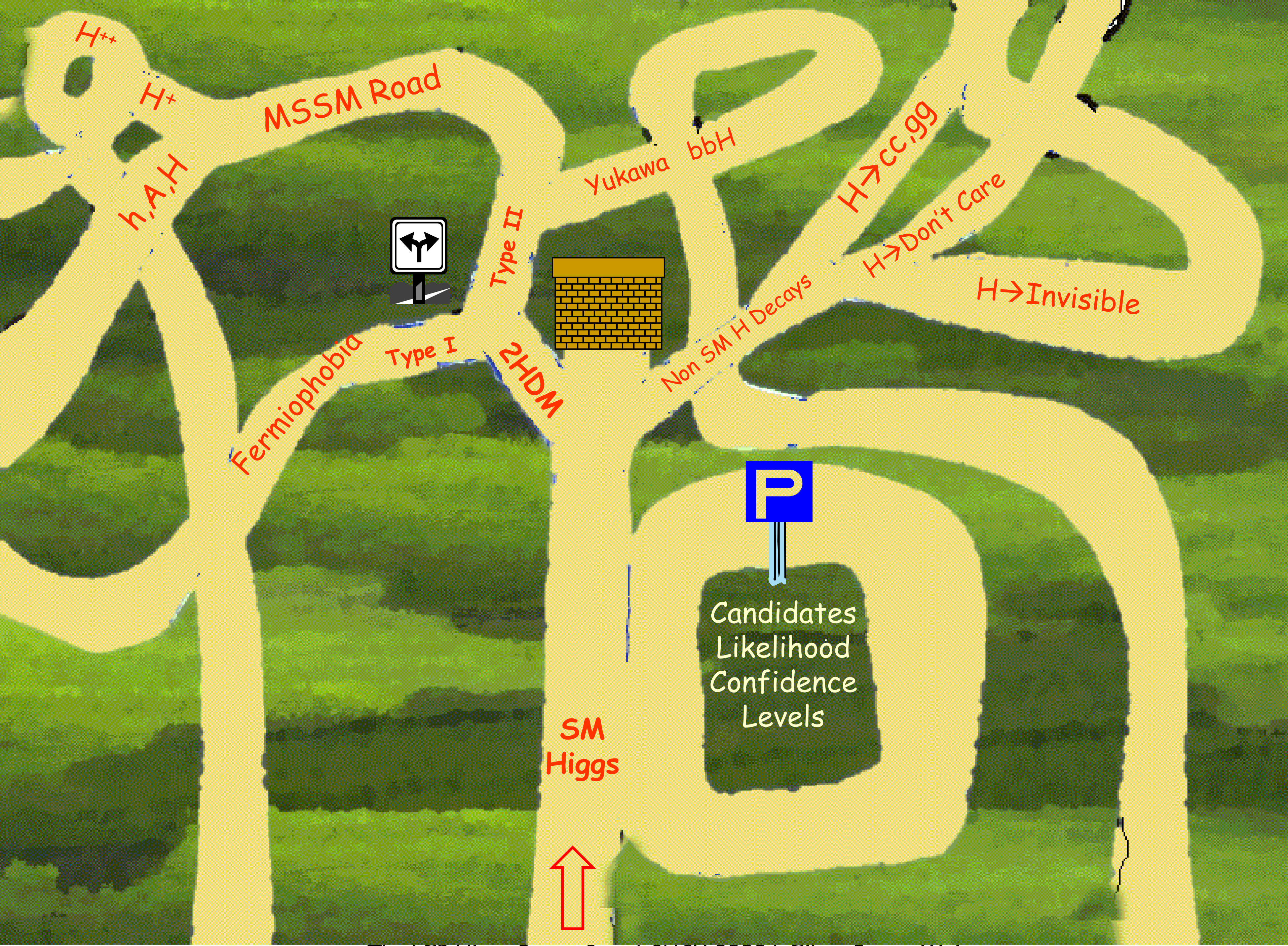
The LEP Higgs Boson Saga

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

Eilam Gross, Weizmann Institute of Science

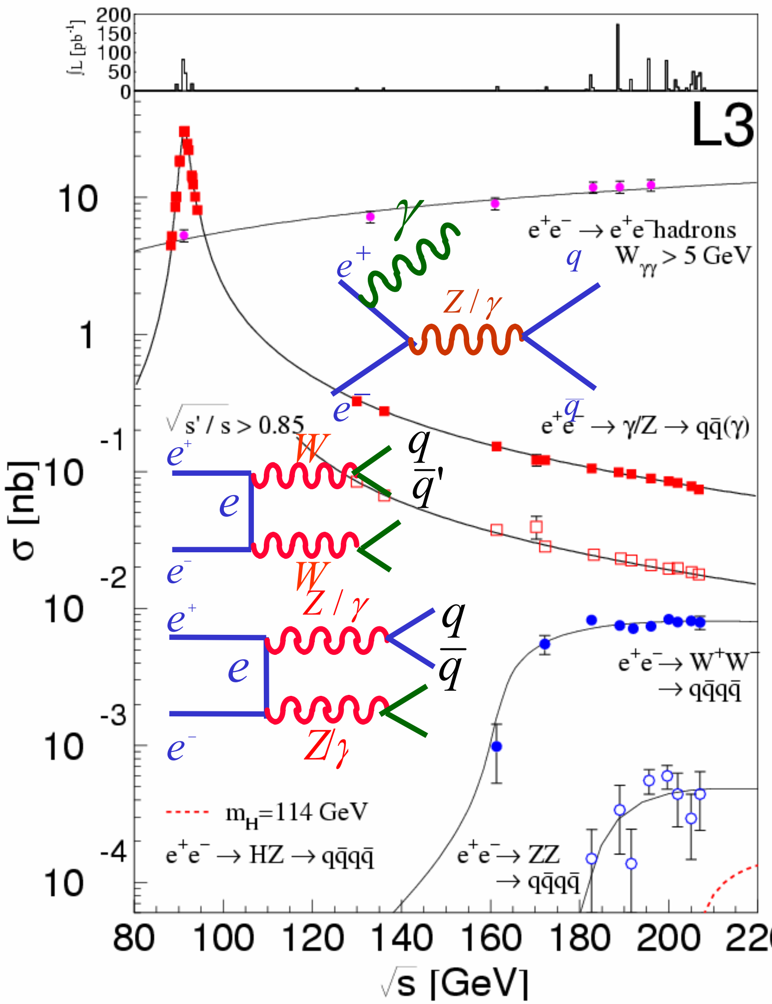


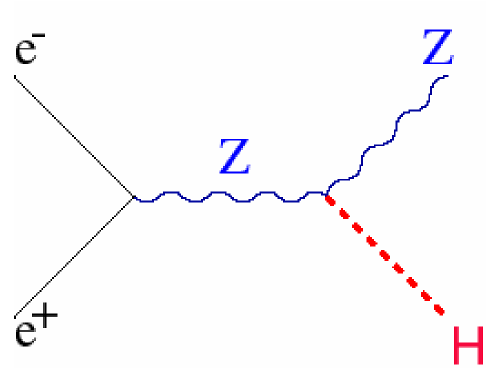




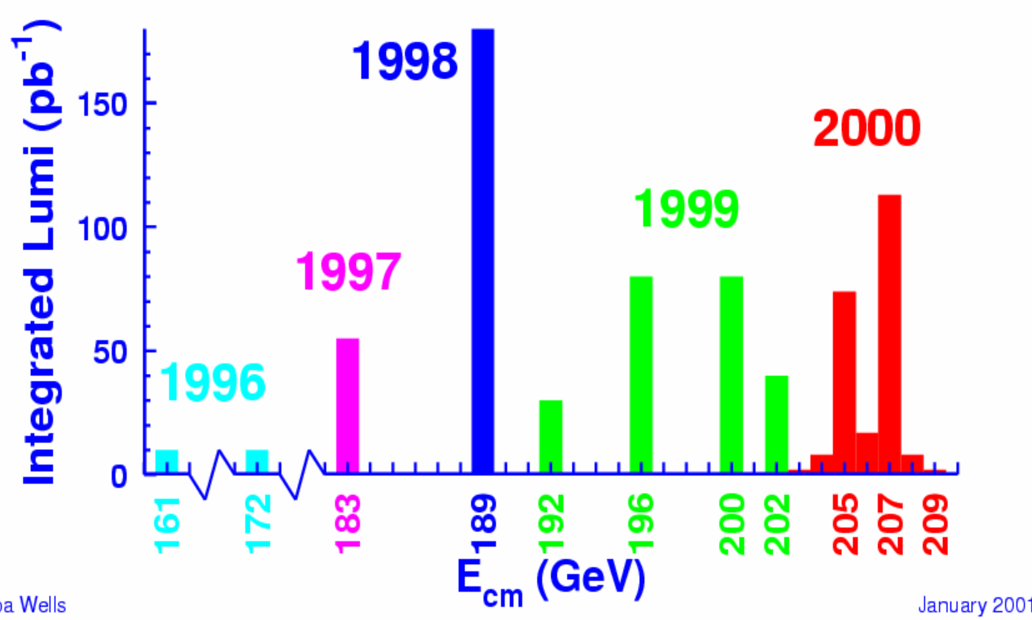
H++
H+
h,A,H
MSSM Road
Yukawa
bbH
H→cc,gg
H→Don't Care
H→Invisible
Type II
Type I
Fermiophobia
2HDM
Non SM H Decays
Candidates
Likelihood
Confidence
Levels
SM
Higgs

LEP

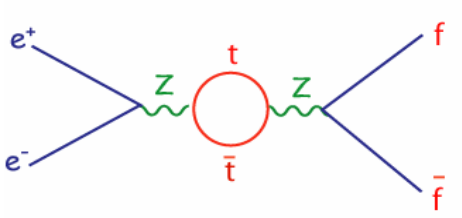




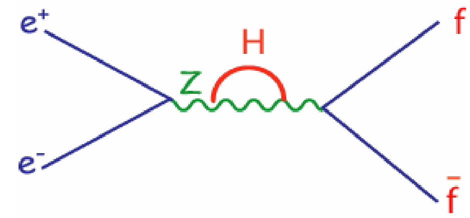
Total LEP I luminosity ~200 pb^{-1}/experiment
LEP II luminosity ~750 pb^{-1}/experiment



Precision Measurements and the Higgs Boson



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



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

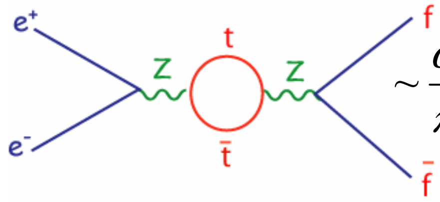
All= LEP I+II, SLD, UA2, CDF, D0,...

m_t=174.3(5.1)

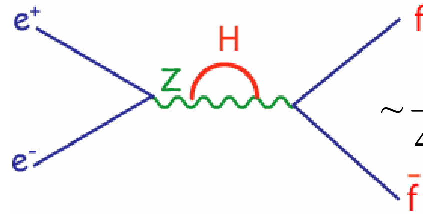
From LEP Electroweak WG and the SLD Heavy Flavor Group, May 2002

	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
χ^2/dof	14.3/9	18.5/12	19.6/14	28.8/15 Stability

Constraints on the Standard Model



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

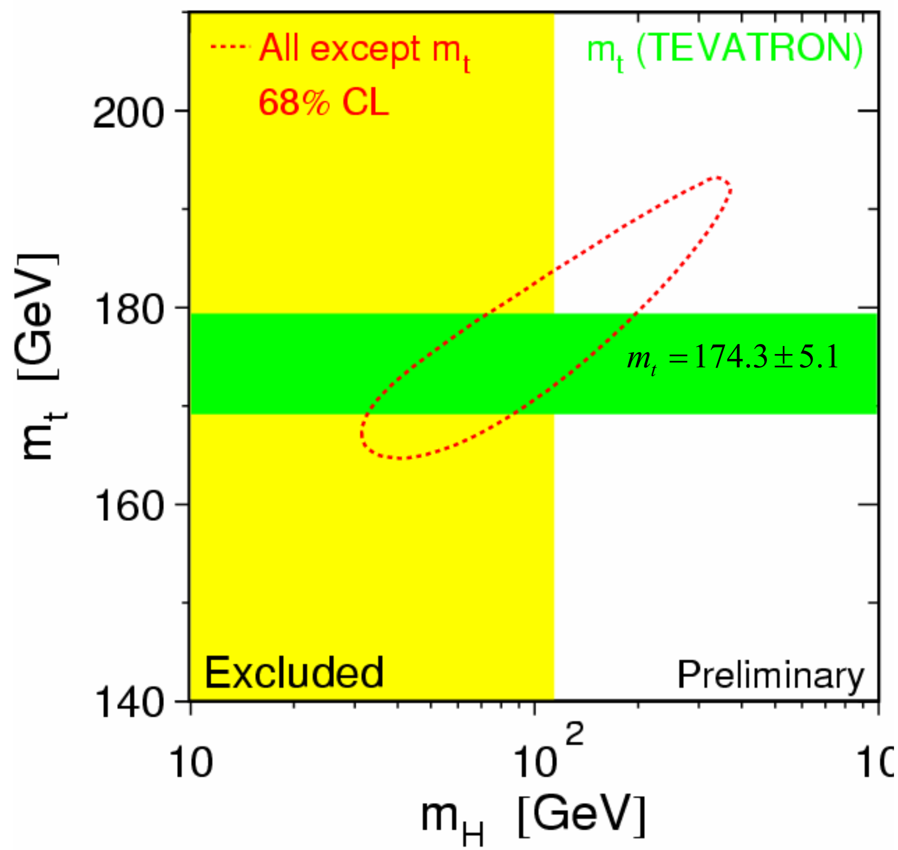


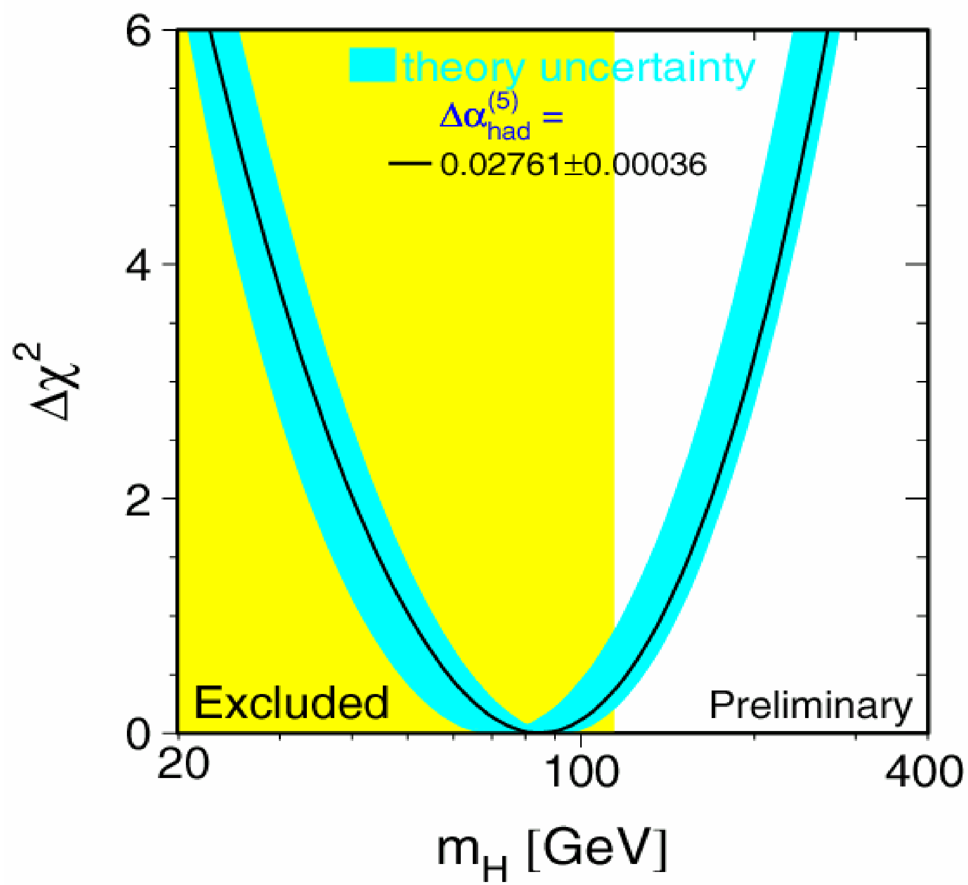
$$\sim \frac{\alpha}{4\pi}\log\frac{m_H^2}{m_Z^2}$$

$$\log m_H = 1.93^{+0.21}_{-0.23}$$

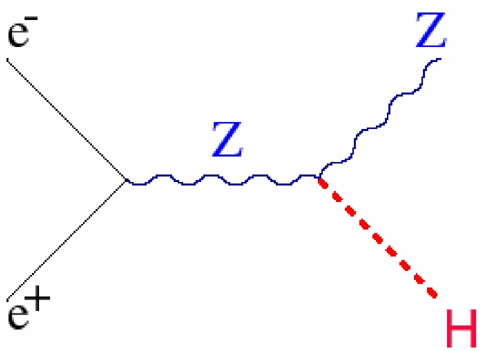
$$m_H = 85^{+54}_{-34}$$

$$m_H < 196\ GeV\ \ @\ 95\%\ CL$$



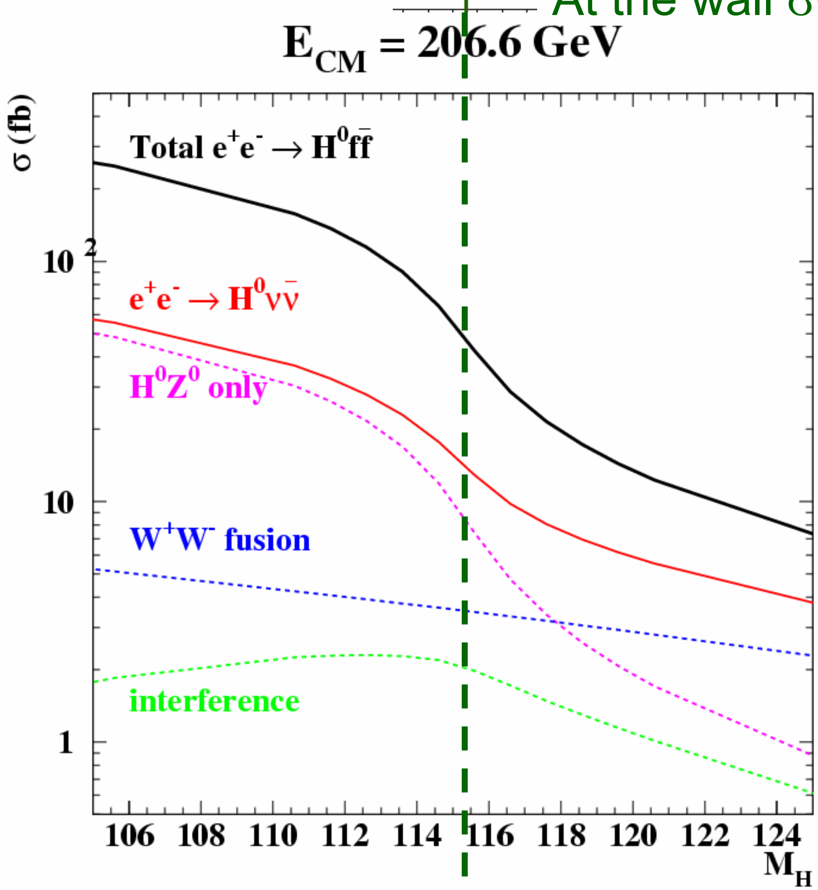


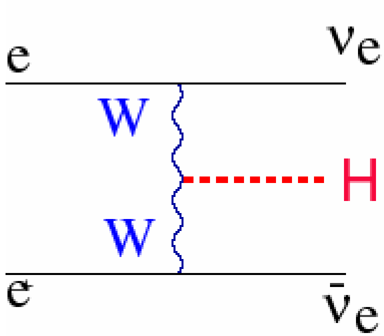
Higgs Production and the Wall

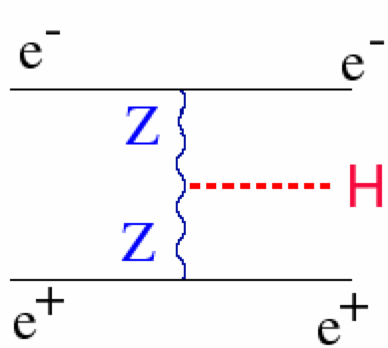


=206.6-91.2=115.4

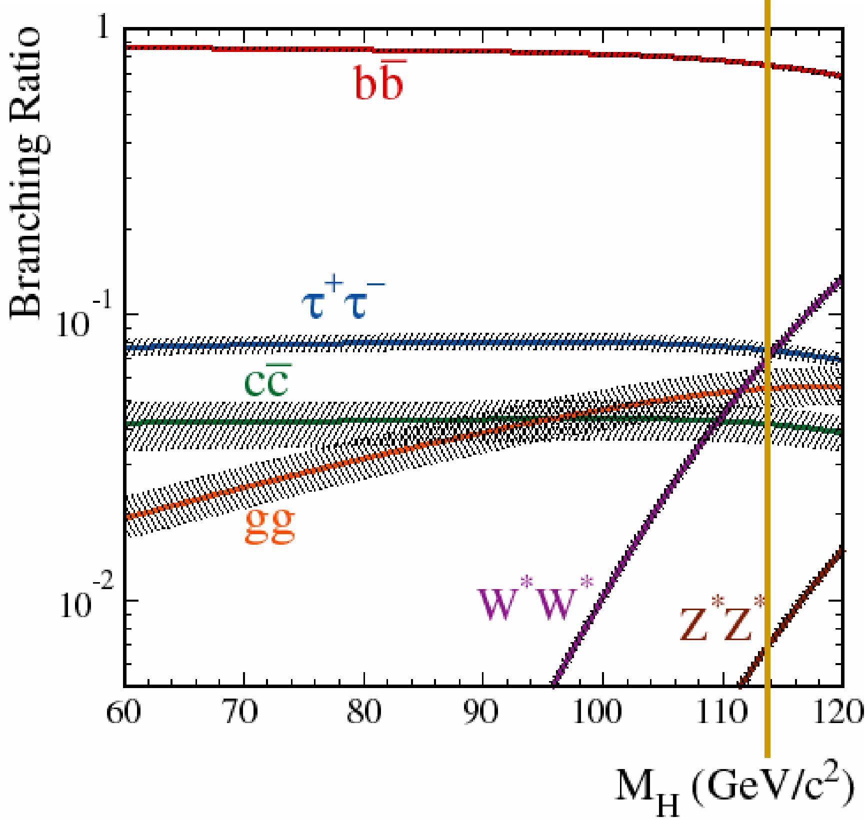
At the wall σ~0.05 pb



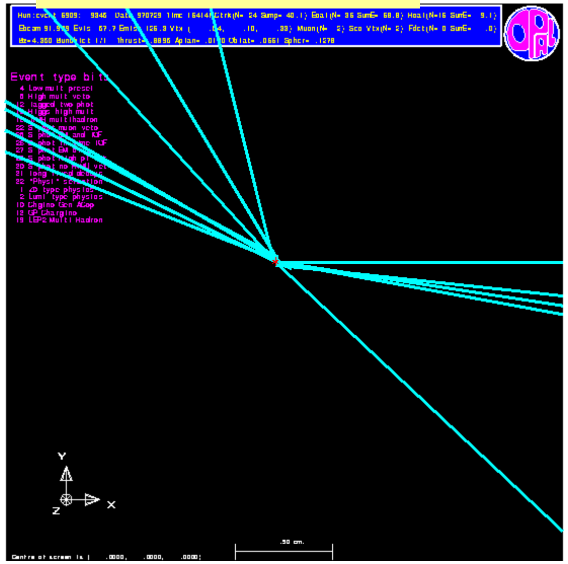




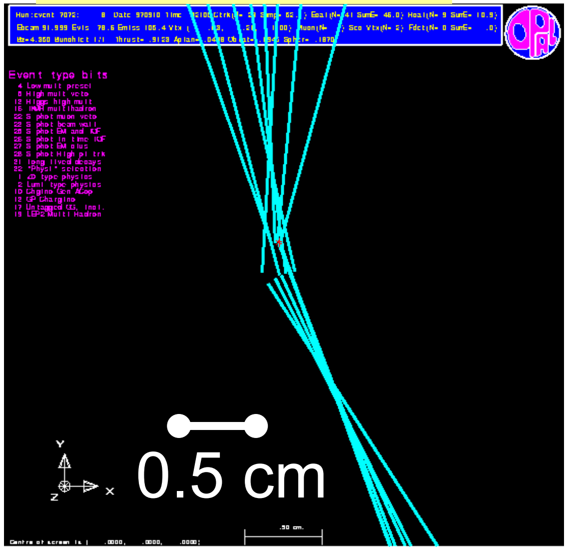
SM Higgs Decay



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



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



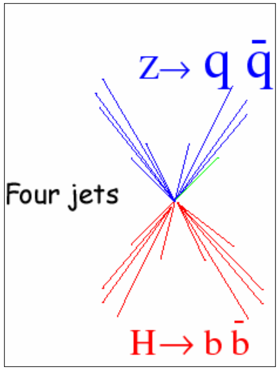
- B-tag is an essential ingredient in Higgs search

Higgs Search Channels

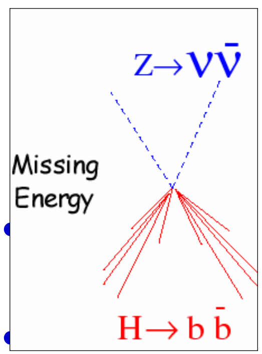
$H \to b\bar{b}(\sim 75-85\%), \tau^+\tau^-(\sim 8\%)$

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

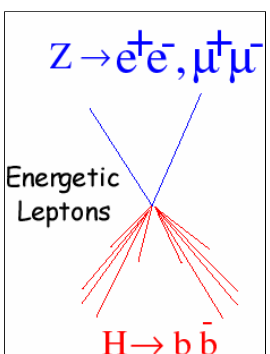
$e^+e^- + \mu^+\mu^-(6.6\%), \tau^+\tau^-(3.3\%)$



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

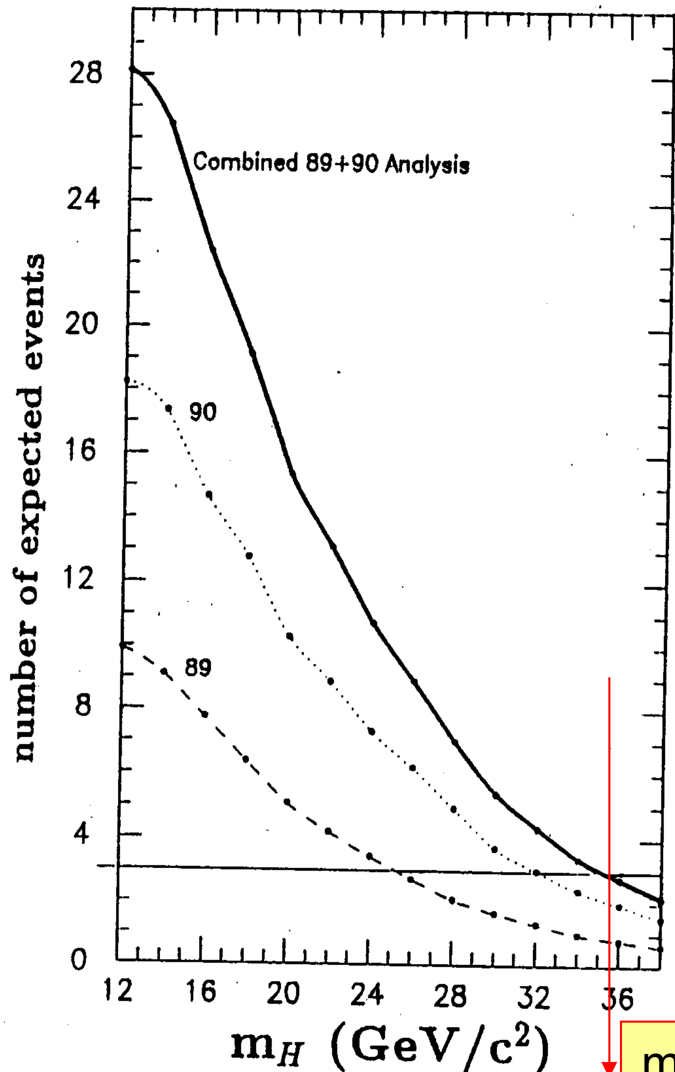


- The recoil mass of the 2 b-tagged jets is compatible with a Z boson



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

First Higgs Limit Procedures



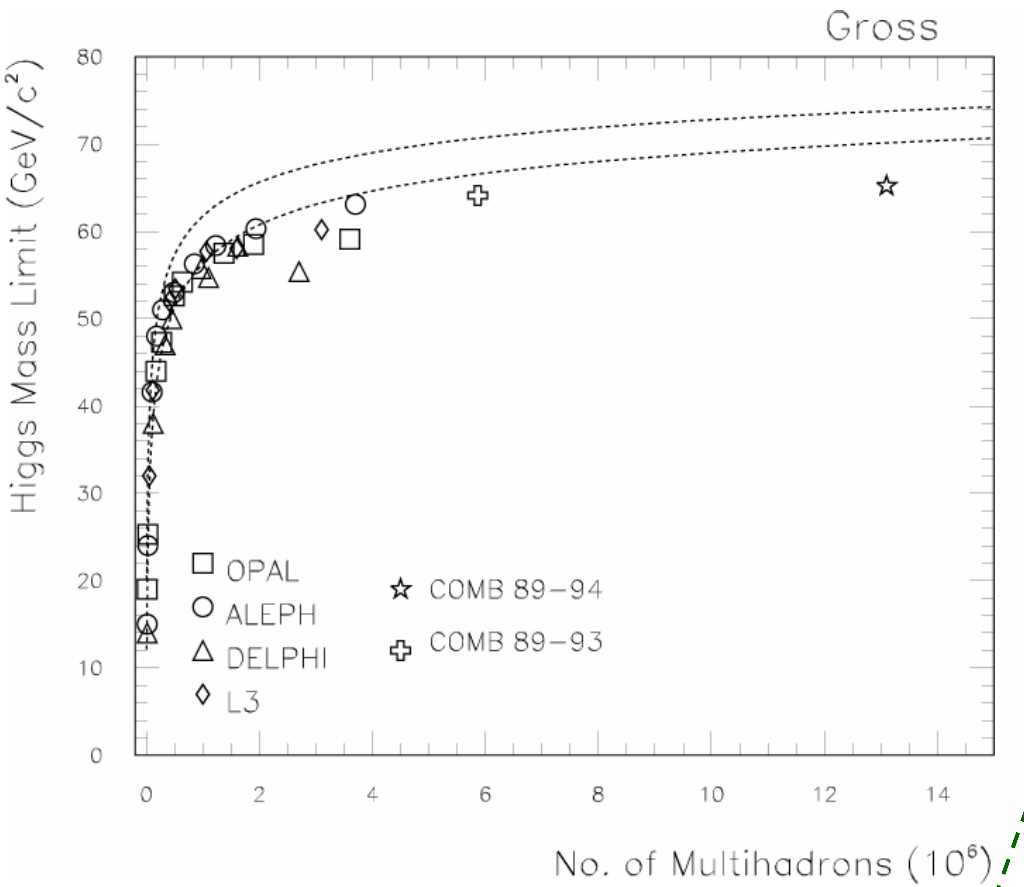
m_H>35.4 GeV

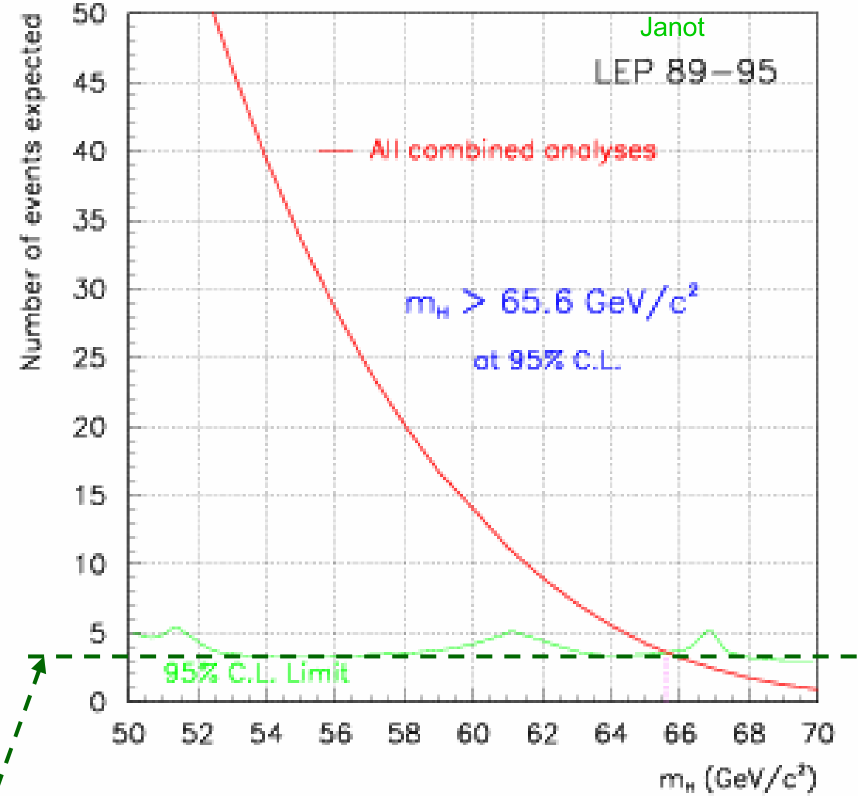
Statistical Procedure in a Background FREE environment

$$N_{\exp} = Lum \bullet \sigma(ee \to hZ) \bullet eff$$

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

LEP 1 Saturation and final Limit



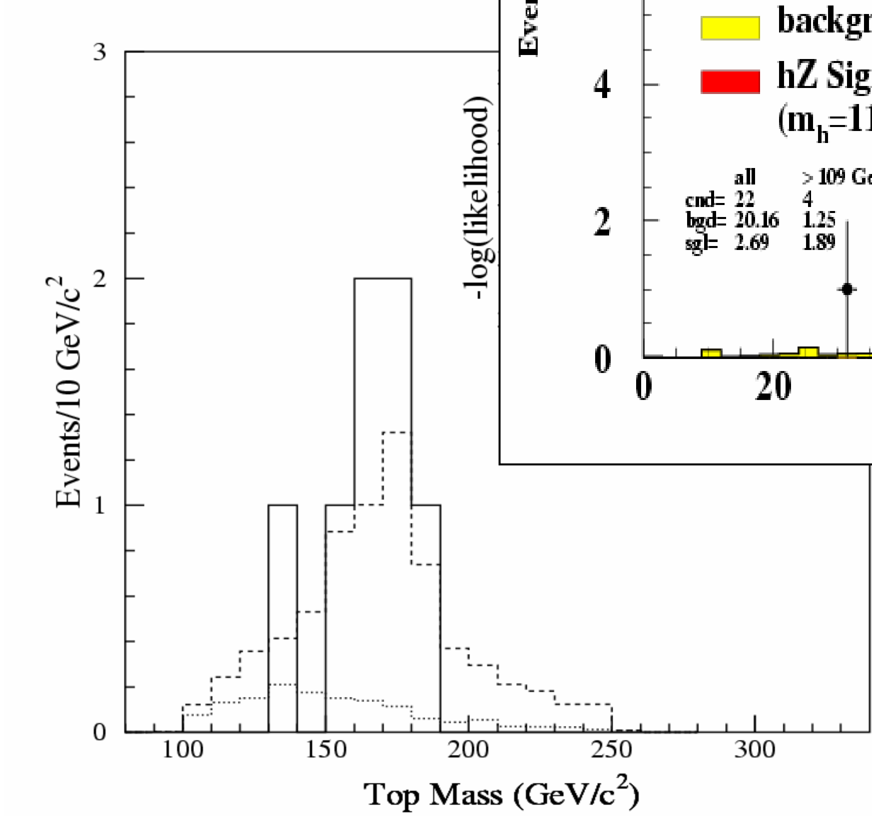


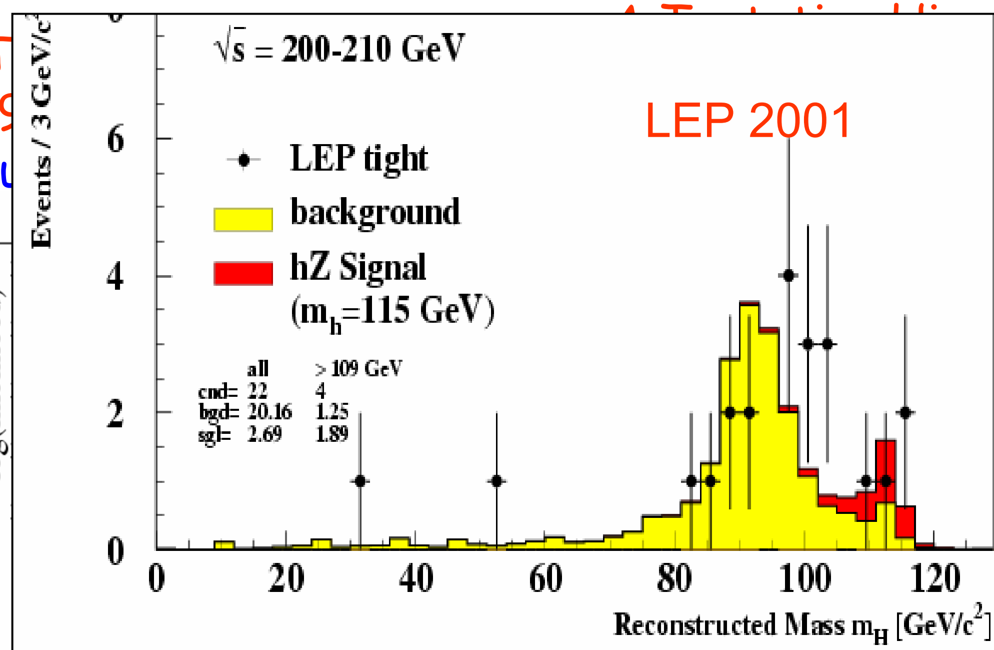
- The final LEP I limit is based on N_{95}~3, i.e. no background
- At the end of LEP I the need to develop a statistical method that can cope with non-vanishing background and events with finite mass resolution was emerged.

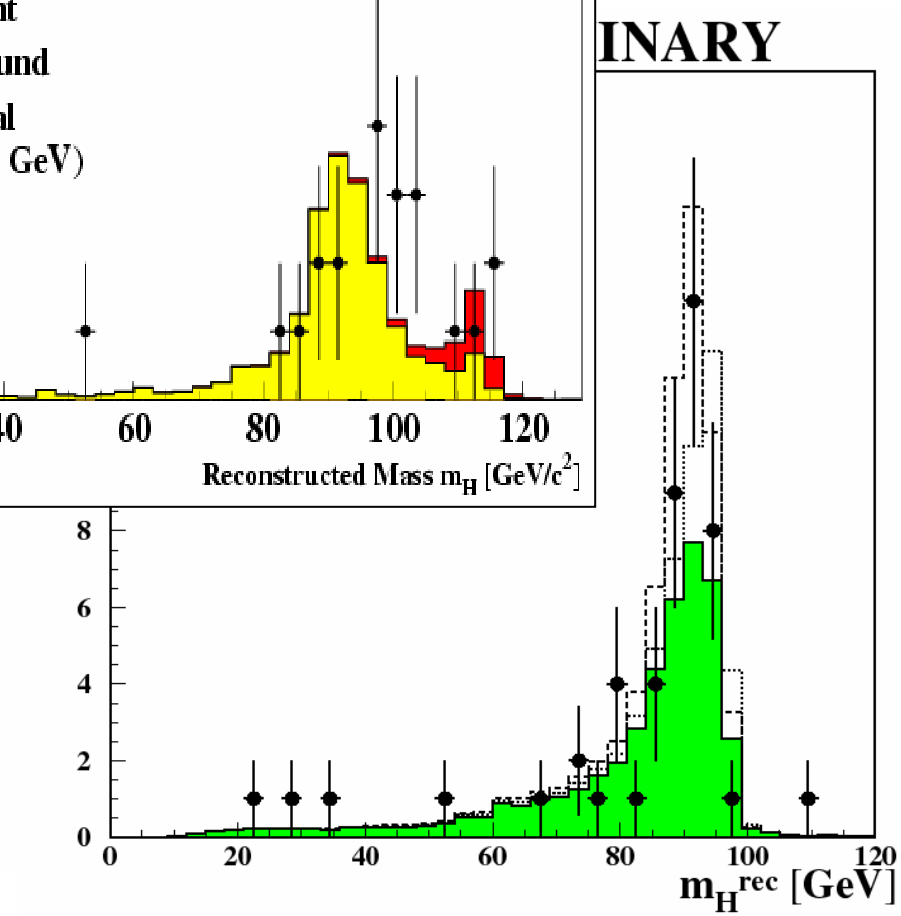
Golden Signatures

Evidence for T
CDF June 13,19
Prob for BG flu

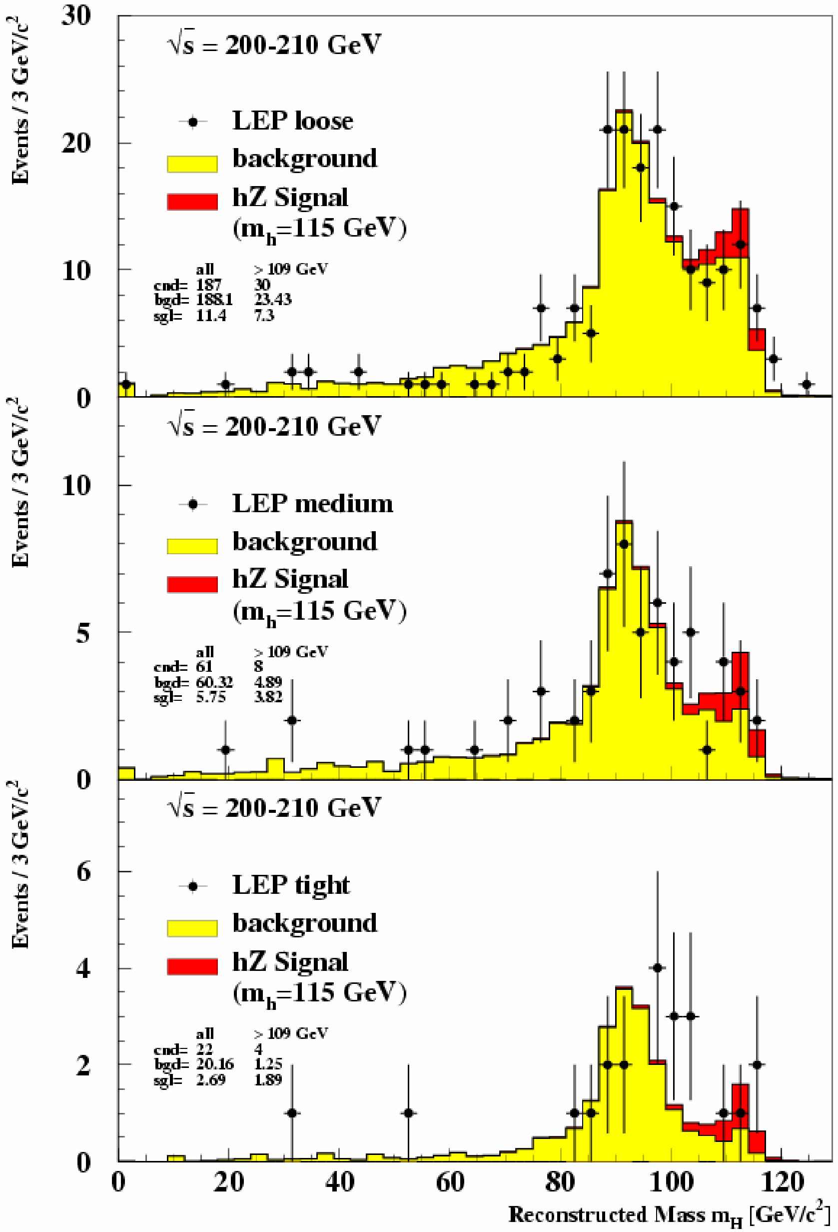
Discovery







Is that IT?



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

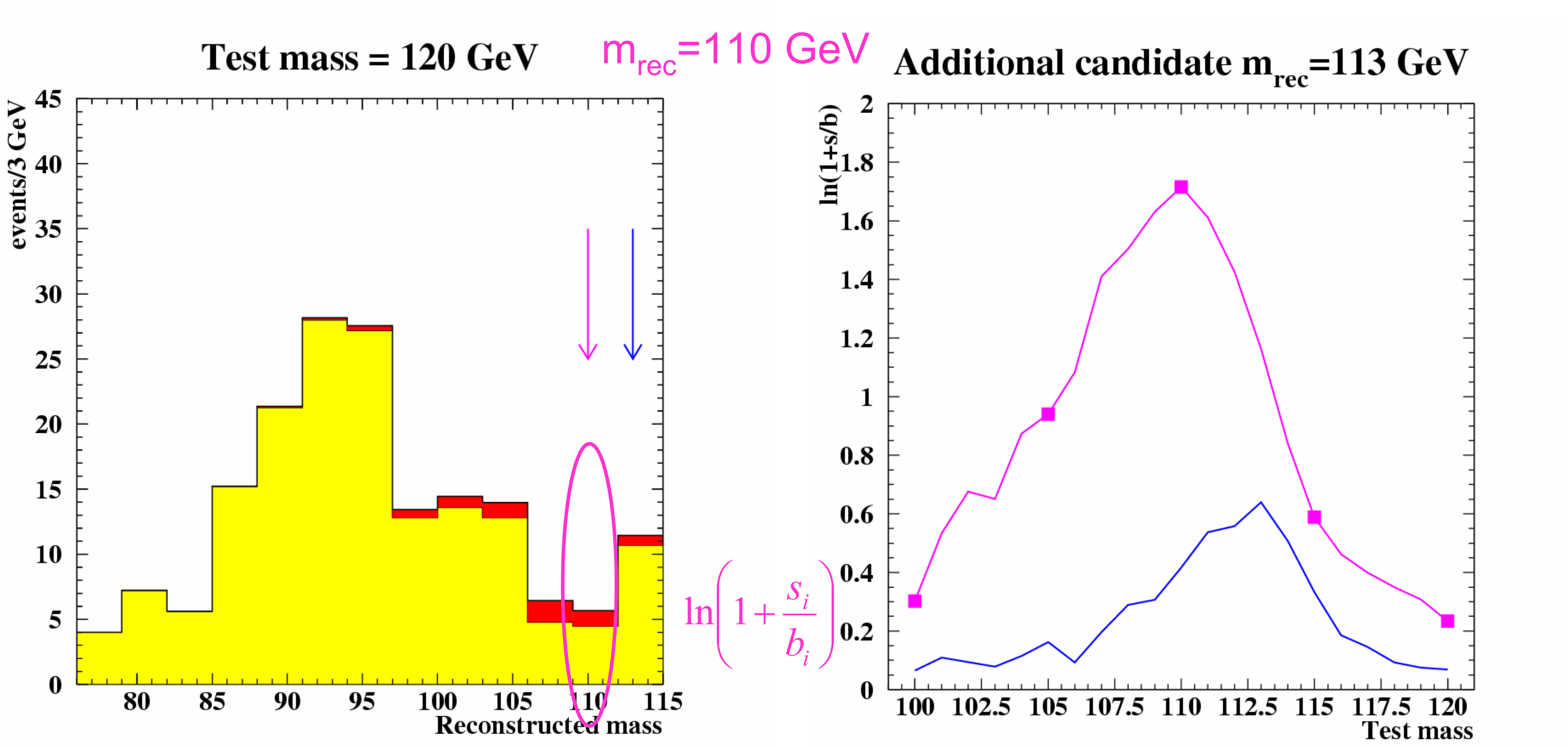
Is there a "hidden" variable behind the signal region events?

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

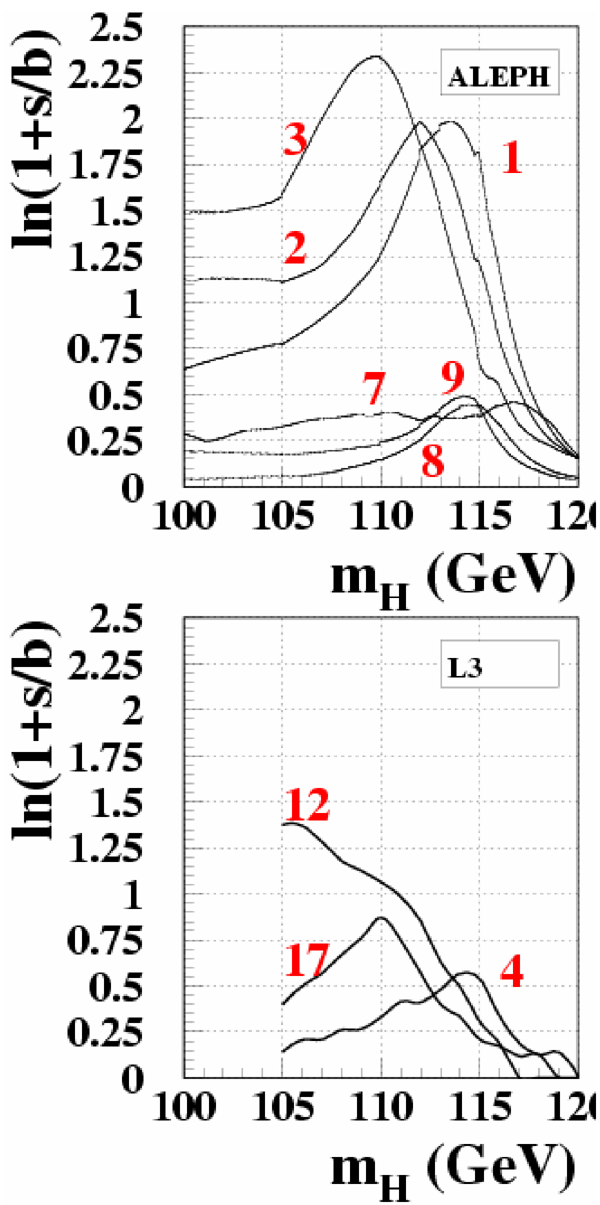
One has to FEEL the statistical procedure at his fingertips to really appreciate if such a signature could indicate a 115 GeV Higgs boson or not!

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 $\ln\left(1+\frac{s_i}{b_i}\right)$

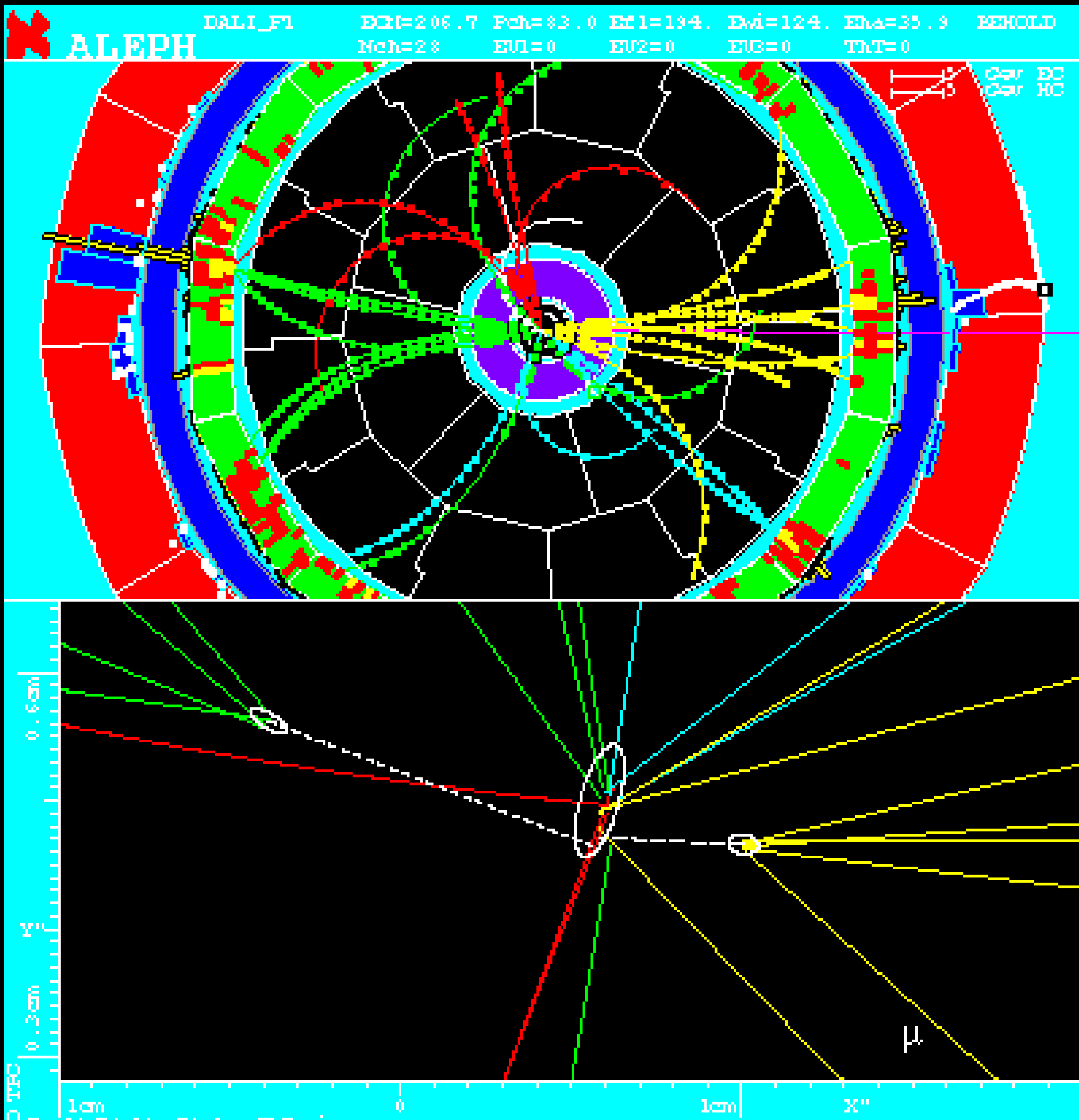


Most Significant Events



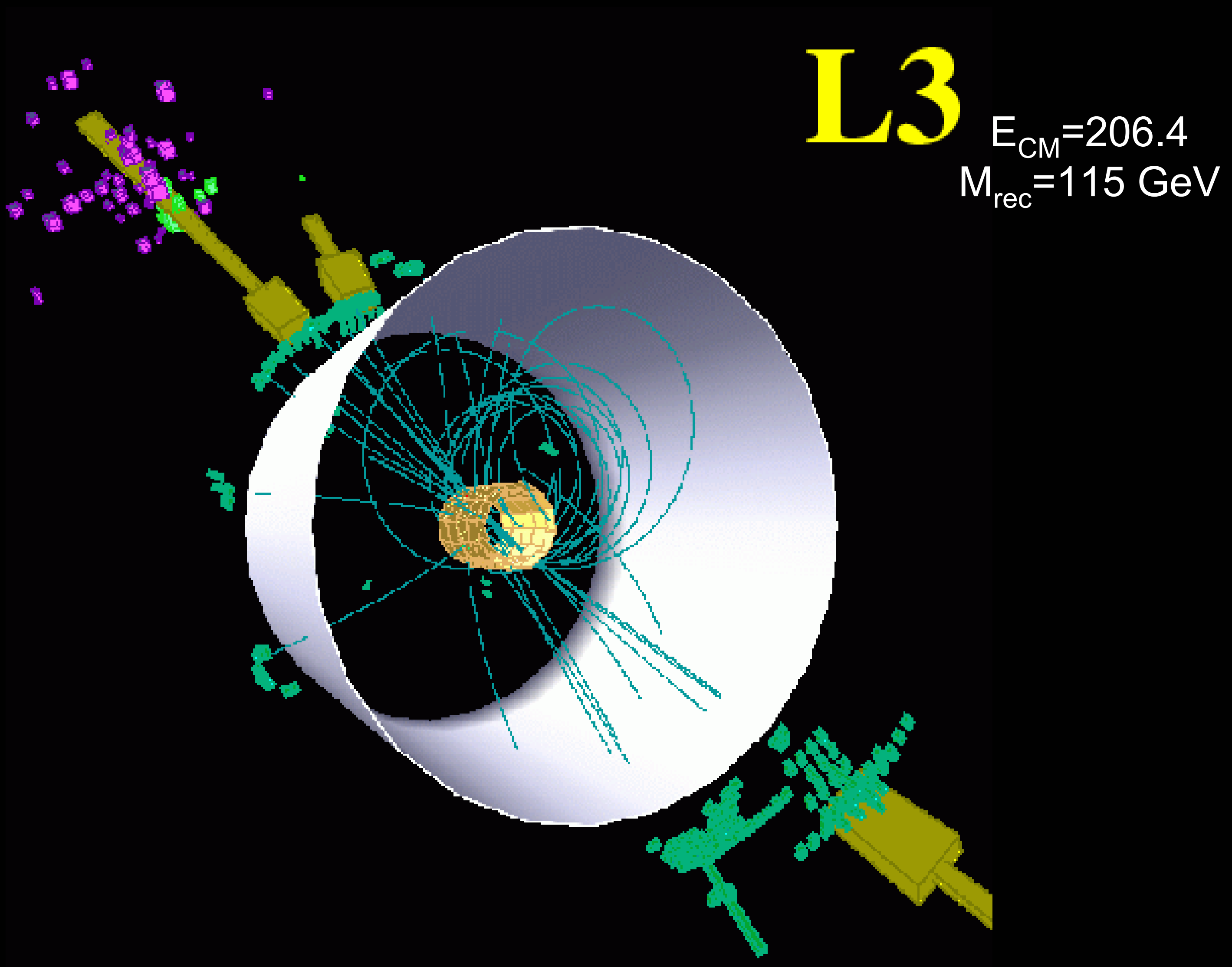
	Expt	E_{cm}	Decay channel	M_H^{rec} (GeV)	$\ln(1+s/b)$ @115 GeV
1	Aleph	206.7	4-jet	114.3	1.73
2	Aleph	206.7	4-jet	112.9	1.21
3	Aleph	206.5	4-jet	110.0	0.64
4	L3	206.4	E-miss	115.0	0.53
5	Opal	206.6	4-jet	110.7	0.53
6	Delphi	206.7	4-jet	114.3	0.49
7	Aleph	205.0	Lept	118.1	0.47
8	Aleph	208.1	Tau	115.4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

4j Aleph Higgs Candidate



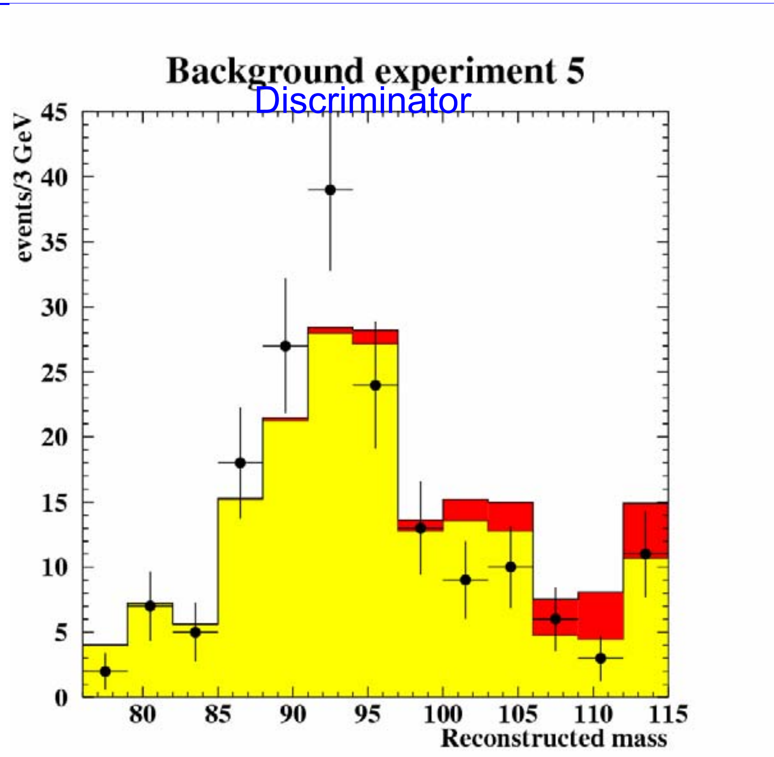
E_{CM}=206.7
M_{rec}=114 GeV
B-tag = 0.99,0.99,0.14.0,0.01

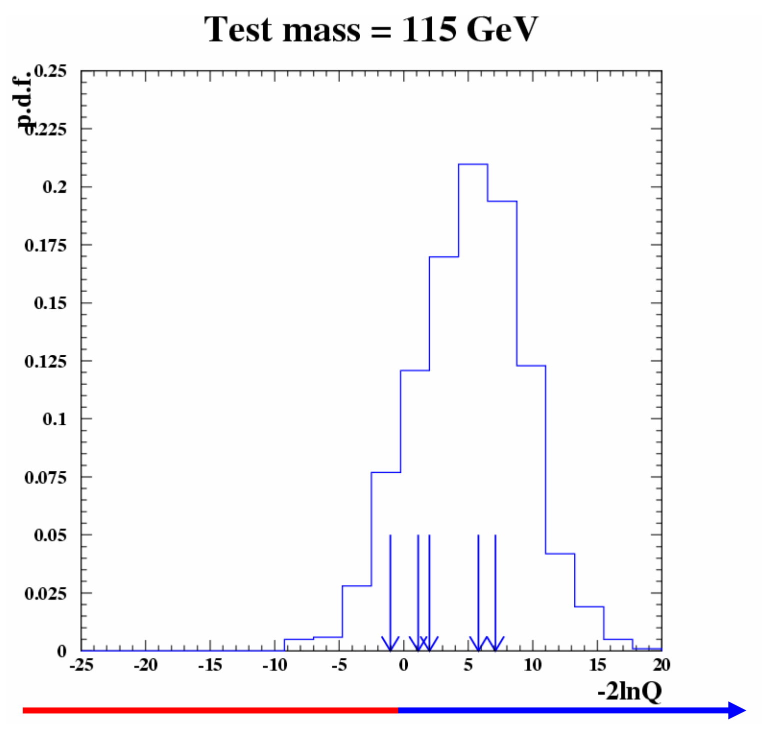
L3 Missing Energy Candidate



Simulating bg Experiments

- Construct a Discriminator (Not necessarily mass, could be 2-D)
- Divide the discriminator to bins i=1,…
  There are N_i observed candidate events in each bin; we then calculate the likelihood ratio –2lnQ
- 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

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

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

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

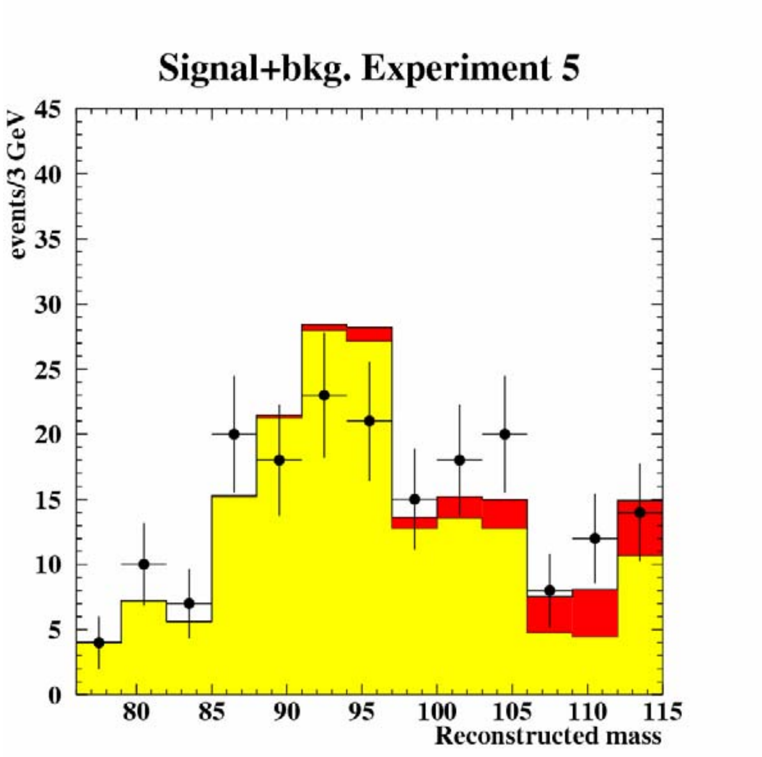
s+b like b-like -2lnQ

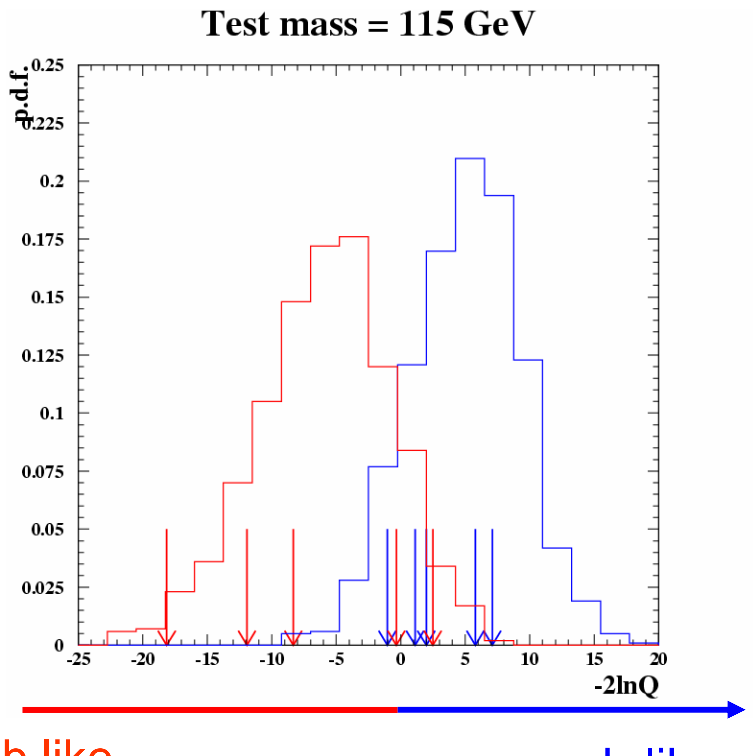
The likelihood ratio, -2lnQ(m_H) ranks the experimental events configuration between two hypotheses: "s+b"-like and "b"-like,

Simulating s+b Experiments (m_H=115)

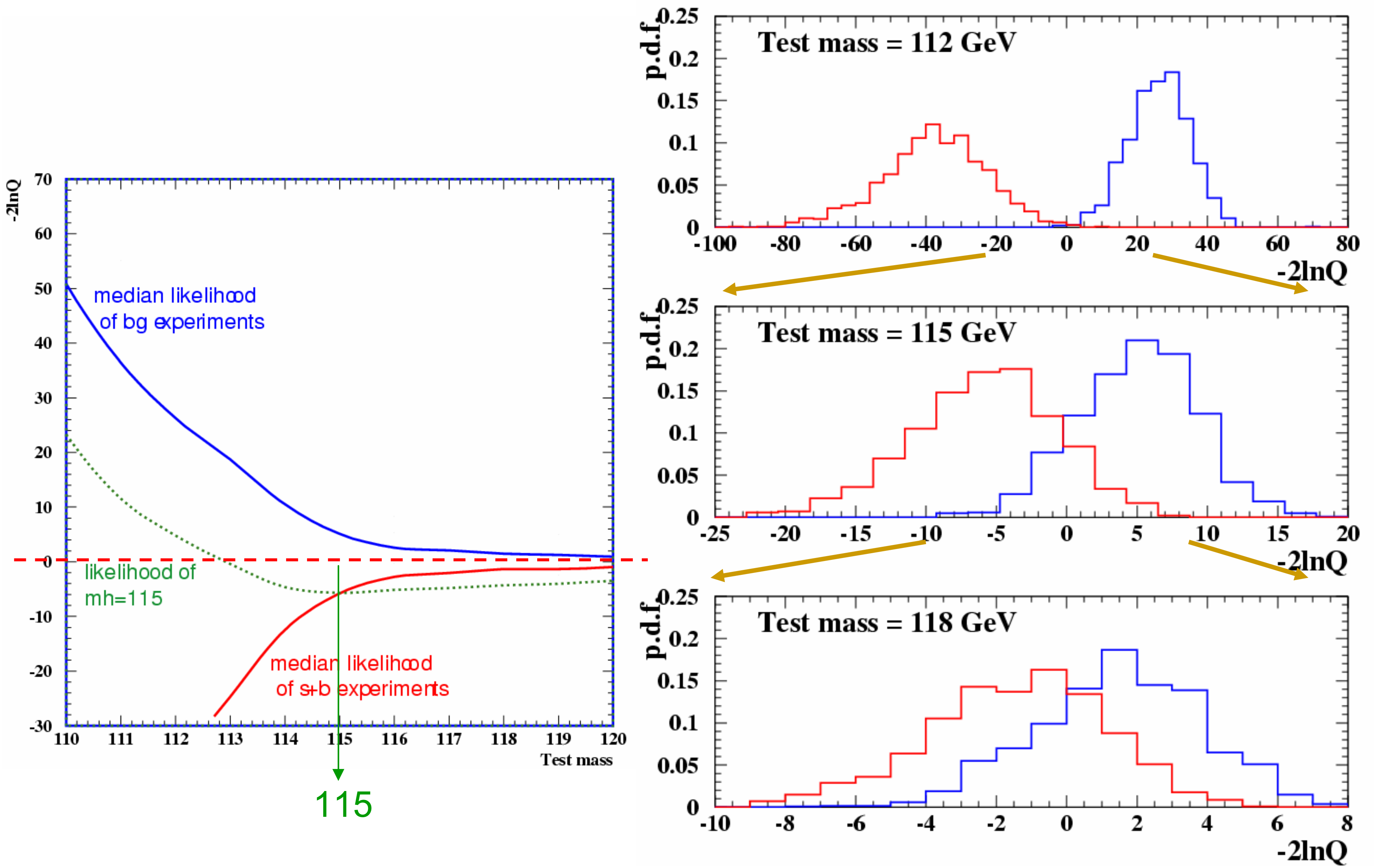
- Now we let's play the "game" from a 115 GeV Higgs point of view…

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

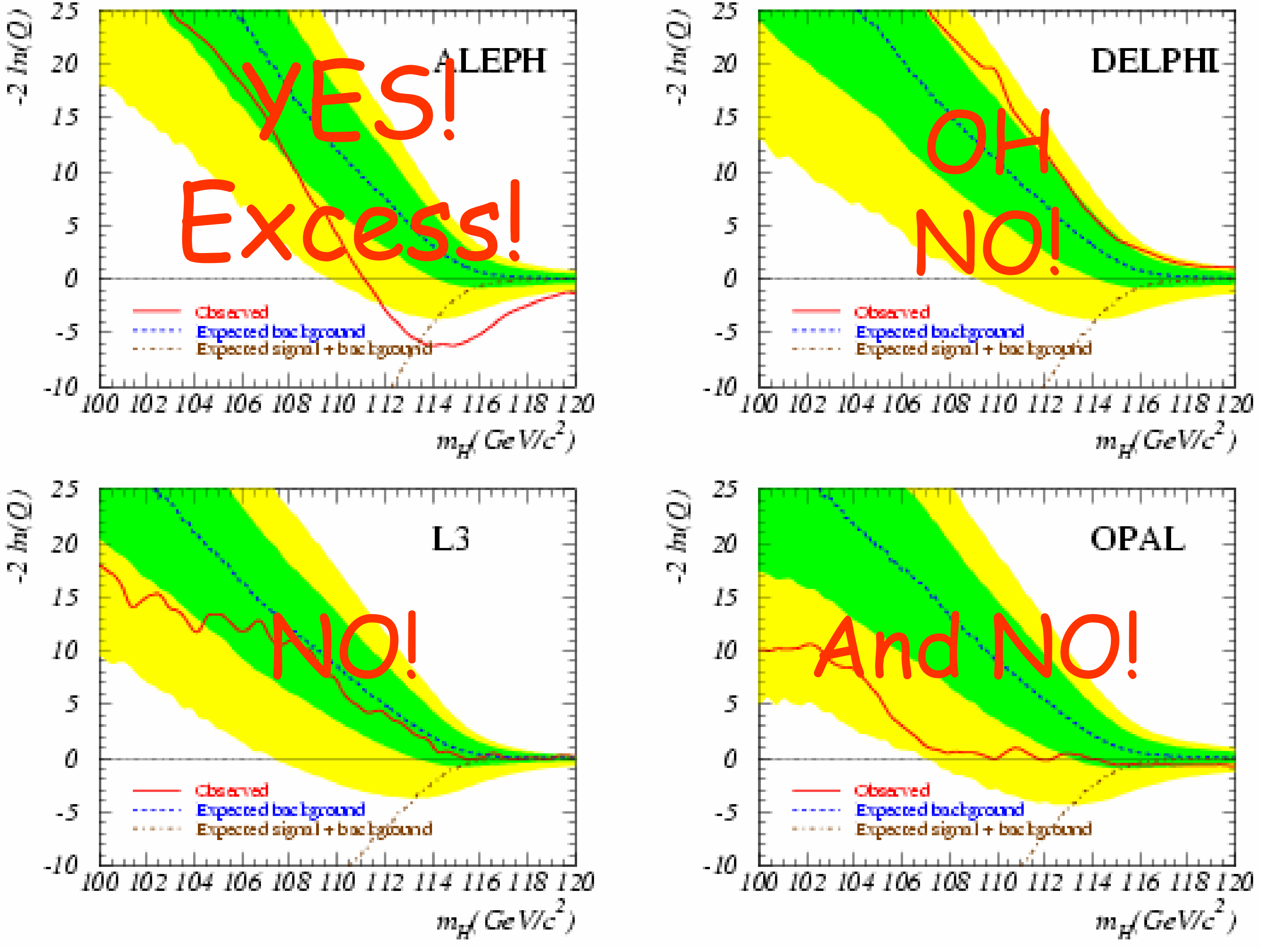




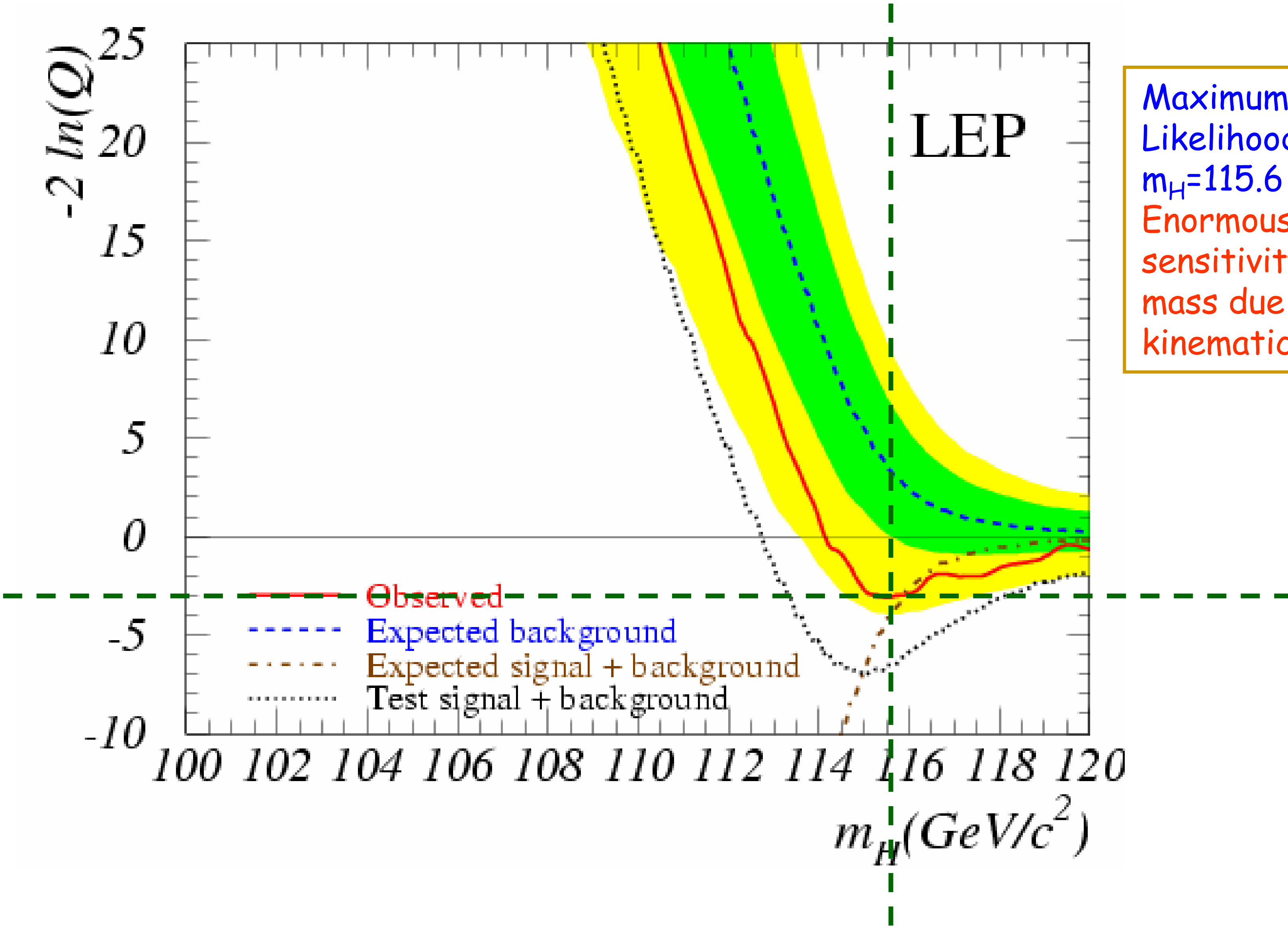
Signal-Background Separation



The Real Thing: 4 Experiments, 4 Likelihoods



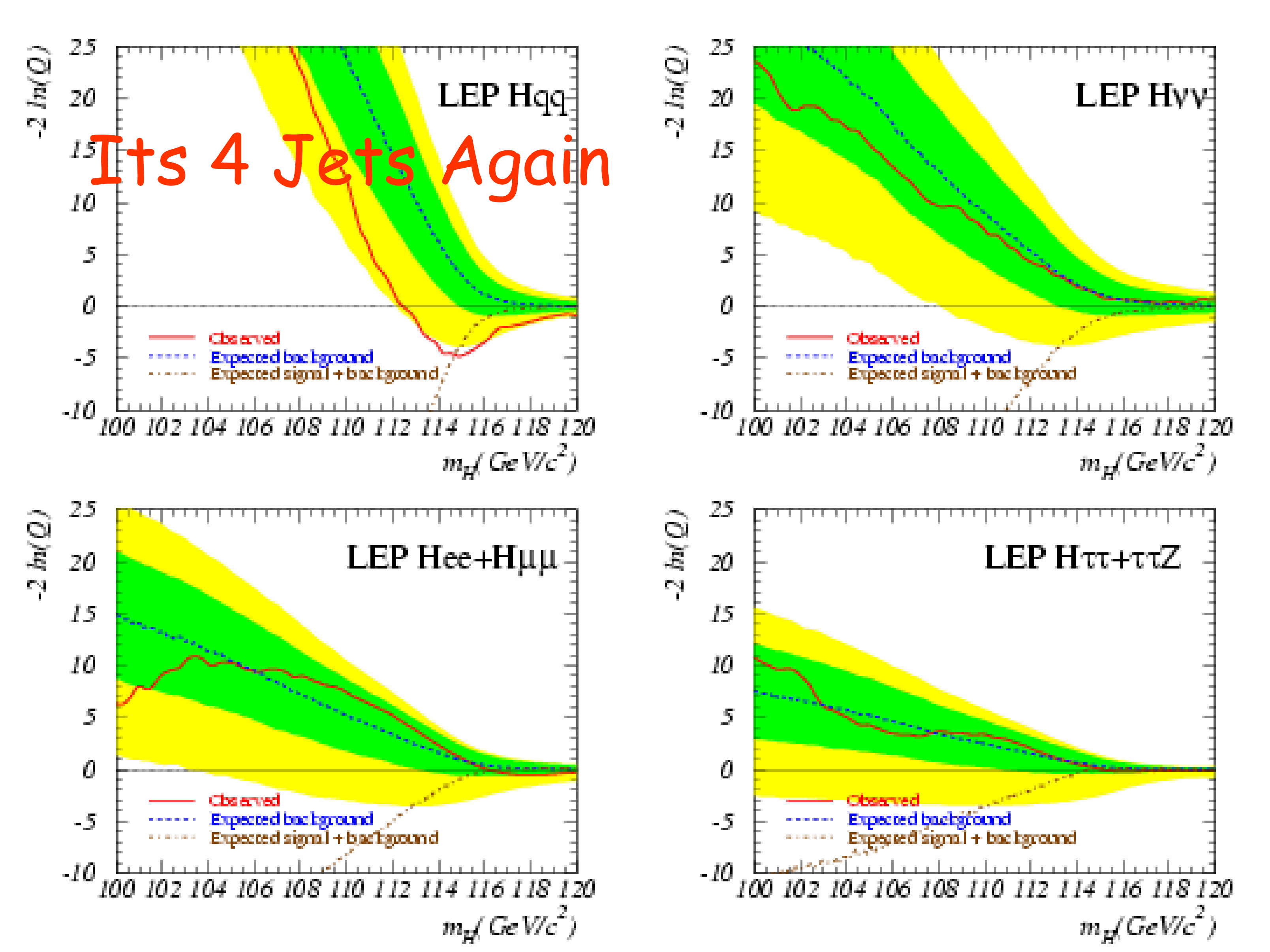
All 4 Experiments Combined Into One: LHWG



Maximum Likelihood for m_H=115.6

Enormous sensitivity to test mass due to the kinematical wall!

Channel By Channel

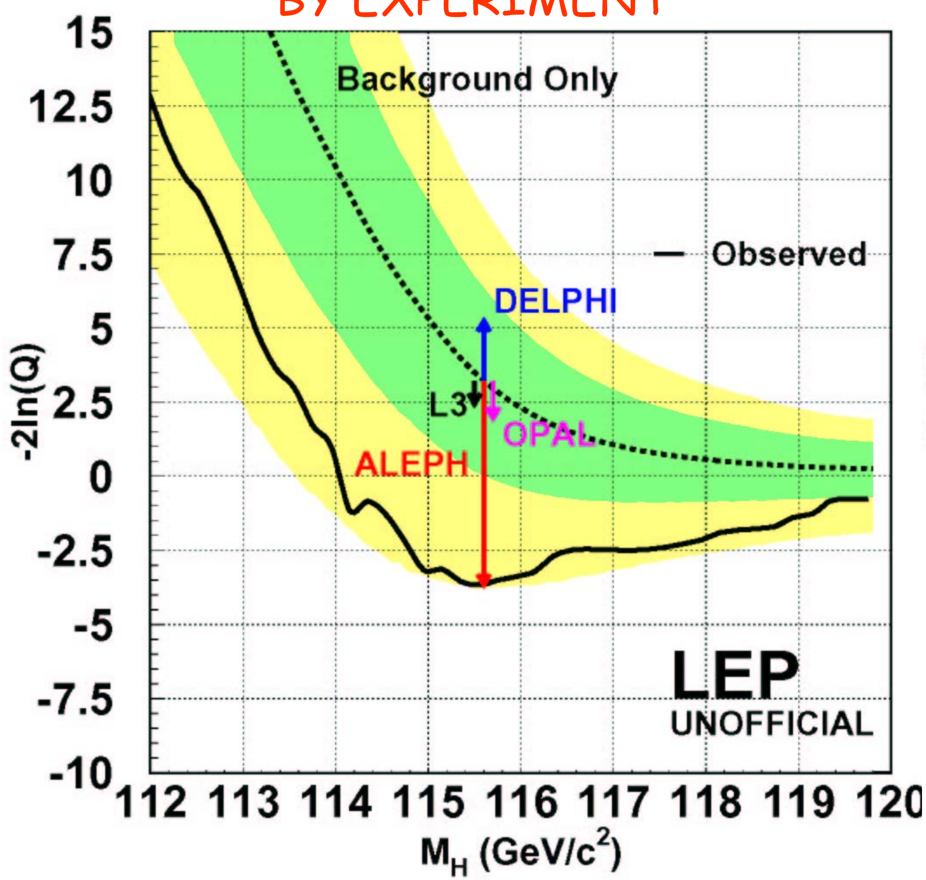


Focus on Year 2000

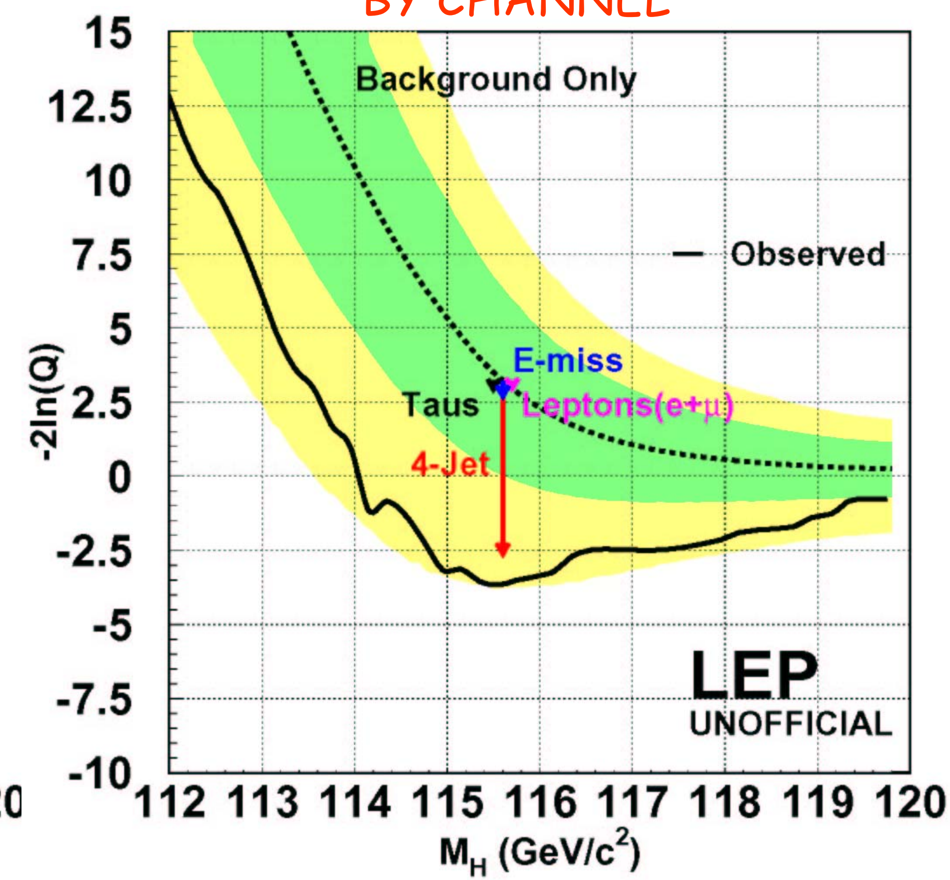
Unofficial plots from C. Tully DPF 2002 BASED on 2000 data ONLY!

- Note that lnQ is additive
- completely dominate the fluctuation

BY EXPERIMENT

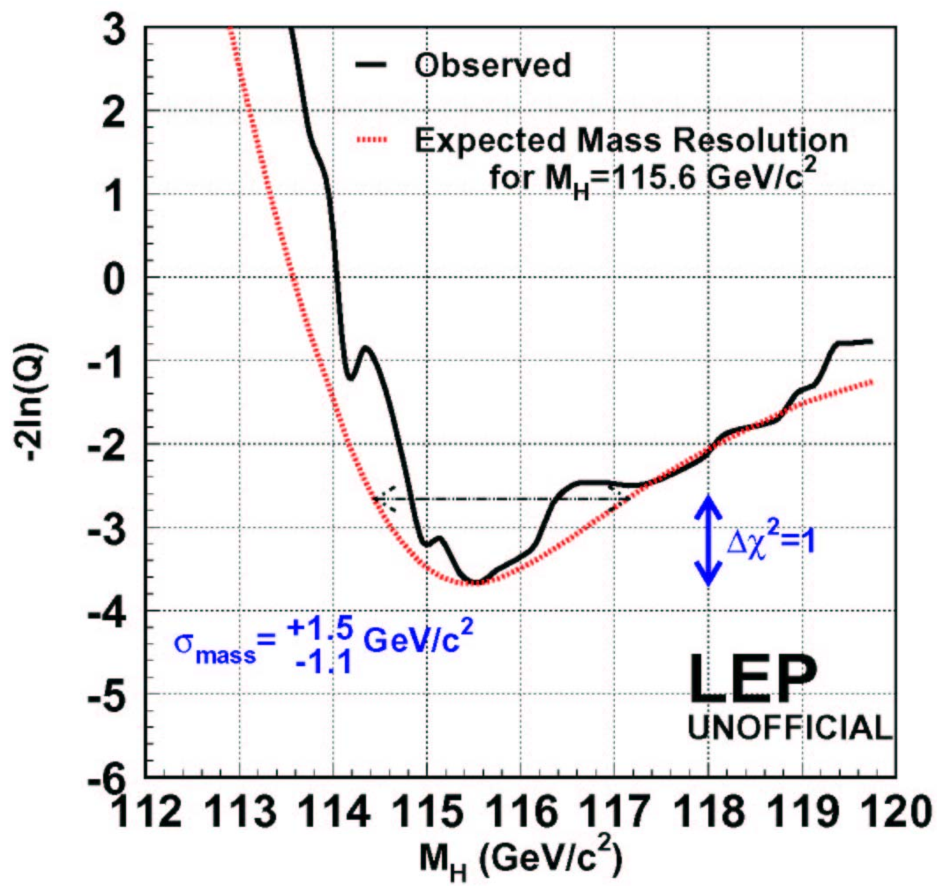


BY CHANNEL



If there is a Higgs

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



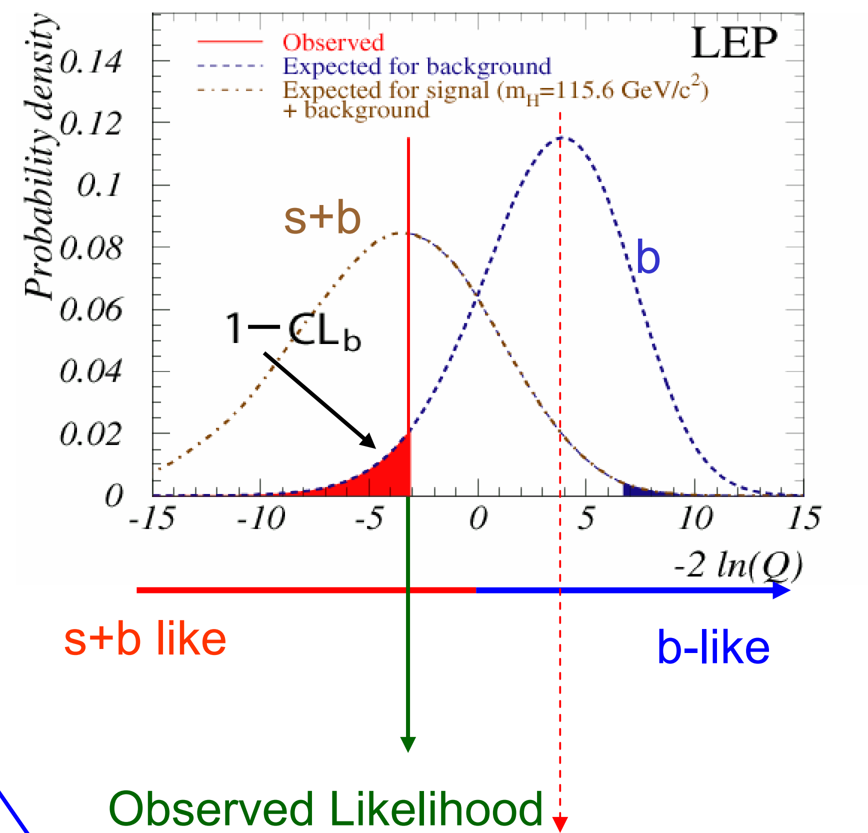
C. Tully DPF 2002

Confidence Levels

- How probable is a result of an experiment?
- The PDF of −2lnQ was created from an ensemble of "b" or "s+b" experiments
- $1\text{-}CL_b$ is the probability for a background only experiment to give a more signal-like likelihood than the observed one!
- LEP Result:

  $1\text{-}CL_b=0.034$ (2.1 σ)

- In 3.4% background experiments we expect to observe at least as signal-like result as we observe

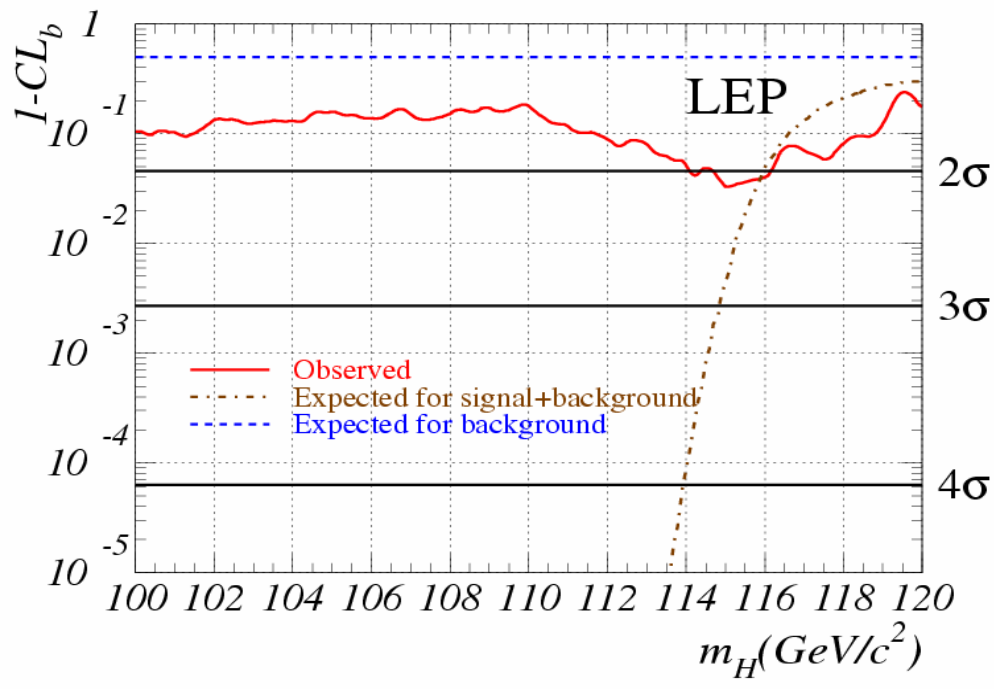


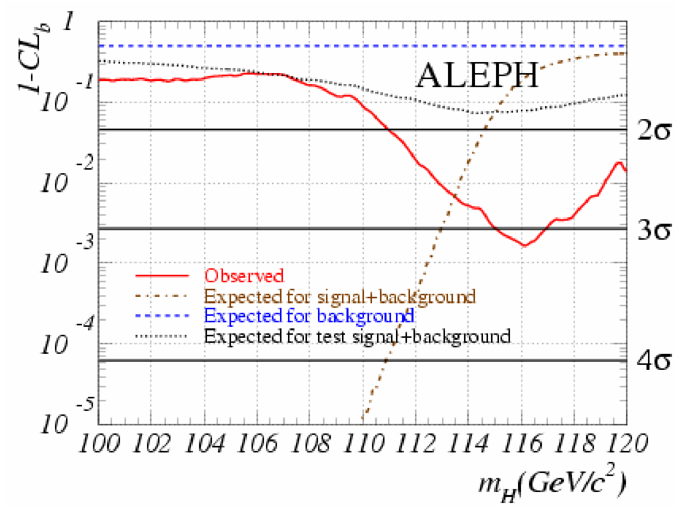
$$\langle 1-CL_b\rangle_b = 0.50$$

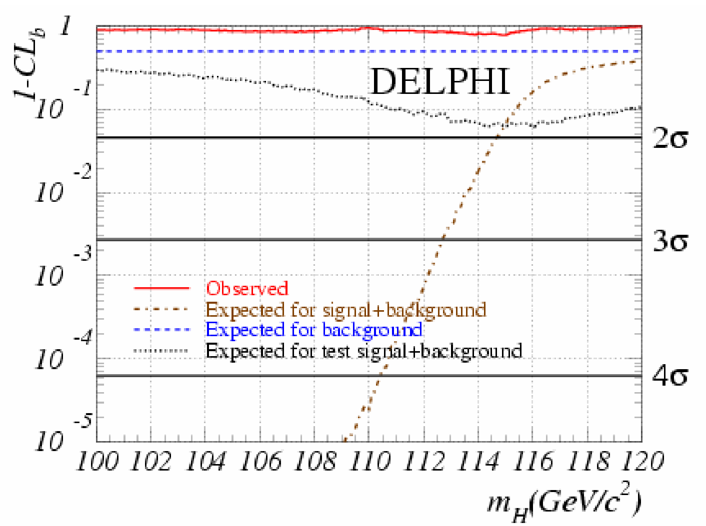
Aleph	2.0×10^{-3}
DELPHI	0.87
L3	0.24
OPAL	0.22
DLO	0.49

$1\text{-}CL_b$	0.32	0.046	2.7×10^{-3}	6.3×10^{-5}	5.7×10^{-7}
	1σ	2σ	3σ	4σ	5σ

A Higgs Discovery?



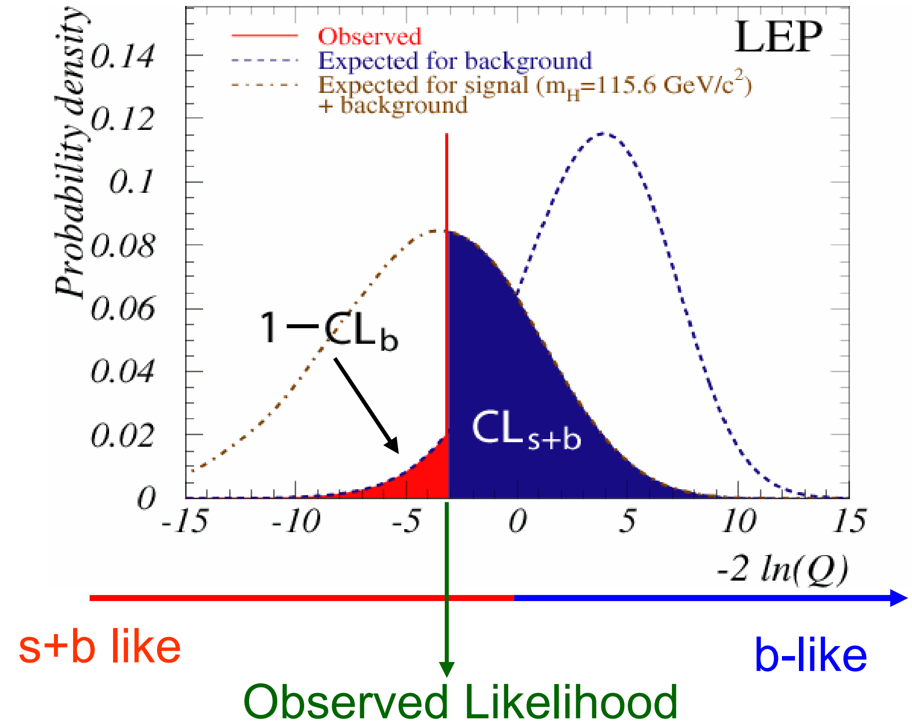




- Look for a minimum in $1\text{-}CL_b$
- A Higgs Discovery?
- Not really....

Signal CL

- CL_{s+b} measures the comatibility 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



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

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

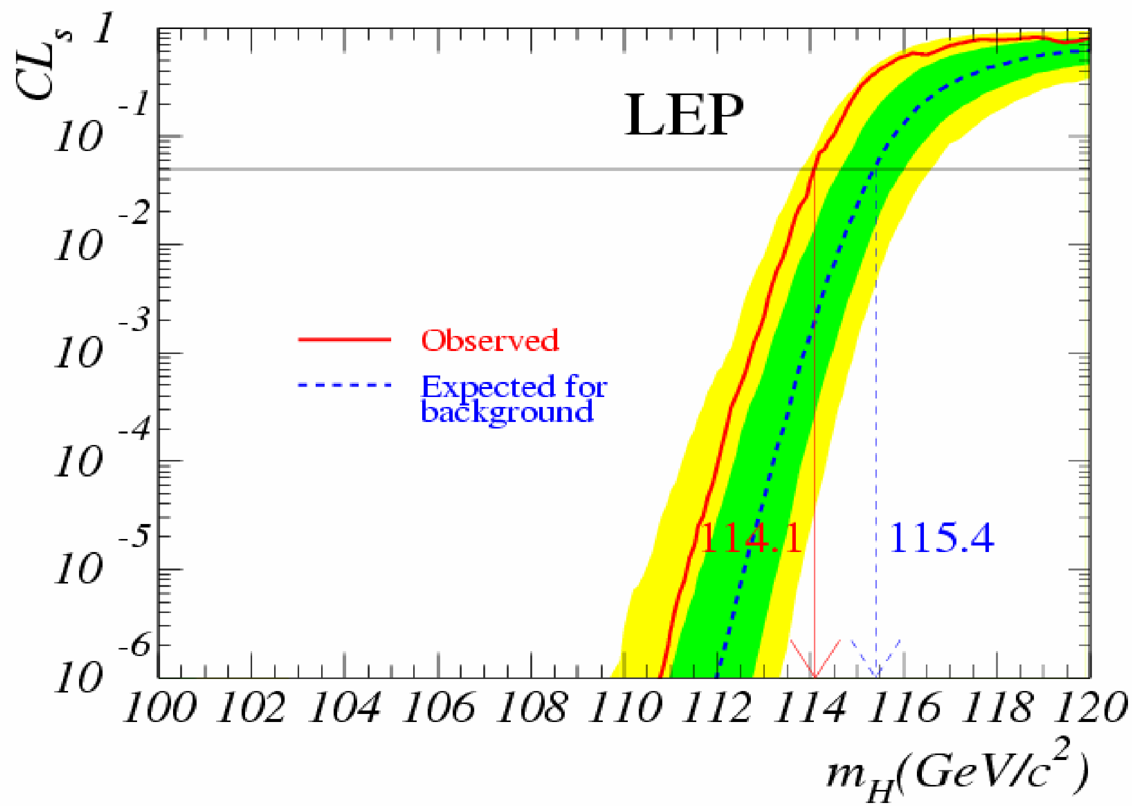
However, can they exclude a 115.6 "s" hypothesis?

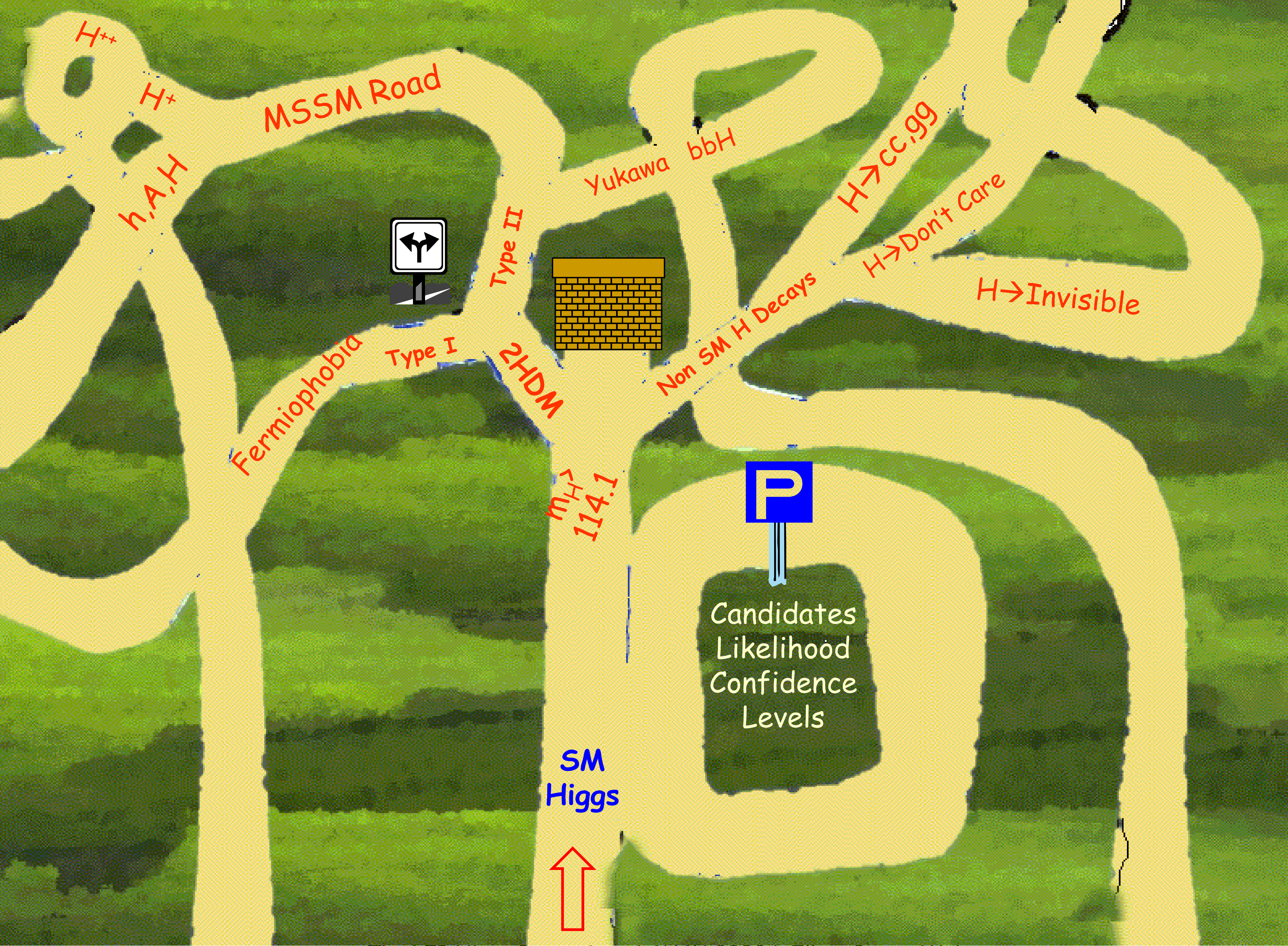
Define $$CL_s = \frac{CL_{s+b}}{CL_b}$$

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




H++
H+
h,A,H
MSSM Road
Yukawa
bbH
Type II
Type I
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$m_H > 114.1$
Non SM H Decays
H→cc,gg
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P
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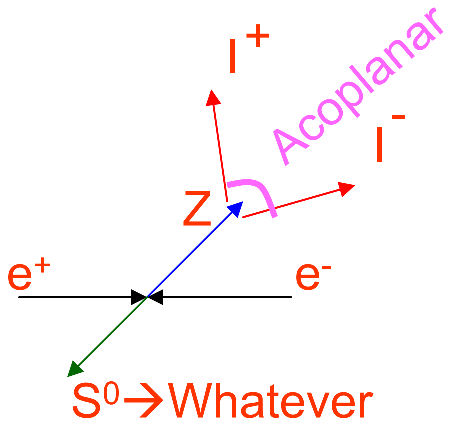
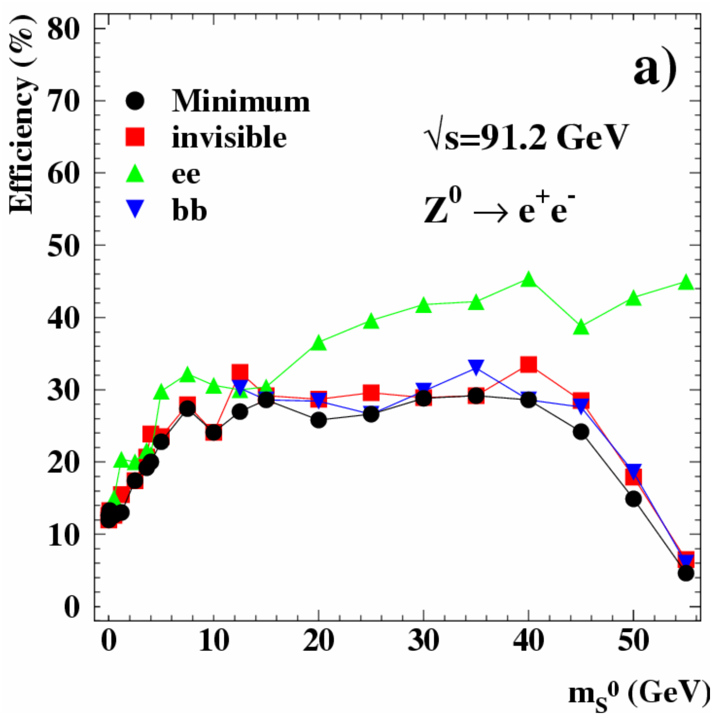
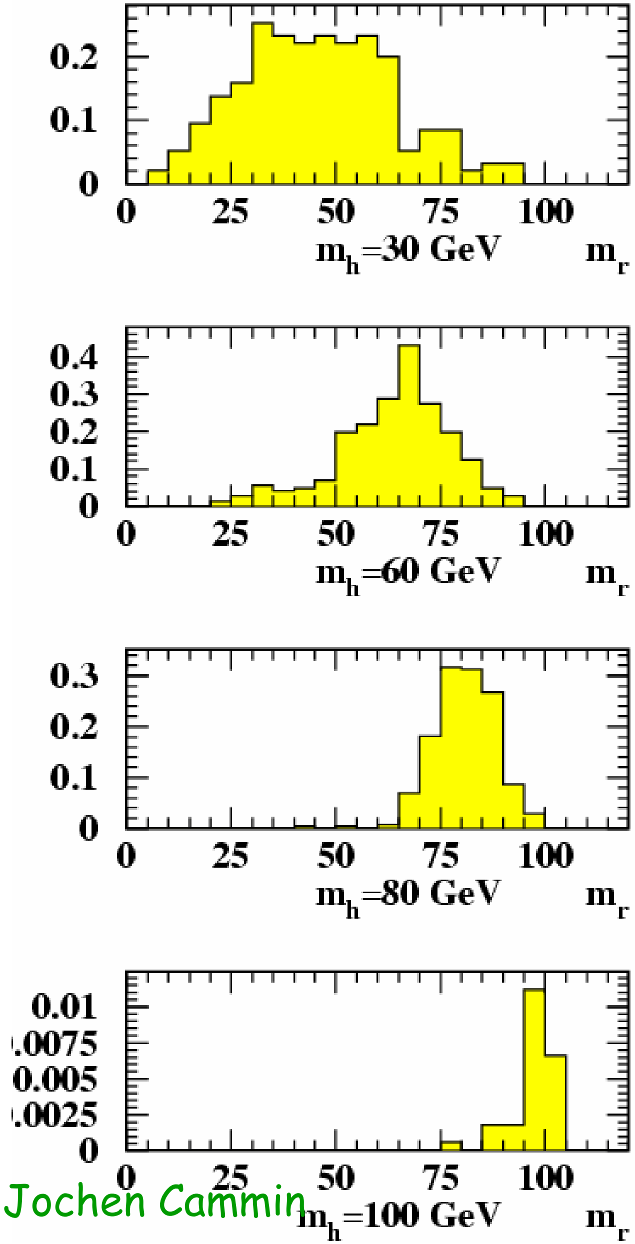
Higgs Decay Mode Independent Searches





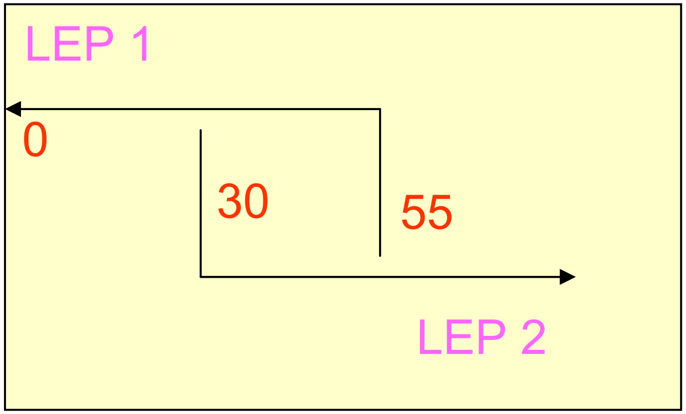
- Search for acoplanar leptons
- Look for a peak in the recoil mass, however, sensitivity is retained for continuous wide recoil mass
- LEP 1: Z is off shell
  - look for acoplanar leptons (μ's and e's) with m_{ll}>20 GeV
  - Use photon and conversions veto
  - For $S^0 \rightarrow \gamma\gamma$ and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

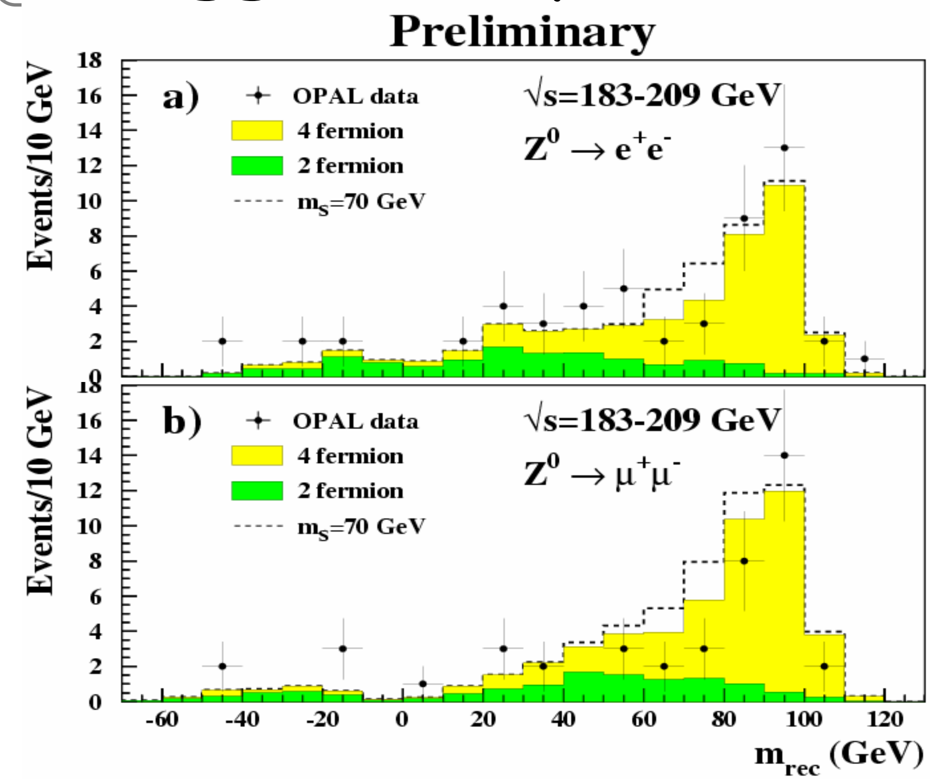


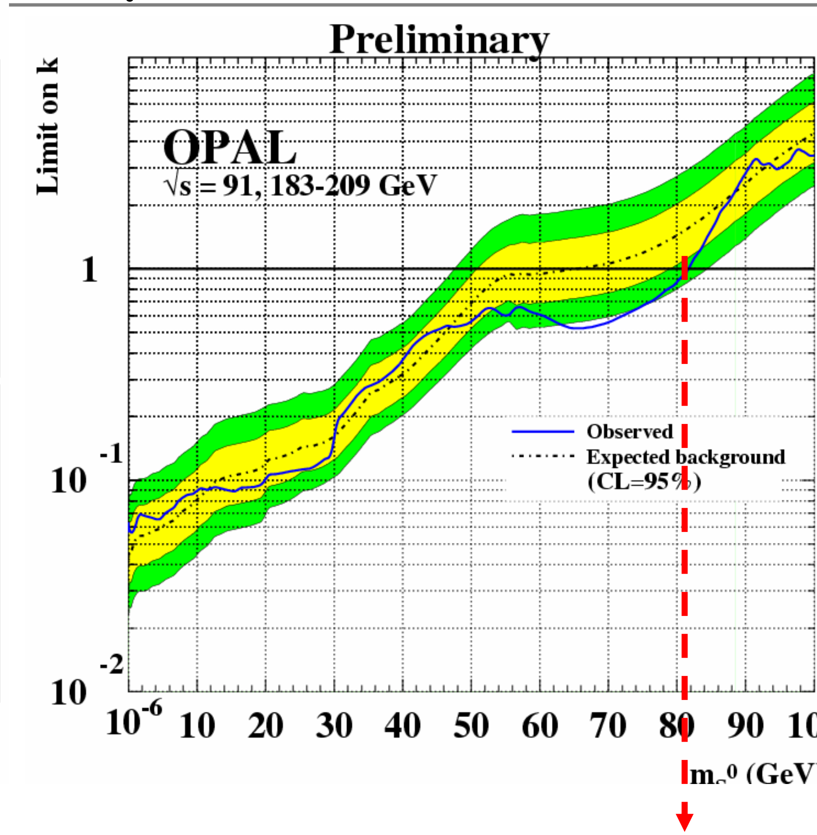
Jochen Cammin

- 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





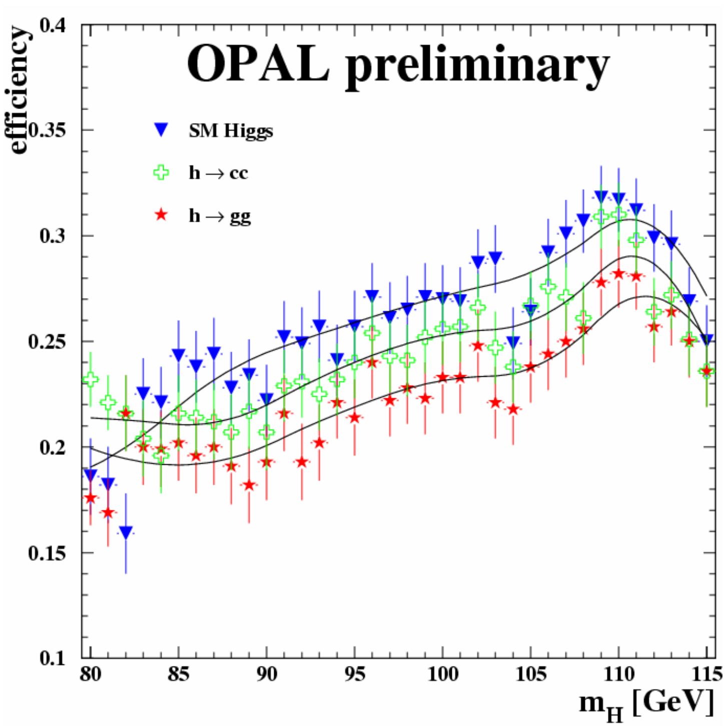
81

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

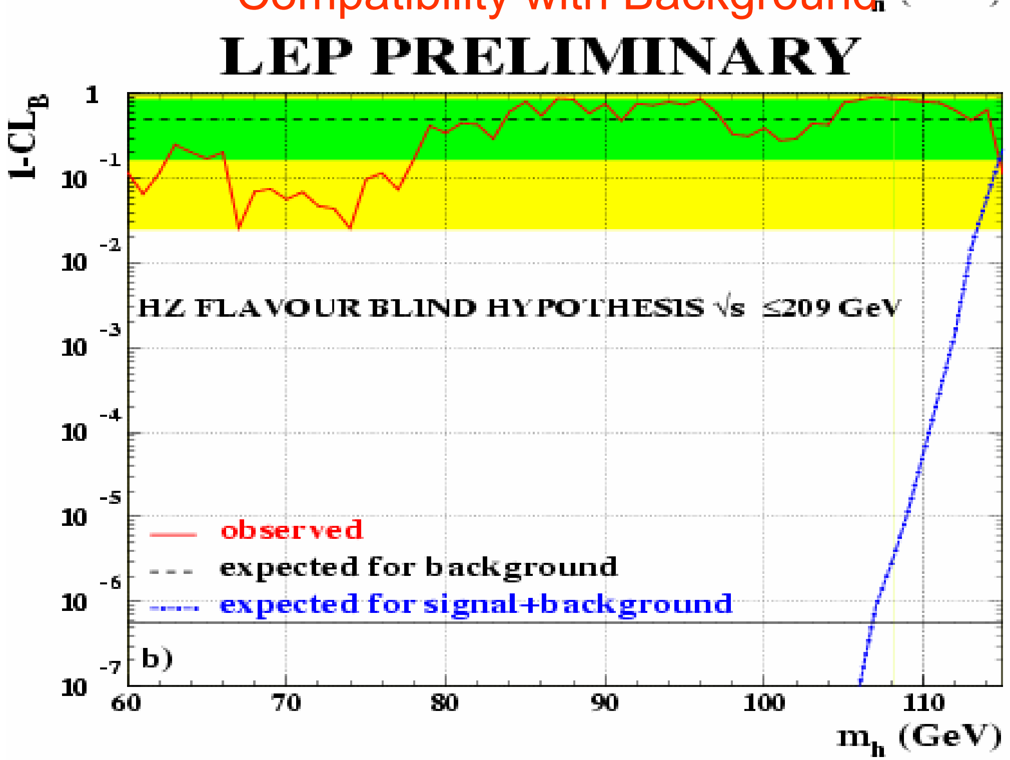
For more details see talk by Jochen Cammin

Flavour Independent Higgs Decay Modes

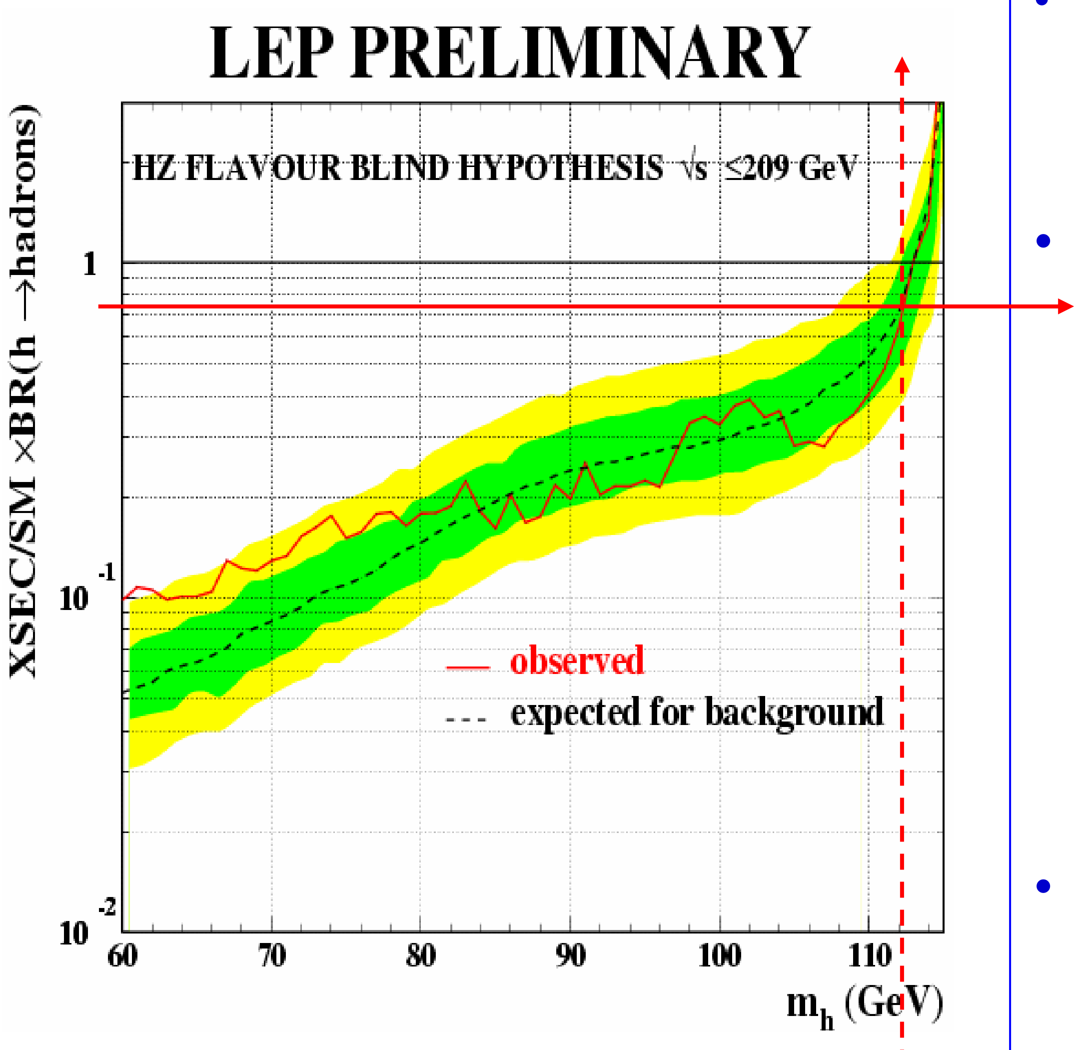
- In various Models H→bb suppressed
- Search for ee→hZ→qqqq,qqνν,qqll
- Optimize event selection for each test mass
- Take lowest efficiency



Compatibility with Background



Flavour Independent Higgs Decay Modes

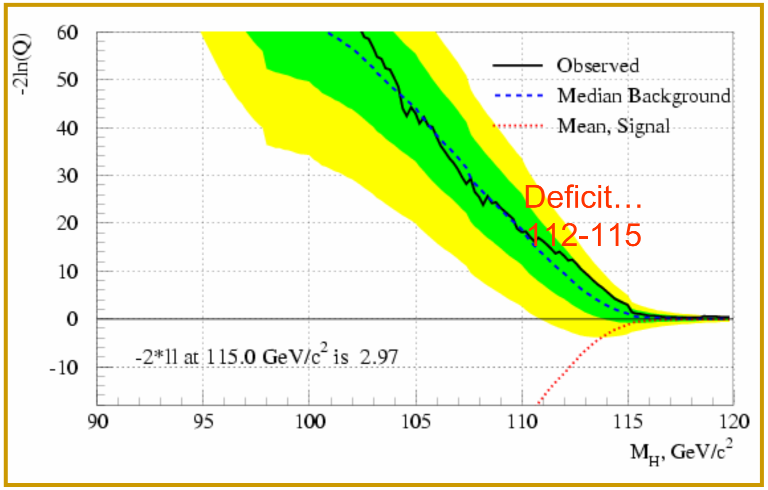


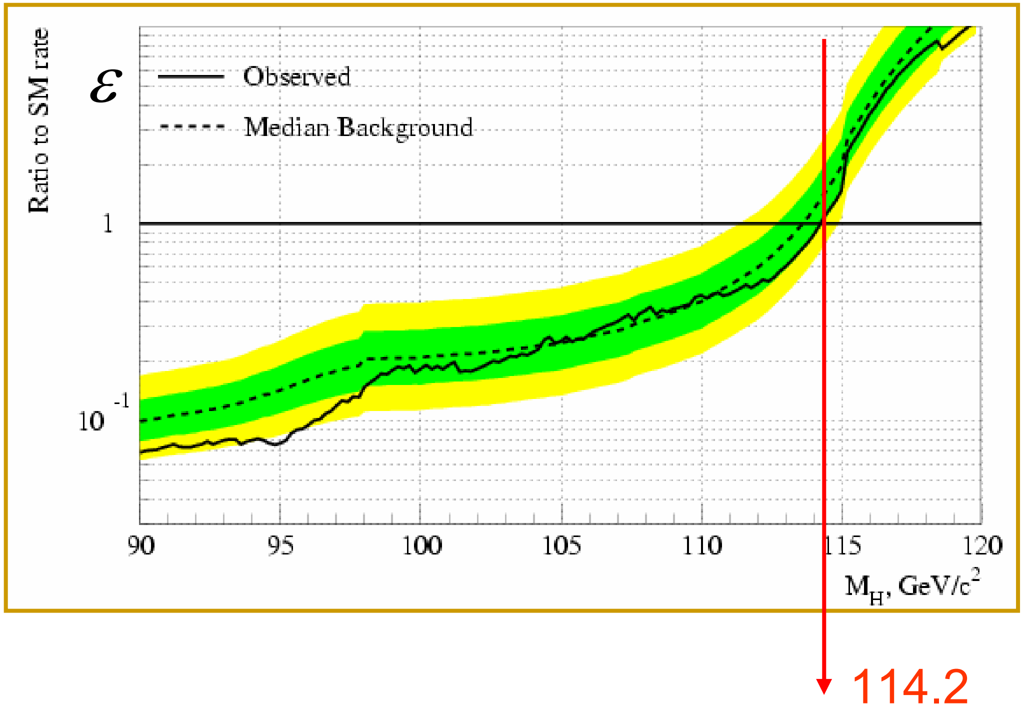
- 95% Upper Limit on the Production Cross-SectionxBR(hadrons)
- For SM-like BR of ~75% (typical for m_H~115 H→bb) a Higgs boson with mass below 112 GeV is excluded, this is almost as strong as the SM Higgs Boson limit (114.1 GeV)
- mH>112.9 (113.0) GeV With BR(H→hads)=1.0

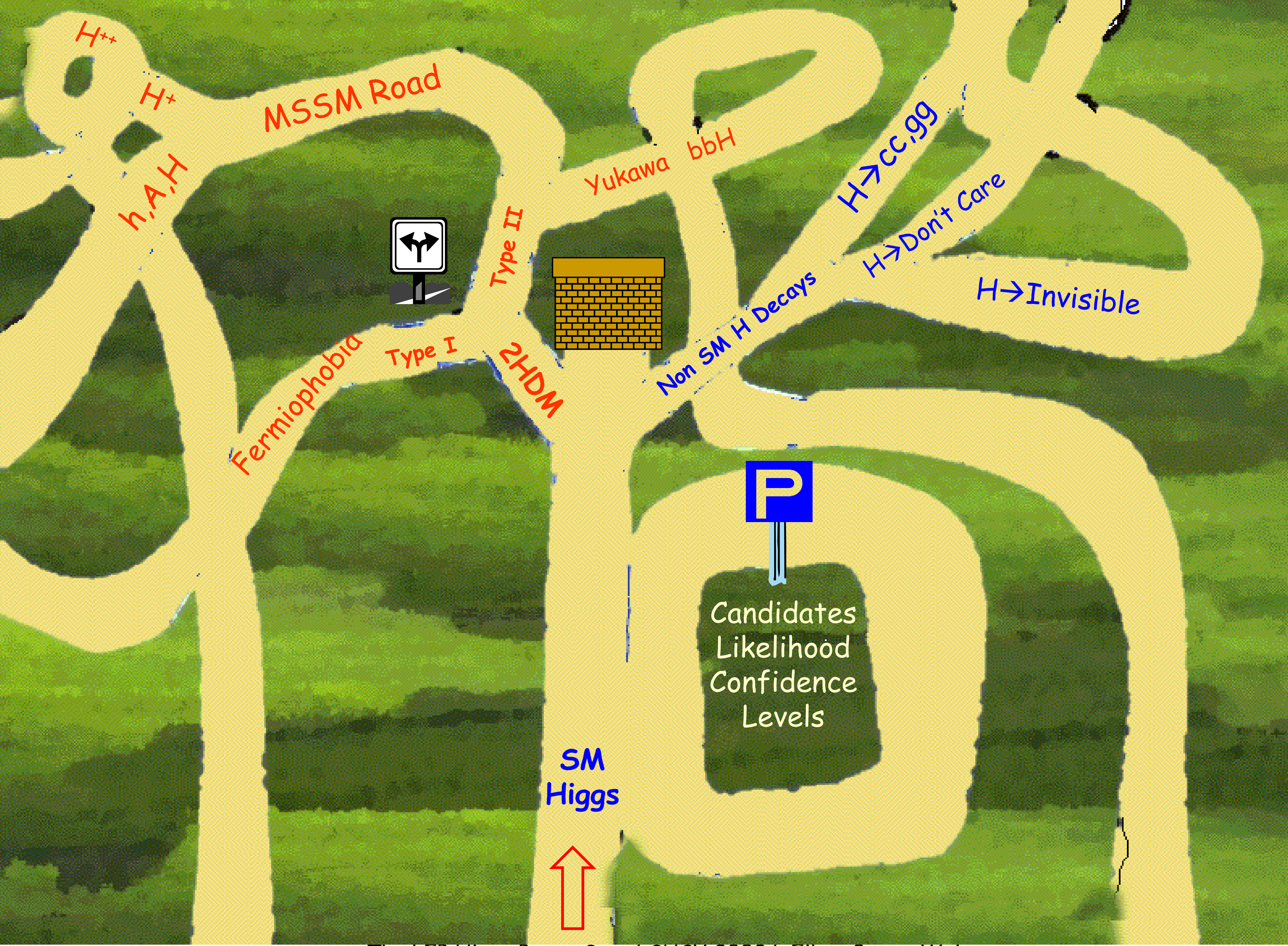
For Exotic Higgs Searches see talk by Marcel Stanitzki

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
  (μ,e and τ 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







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2 Higgs Doublets Models (2HDM)

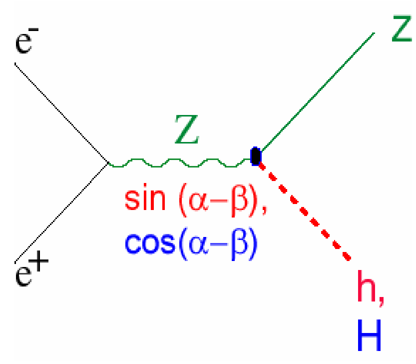
- Addition of doublets to the SM keeps the parameter $\rho_{tree} = \frac{m_W}{m_Z \cos\vartheta_w} = 1$

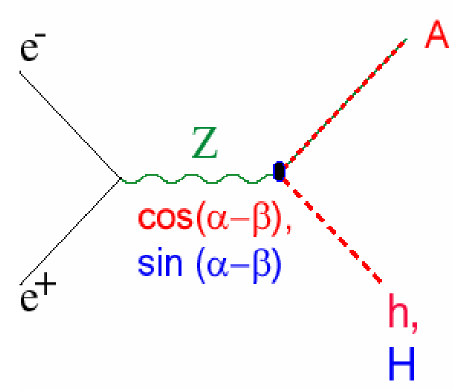
$$H_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \qquad H_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

- Real parts mix with an angle α 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:

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

- Complementarity

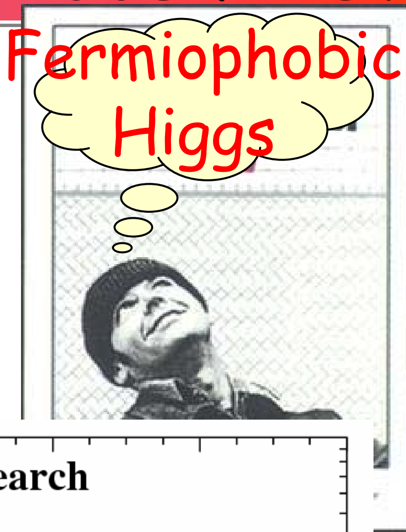




$$\sigma_{hz} = \sigma_{HZ}^{SM} \sin^2(\alpha-\beta) \qquad \sigma_{hA} = \sigma_{HZ}^{SM} \lambda \cos^2(\alpha-\beta)$$

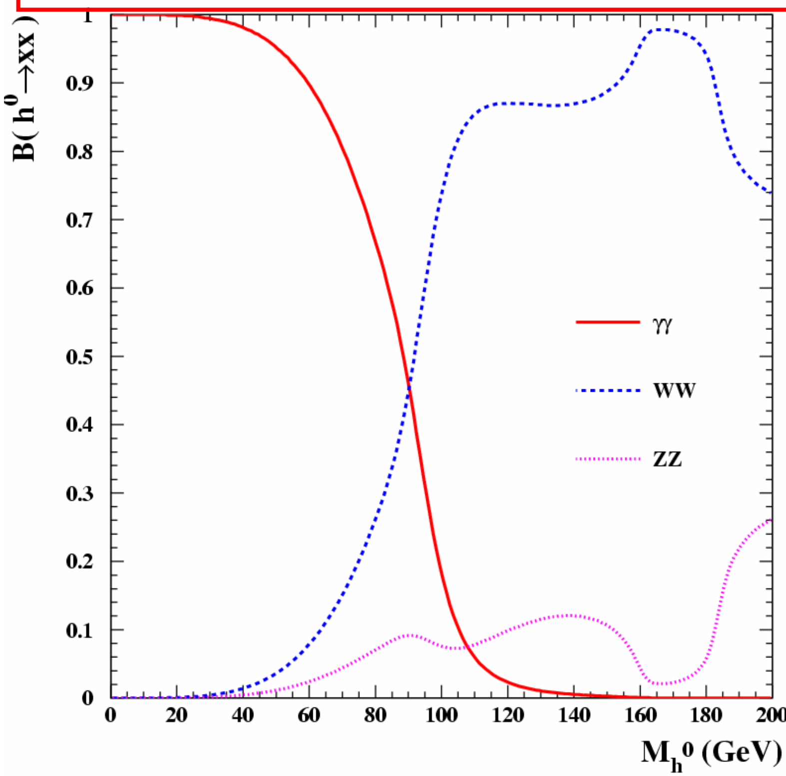
Couples to	Type I	Type II
d-type leptons	H_2	H_1
u-type quarks	H_2	H_2
d-type quarks	H_2	H_2
	$g_{hff} \sim \cos\alpha$ For α=π/2 fermiophobic	e.g. MSSM

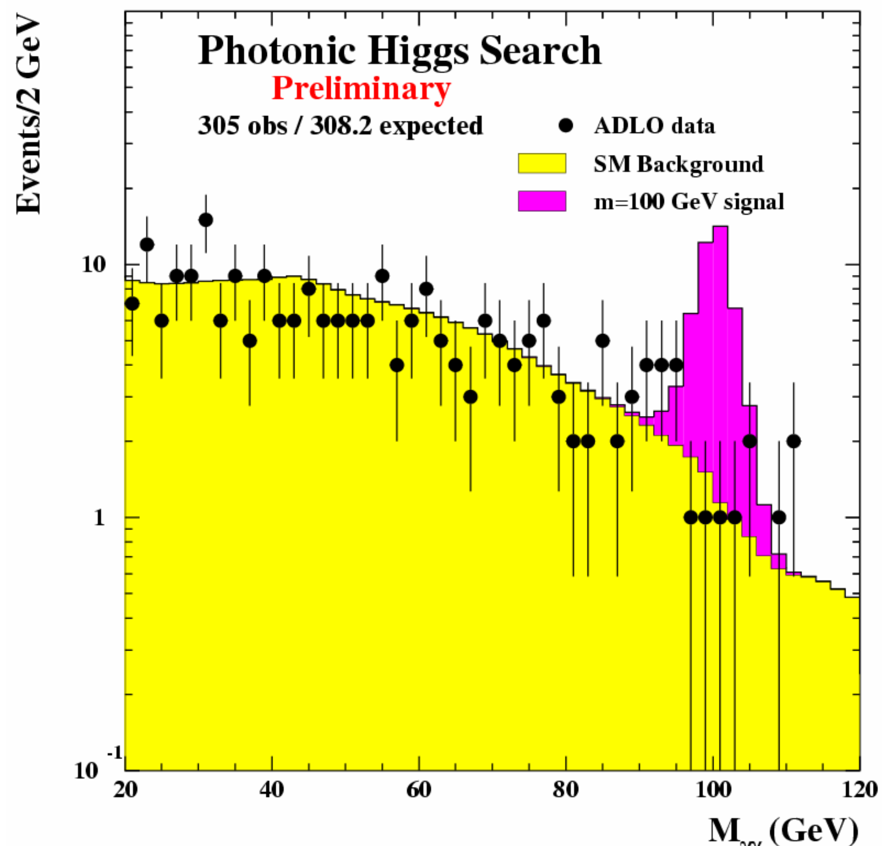
2HDM(I): One Higgs Over the Cuckoos Nest



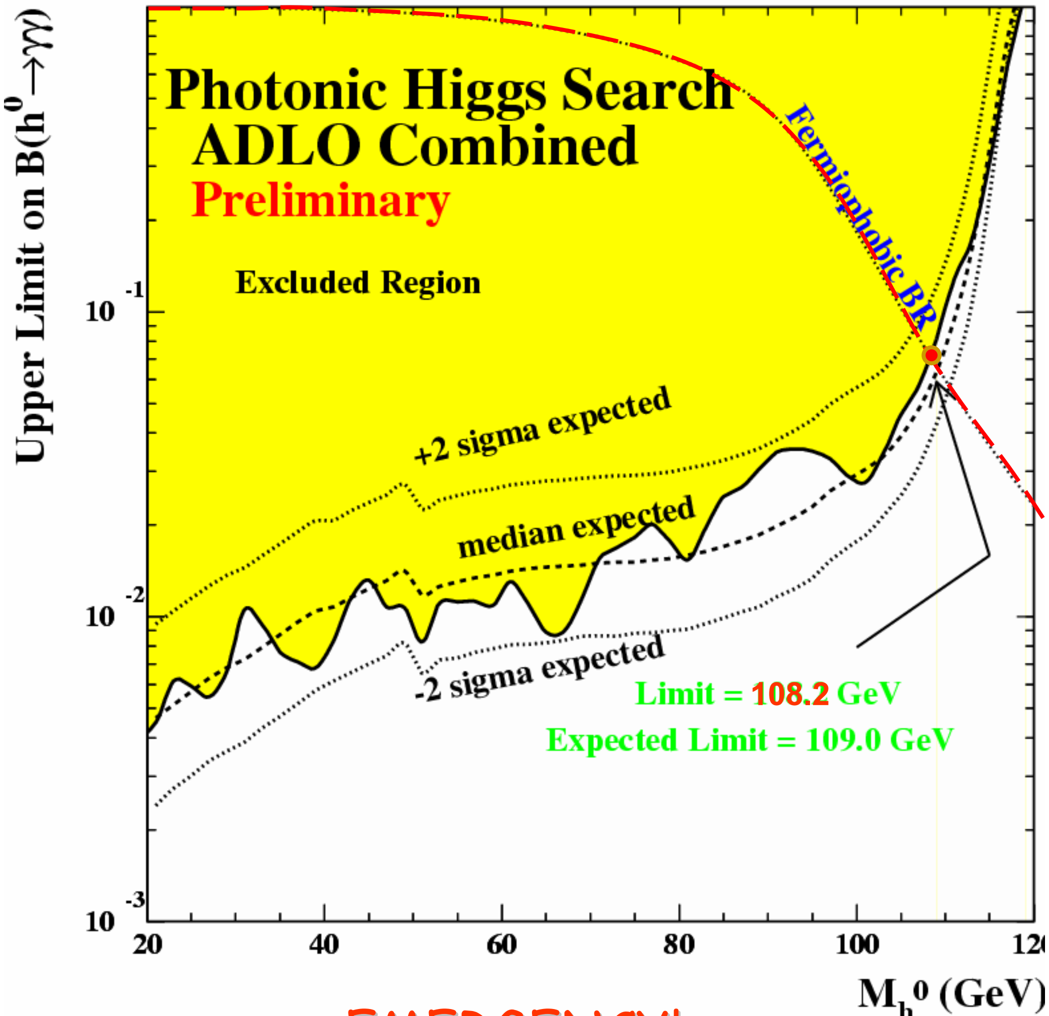
- In 2HDM (type I) and other models H→γγ,WW dominantly.
- All experiments searched for the two-photons final state. L3 also searched for the WW decay mode.

SM BRs with fermionic modes turned off





One Higgs Over the Cuckoos Nest - Fermiophobic



EMERGENCY!

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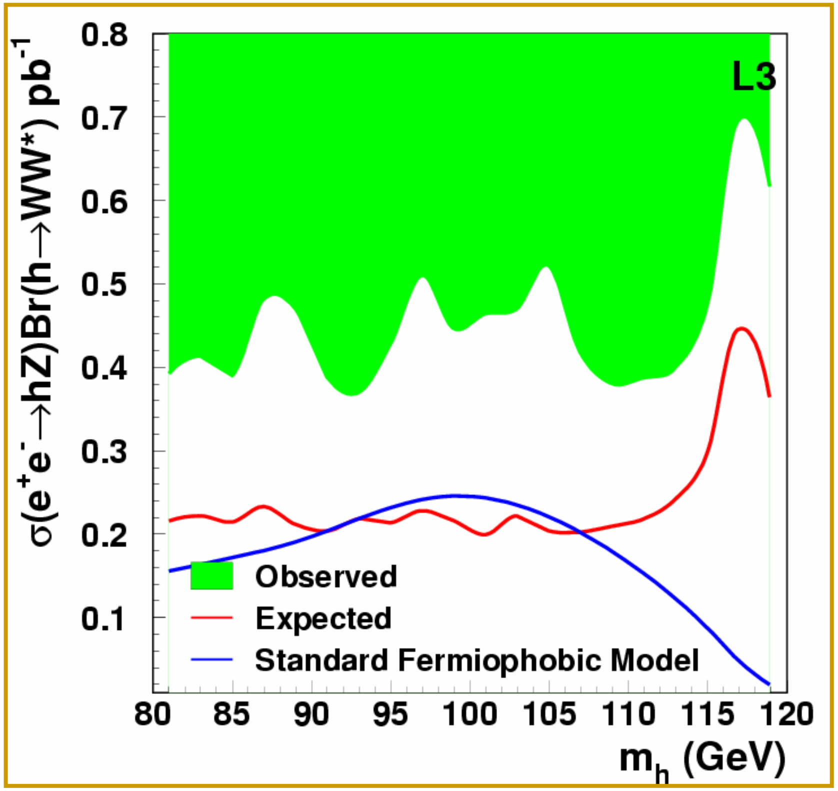
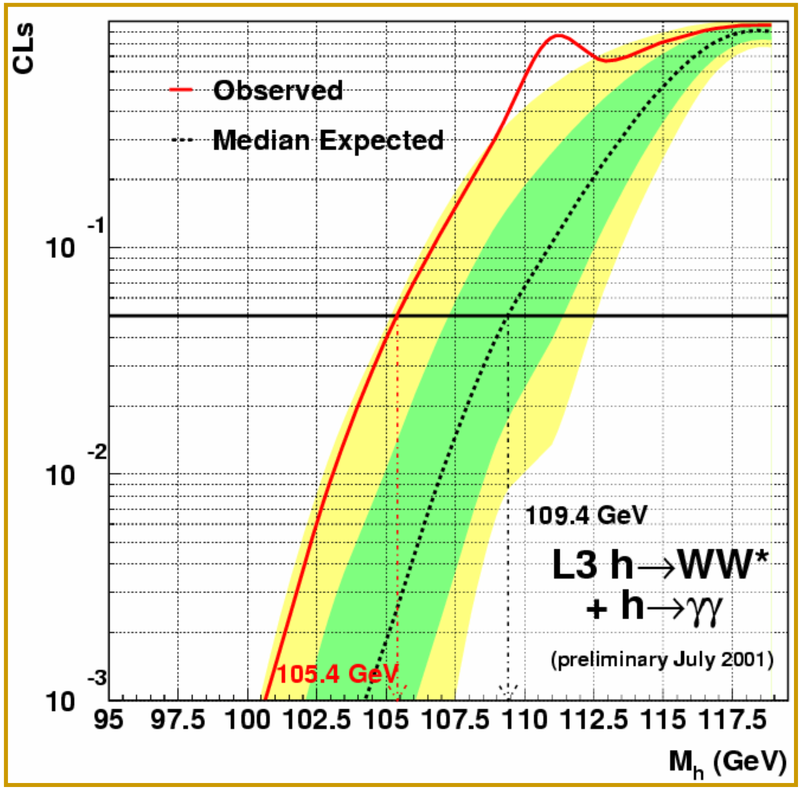
- Higer expected σxBR are easier to exclude
- LEP published a combined upper limit on the H→γγ BR
- Assuming a Fermiophobic Higgs one gets m_H>108.2 (109.0) GeV lower limit on the Higgs mass
- A 115 GeV Fermiophobic Higgs has a BR(H→gg)<0.3 and is therefore NOT excluded
- Individual experiments limits based on H→γγ: 106.4 (Aleph),105.4(L3)…

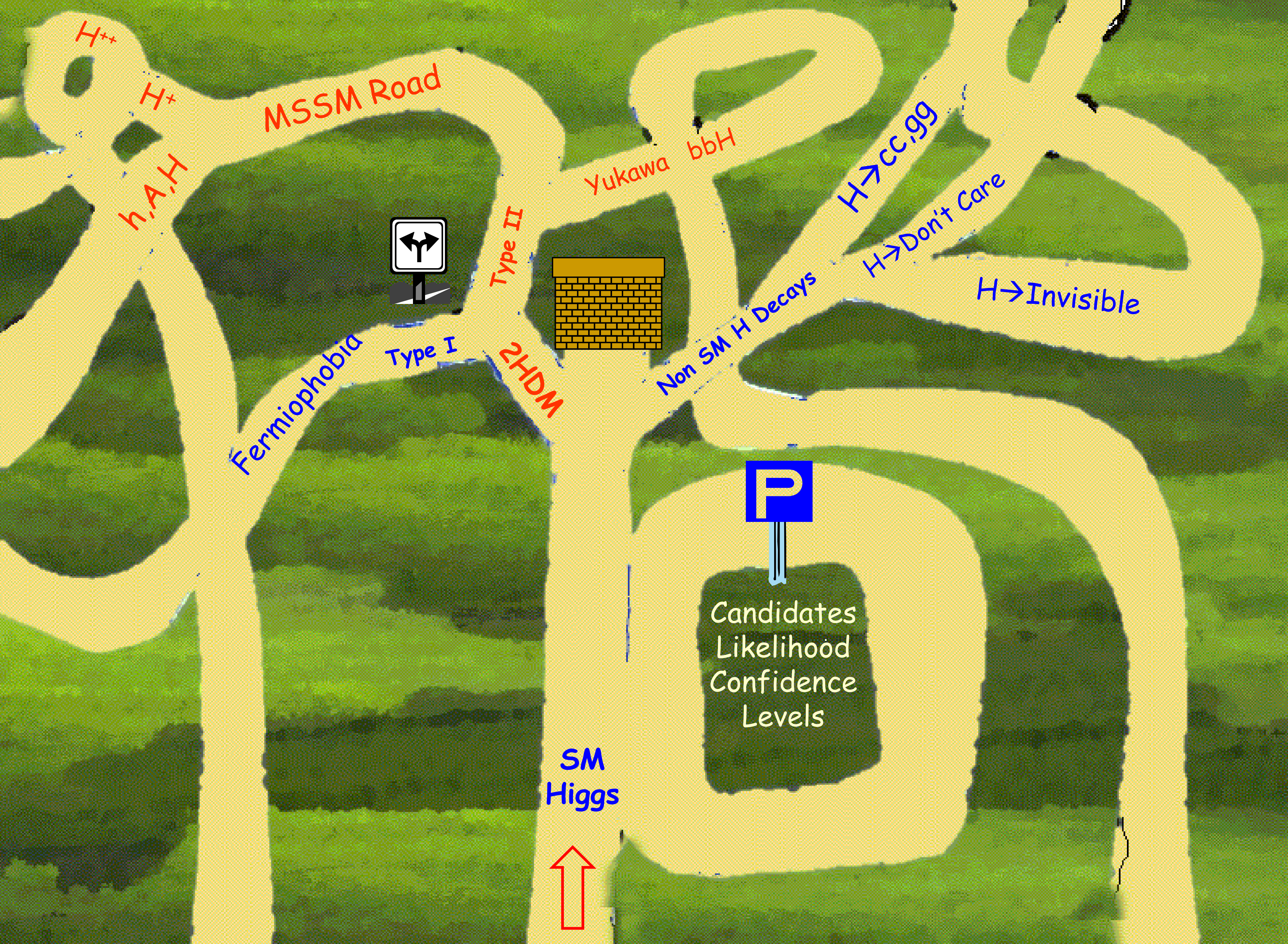
Fermiophobic Higgs: h→WW Decay Mode

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





For more details see talk by Marcel Stanitzki



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Two Higgs Double Models (2HDM) type II

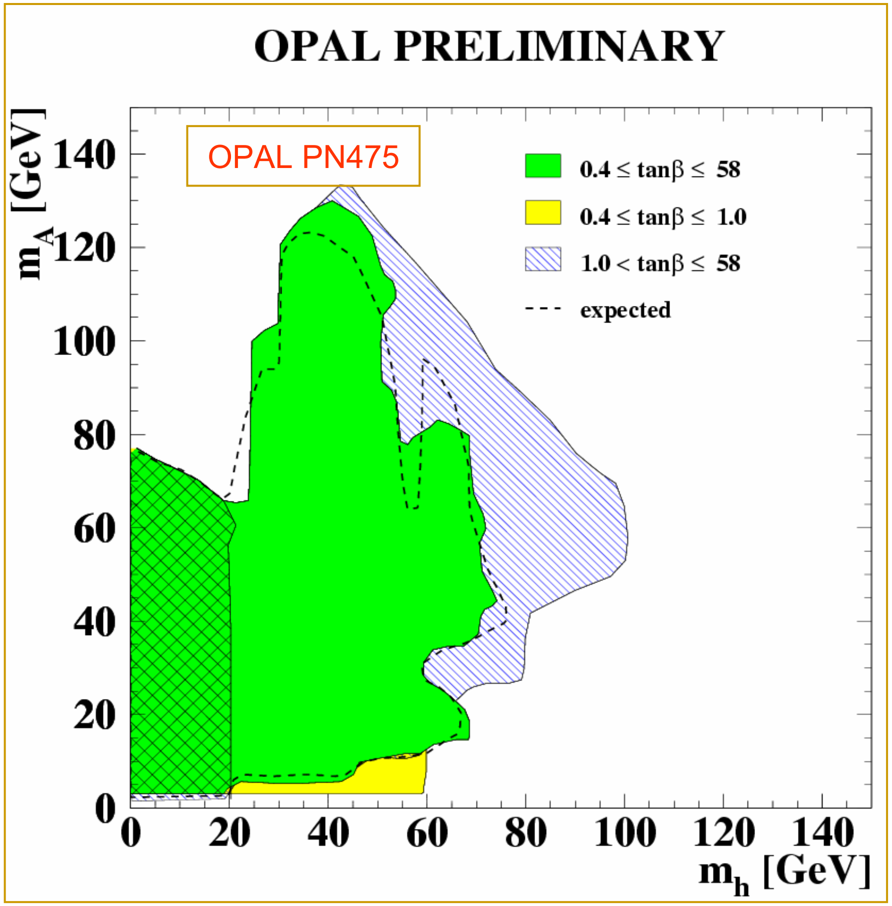
- $$hc\bar{c} : \frac{\cos\alpha}{\sin\beta}; \quad hb\bar{b} : -\frac{\sin\alpha}{\cos\beta};$$
  $$Ac\bar{c} : \cot\beta; \quad Ab\bar{b} : \tan\beta$$

- Parameter Scan in General 2HDM(type II)

$$1 \le m_h \le 120\ GeV$$
$$3 \le m_A \le 2000\, GeV$$
$$0.4 \le \tan\beta \le 58.0$$
$$\alpha = \pi/2,\ \pi/4,\ -\pi/4,\ -\pi/2$$

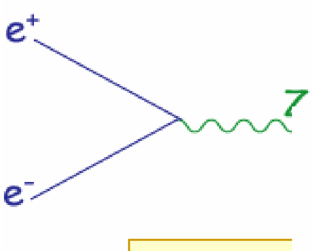
$$m_{H^\pm} \quad and \quad m_H$$
$$beyond \ \ kinematic \ \ reach$$

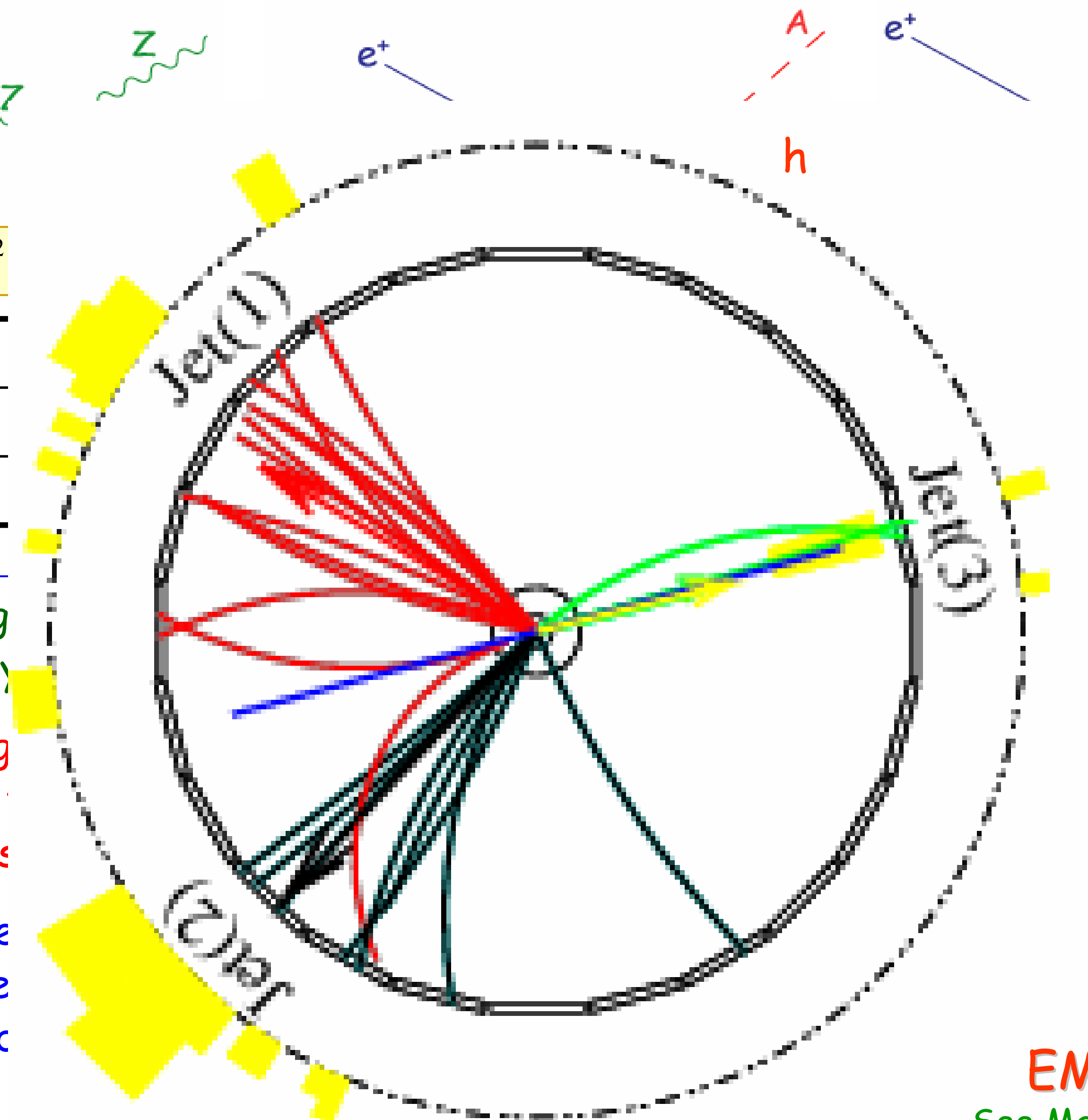
- Below tgβ=0.4 m_A and m_h not well defines, below m_A~3 radiative correctuons unstabe

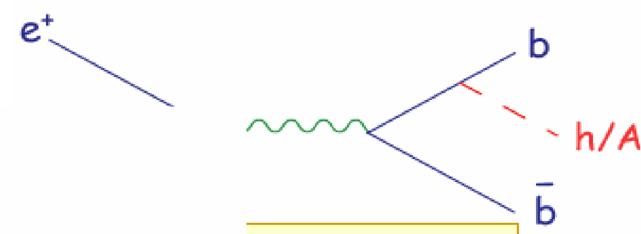


The lower you allow tgβ the exclusion is weaker

Yukawa Production of Light Higgs



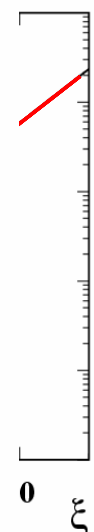




$\sigma \sim \sin^2$

$m_f^2 \cdot \xi_f^2(\alpha,\beta)$

A
h



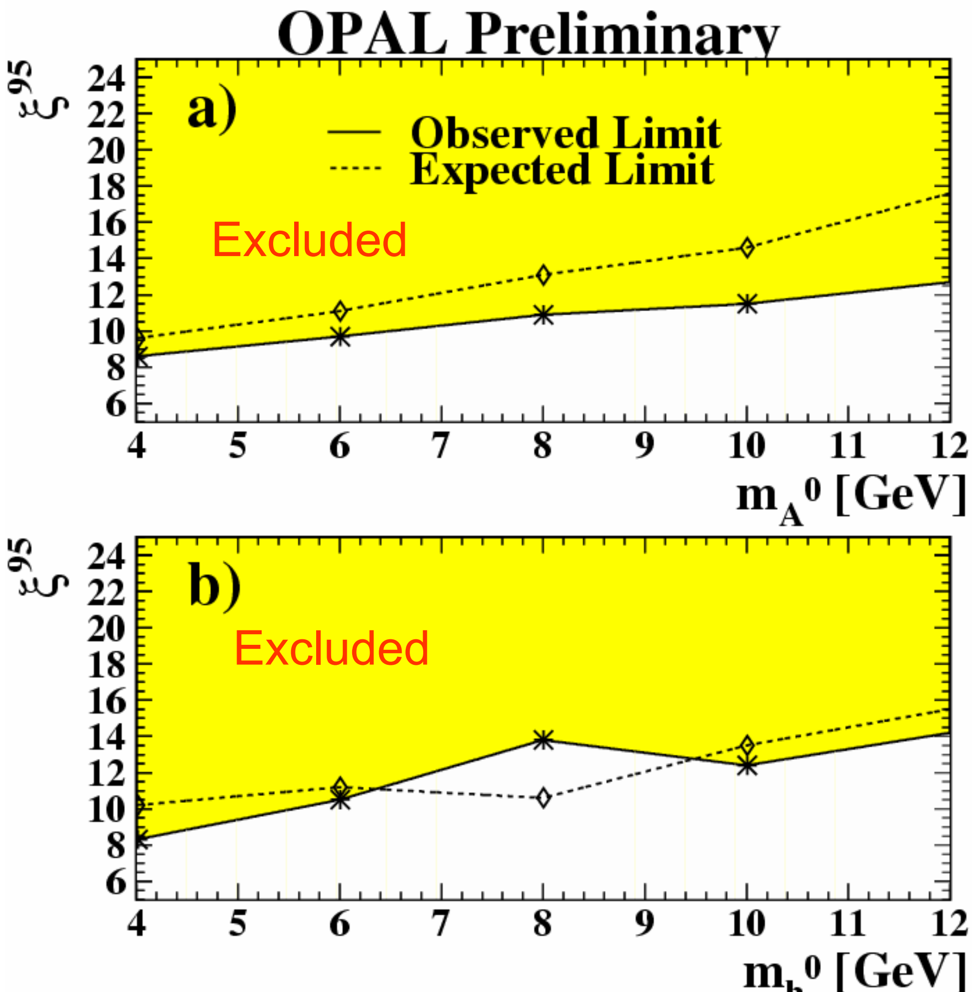
- A light Hig
  could easily
- Even thoug
  luminosity
  of Z→bb is
- Analysis pe
  data in the
  (OPAL) and
  Prel)

EMERGENCY!

See Marcel Stanitzki Talk

Yukawa Production of Light Higgs

- With BR($h \rightarrow \tau\tau$)=100% one finds limits on
  - ξ_A^b~8.6-11.6 and
  - ξ_h^b~8.3-13.8



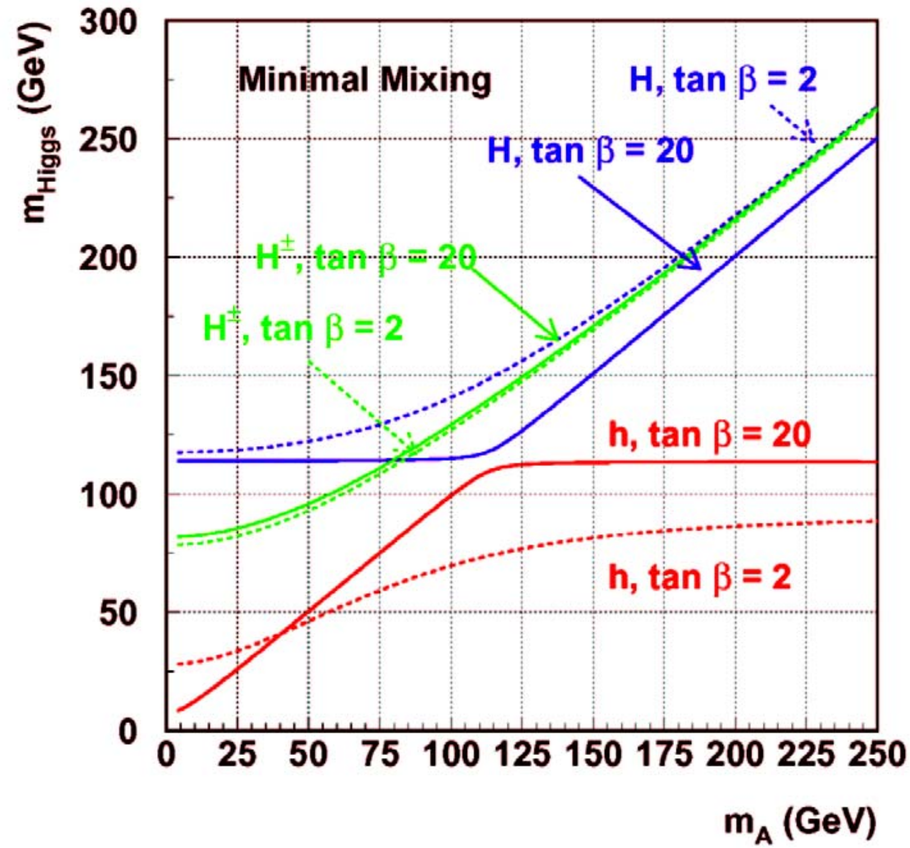
MSSM

- MSSM is a 2HDM type II Supersymmetric Model
- Tree level: 2 pars (m_h, m_A) or $(tg\beta, m_h)$ or (tgb, m_A) determines α 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 $tg\beta$ gets bigger $m_h \sim m_A$ till it saturates at mh_{max}

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

MSSM - Radiative Corrections

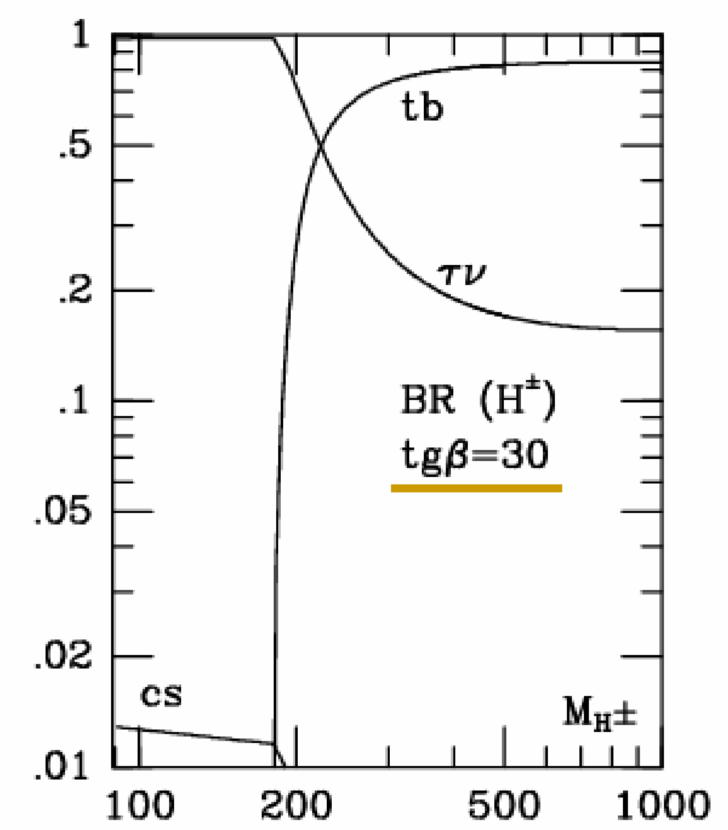
- $$m_h^2 = m_Z^2 \cos^2 2\beta \quad f_1\left(\frac{m_t^2}{v^2}\log\frac{m_s^2}{m_t^2}\right) + \frac{m_t^4}{v^2} f_2\left(\tilde{A}_t, \log\frac{m_s^2}{m_t^2}\right)$$
- $$\boxed{m_s = \sqrt{\frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{2}}}$$ A_t The trilinear Higgs-stop coupling $\boxed{A_t g_{ht\bar{t}} \varepsilon_{ij} H_2^j \tilde{Q}^i \tilde{t}_R^*}$
- A_t controls the mixing in the stop sector $$\boxed{\begin{pmatrix} m_{\tilde{t}_L}^2 & m_t \tilde{A}_t \\ m_t \tilde{A}_t & m_{\tilde{t}_R}^2 \end{pmatrix} \Rightarrow m_{\tilde{t}_1}, m_{\tilde{t}_2}}$$
  $$\tilde{A}_t = A_t - \mu \quad ctg\beta$$
- μ Higgs mixing parameter $\boxed{\mu \varepsilon_{ij} \hat{H}_1^i \hat{H}_2^j}$
- Charged Higgs mass can go Below the W mass for small A mass

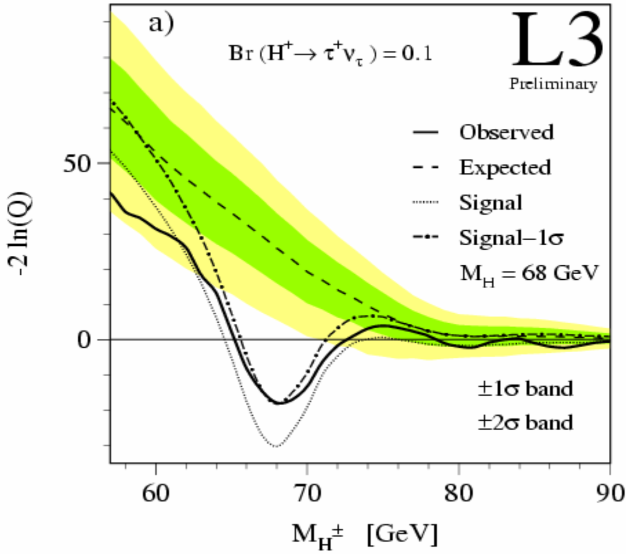
$$\boxed{m_{H^\pm} \approx m_A^2 + m_W^2 + \frac{\mu^2 m_t^4}{\sin^2\beta} f\left(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2\right)}$$

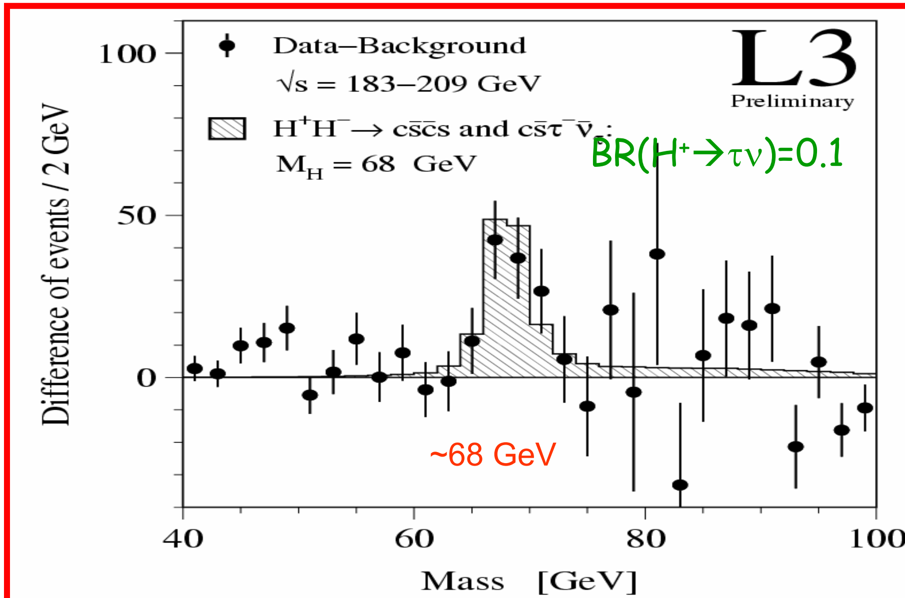
L3 Charged Higgs Anomaly

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

Djouadi, Kalinowski, Zerwas, hep-ph/9511342



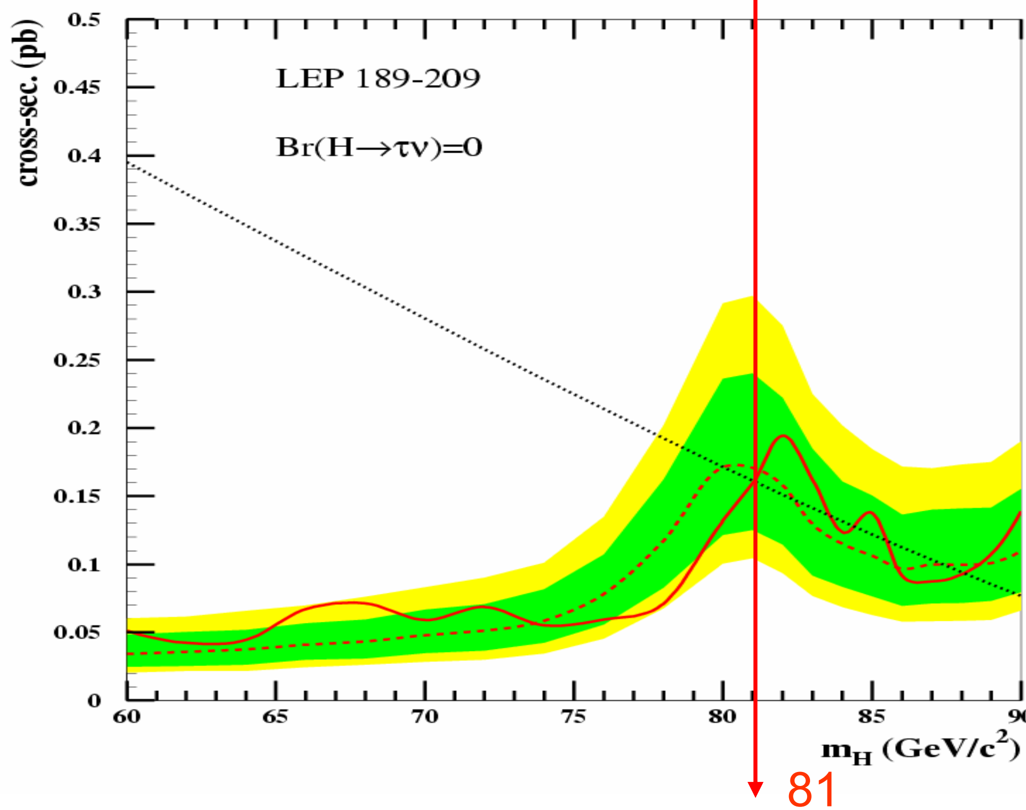


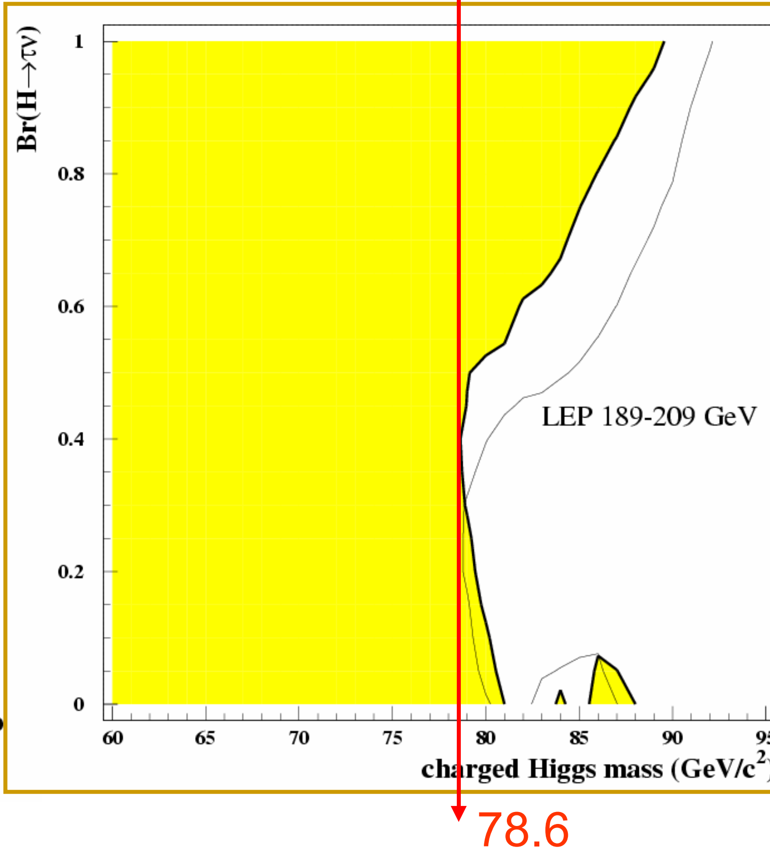


- This 4.2σ anomaly has not been seen by any other experiment!

Charged Higgs

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





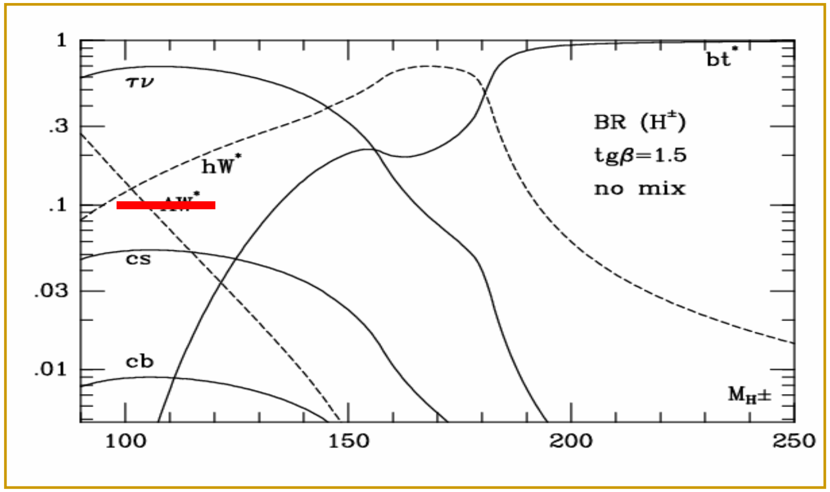
- There is loss of sensitivity near m_W
- LEP combined limit

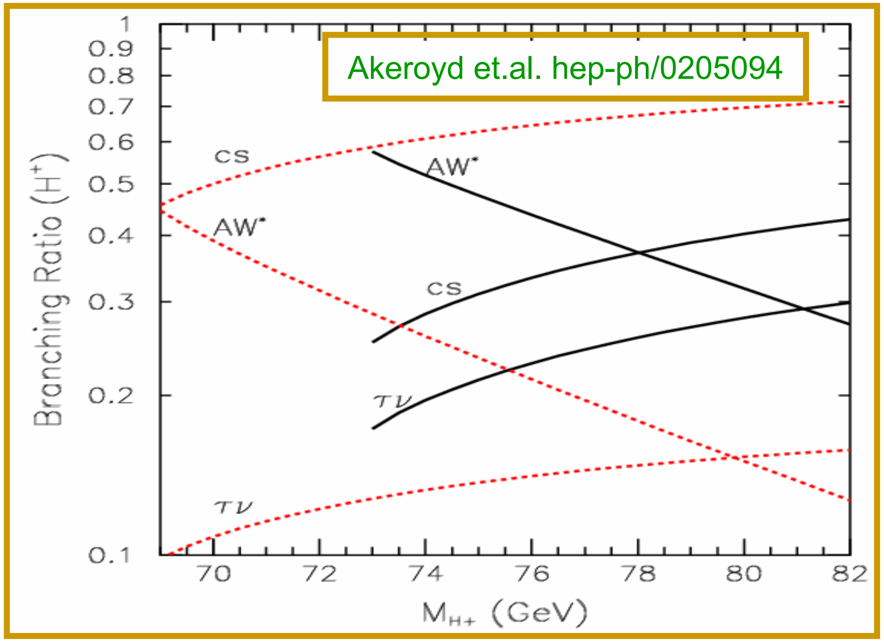
$m_{H^+} > 81 \ GeV \ \ for \ \ BR(H^+ \to \tau\upsilon) = 0$

$m_{H^+} > 78.6 \ GeV \ \ for \ \ any \ BR(H^+ \to \tau\upsilon)$

Charged Higgs At Low tg β

Djouadi, Kalinowski, Zerwas, hep-ph/9511342





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

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

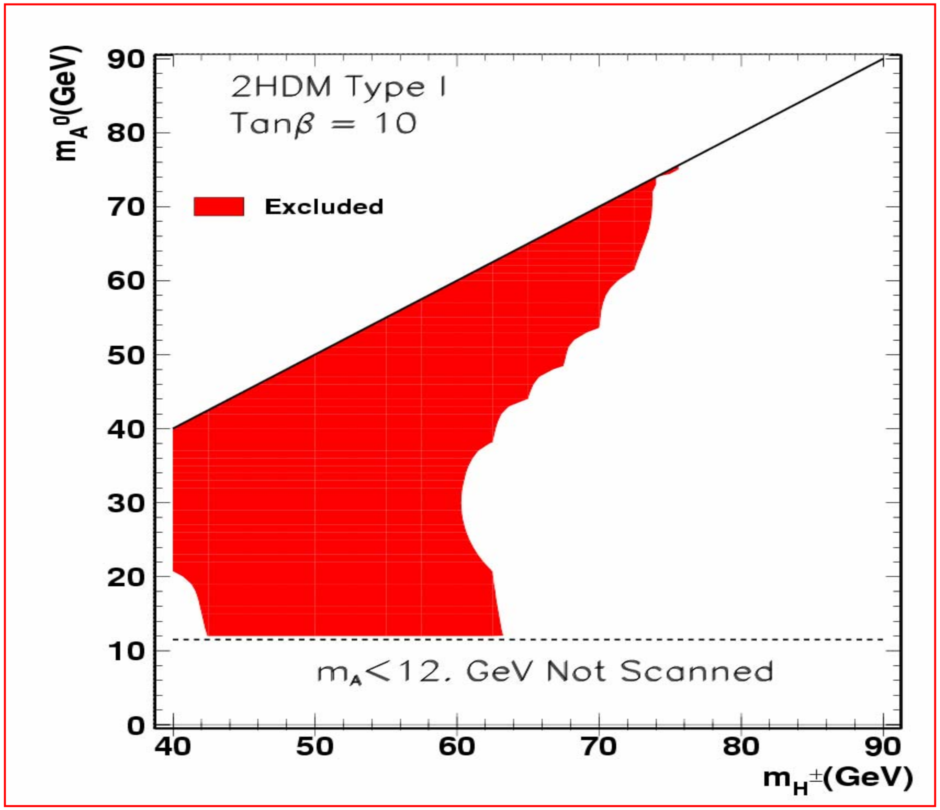
  BREAKS!
- The $H^+ \to AW^{*+}$ decay mode must be taken into account!
- LEP has just now started to look into that (in the framework of 2HDM (II)
- However…. next

EMERGENCY!

See Marcel Stanitzki Talk

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

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



EMERGENCY!
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Search for Doubly Charged Higgs Boson

- Doubly charged Higgs bosons, $H^{\pm\pm}$ exist in LR symmetric models
- In LR symmetric models $\sigma\left(ee \to H_L^{++} H_L^{--}\right) \neq \sigma\left(ee \to H_R^{++} H_R^{--}\right)$
- $H^{++} \to e^+e^+, \mu^+\mu^+, \tau^+\tau^+, e^+m^+, \ldots$
- $\Gamma\left(H^{++} \to \tilde{l}^+ l^+\right) \sim h^2_{H\tilde{l}^+l^+} \cdot m_{H^{++}}$
- Indirect constraints

$$\mu^- \to e^- e^+ e^- \quad \Rightarrow h_{He\mu} h_{Hee} < 4.7 \cdot 10^{-11}\, GeV \cdot m^2_{H^{++}}$$
$$Bhabha \quad \Rightarrow h^2_{Hee} < 9.7 \cdot 10^{-6}\, GeV \cdot m^2_{H^{++}}$$
$$\mu^+ e^- \to \mu^- e^+ \quad \Rightarrow h_{Hee} \cdot h_{H\mu\mu} < 5.8 \cdot 10^{-5}\, GeV \cdot m^2_{H^{++}}$$

Huitu-Maalampi
Hep-ph/9410342

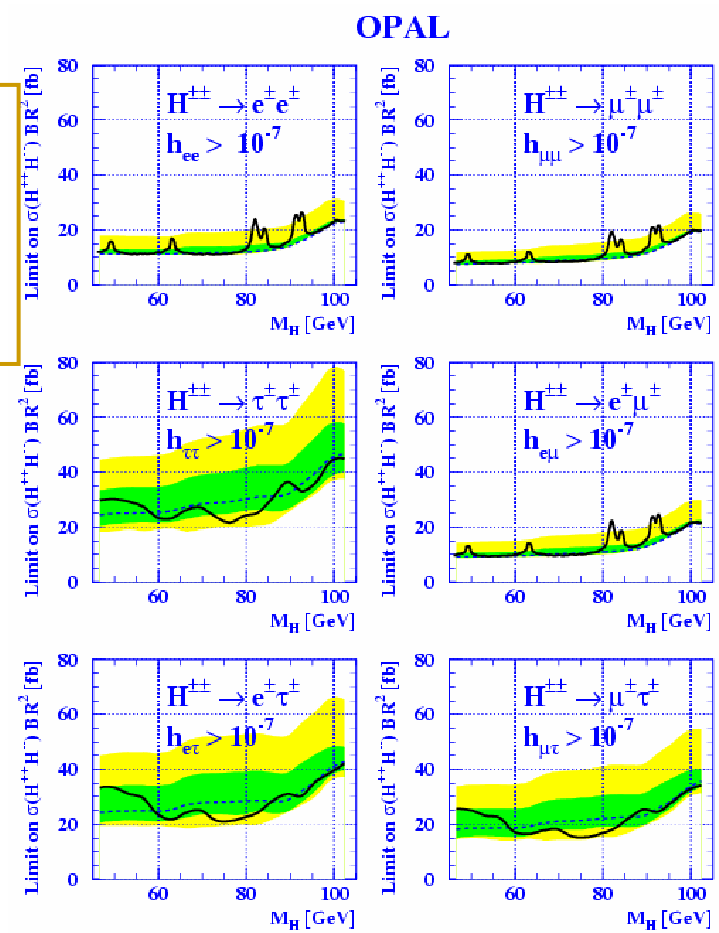
- $h_{H\tau\tau} > 10^{-7}$ → Decay at Interaction Point,
  smaller couplings → long lived doubly charged (large impact parameter, kinked tracks, stable long lived).
- DELPHI searched only for $\tau\tau$ decays but all possible lifetimes, OPAL for all possible decay channels assuming decay at IP

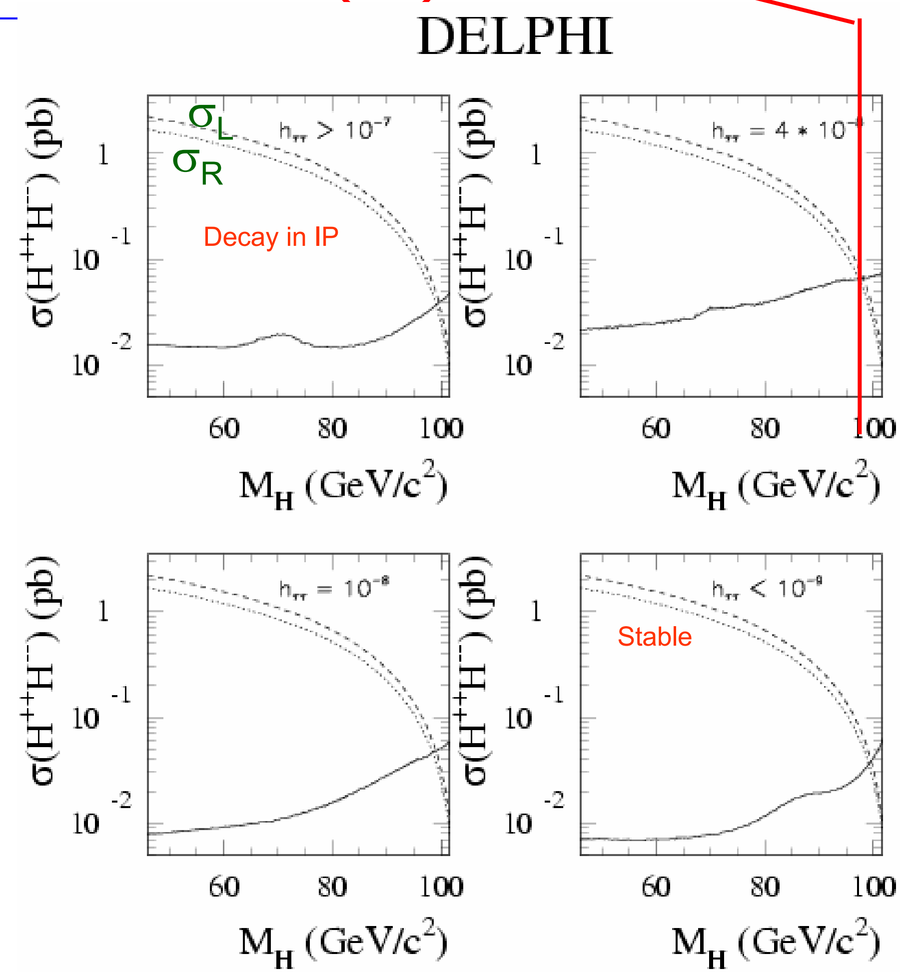
EMERGENCY!
See Marcel Stanitzki Talk

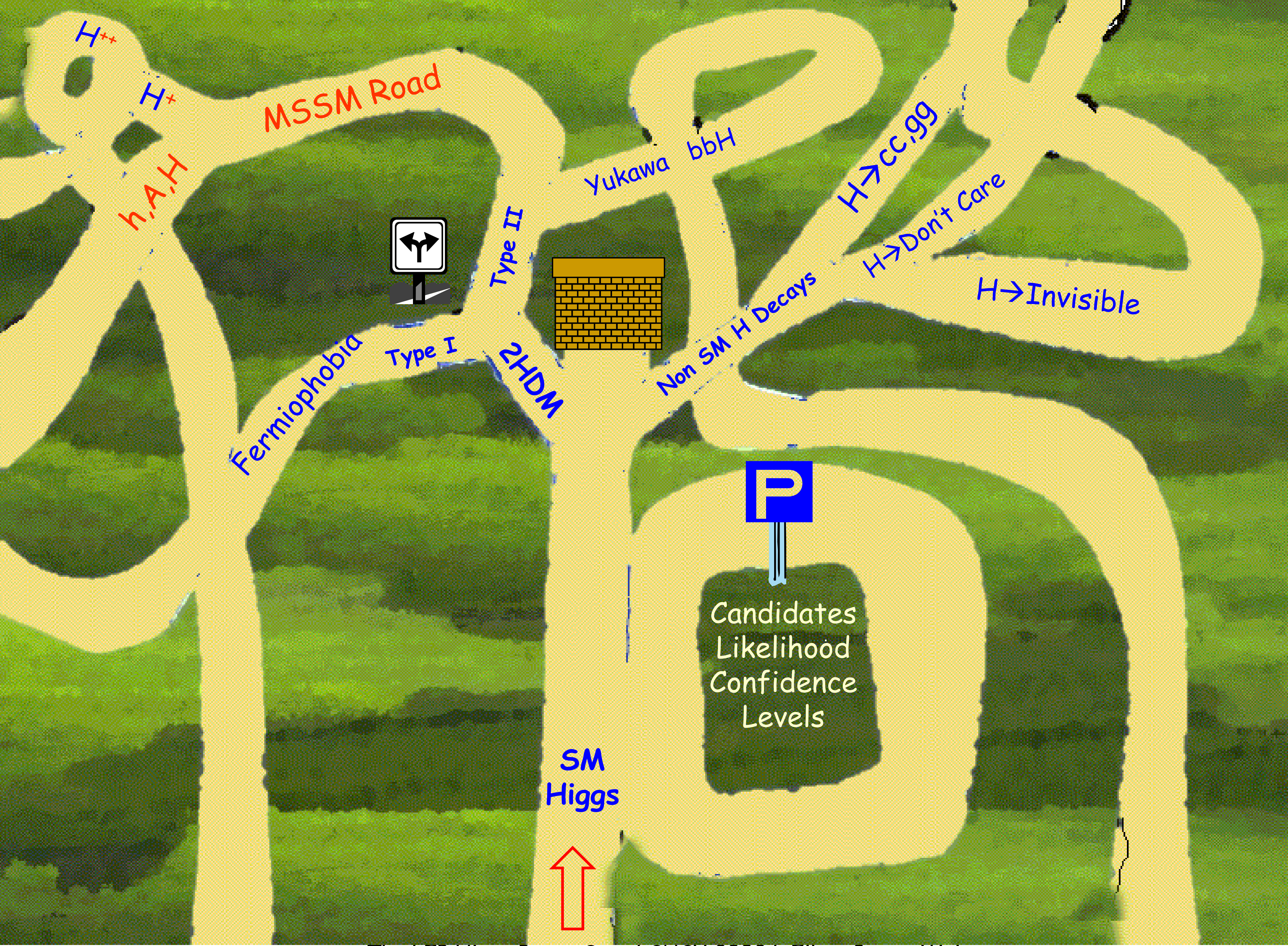
Search for Doubly Charged Higgs Boson

- 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



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Type I
Fermiophobia
2HDM
Non SM H Decays
P
Candidates
Likelihood
Confidence
Levels
SM
Higgs

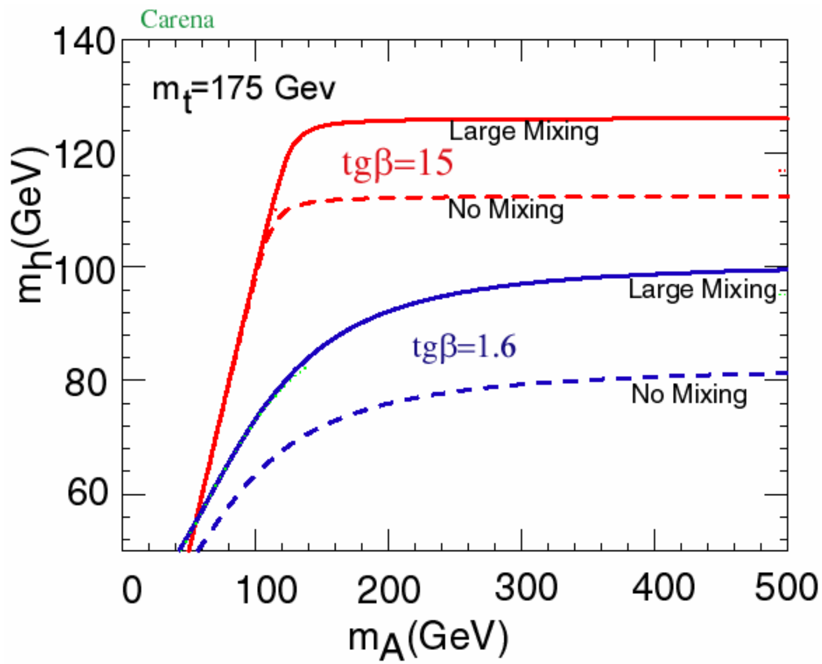
Benchmarks

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

Benchmark	μ	$X_t = A_t - \mu / tg\beta$	A_b	M_{SUSY}	M_{gluino}	M_h^{max}
	Mass	*Parameters*	(GeV)			
$No - Mixing$	-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

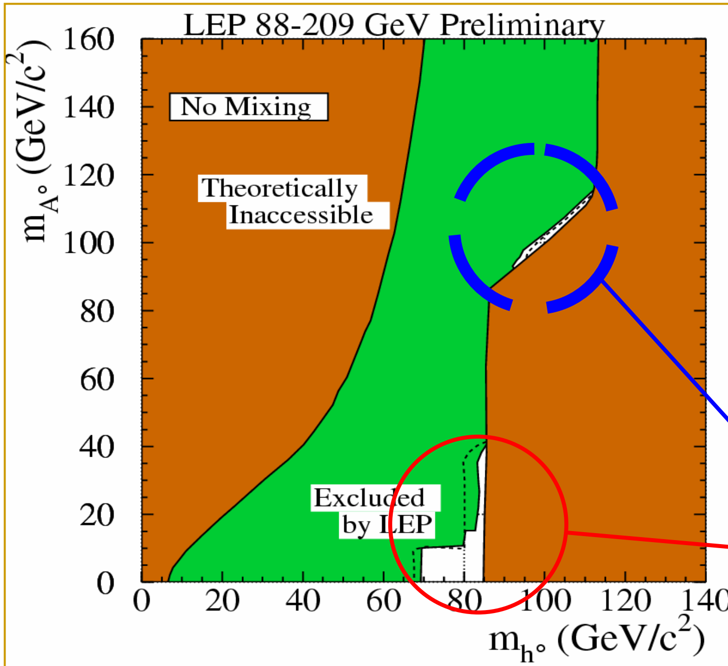
The Max m_h scenario was designed to yield the maximal value of the higgs mass

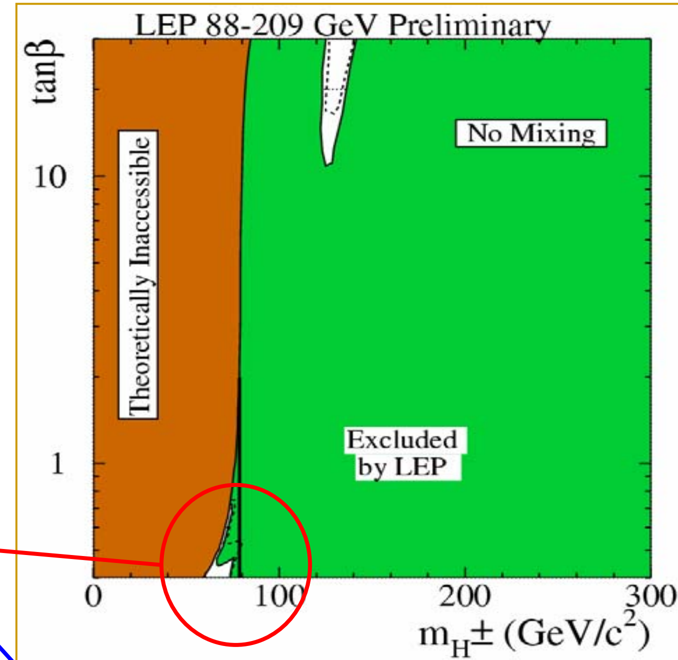
The Large μ scenario is designed to produce suppressed Higgs to bb decays, yet either the h or the H are kinematically accessible at LEP 2.

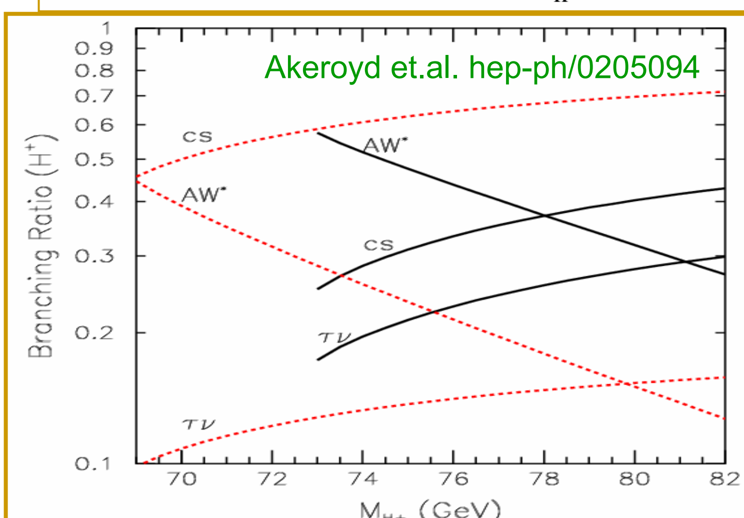


Analysis is done using FeynHiggsDecay (Heinemeyer, Hollik, Weiglein '98)
Incorporating HDecay (Djouadi, Kalinowski, Spira), www.feynhiggs.de

Minimal Mixing







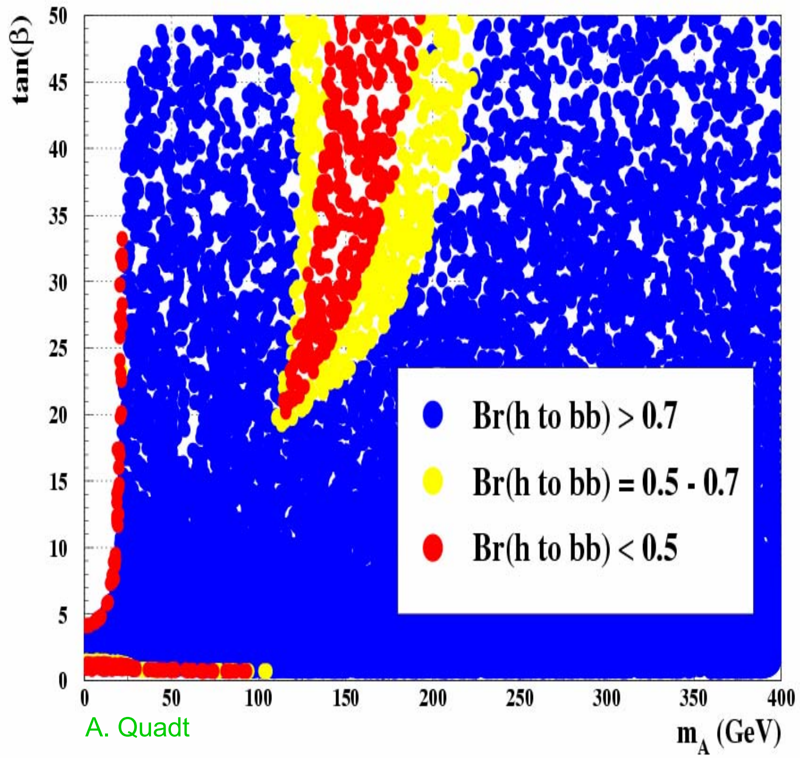
In this region tgβ~0.4 and $m_{H}+$~74 GeV. Dedicated searches to H^+->WA and flavour independent searches can help.

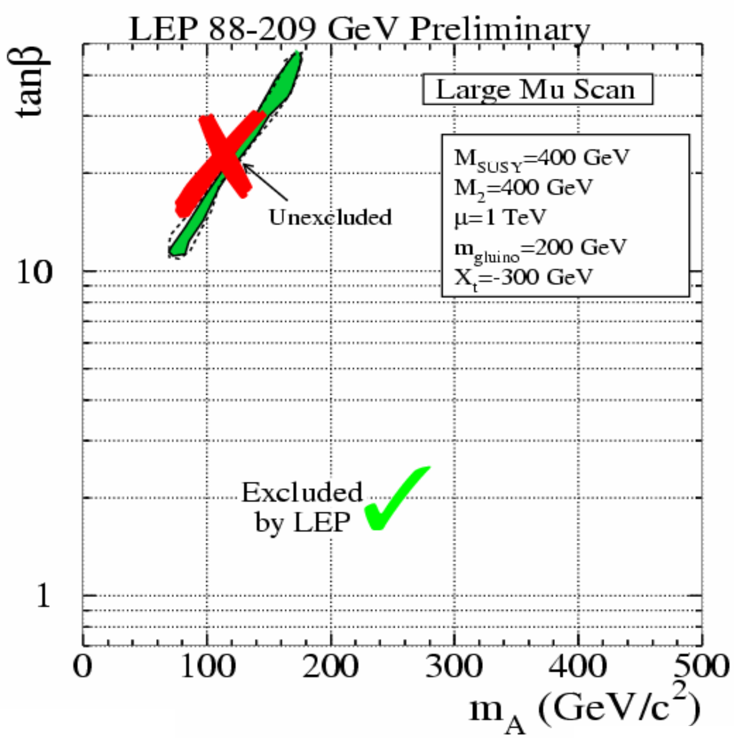
This region is beyond the Ah kinematical reach. This would have probably been covered with a mild update of LEP energy

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 μ Scenario

March 2001→July 2001

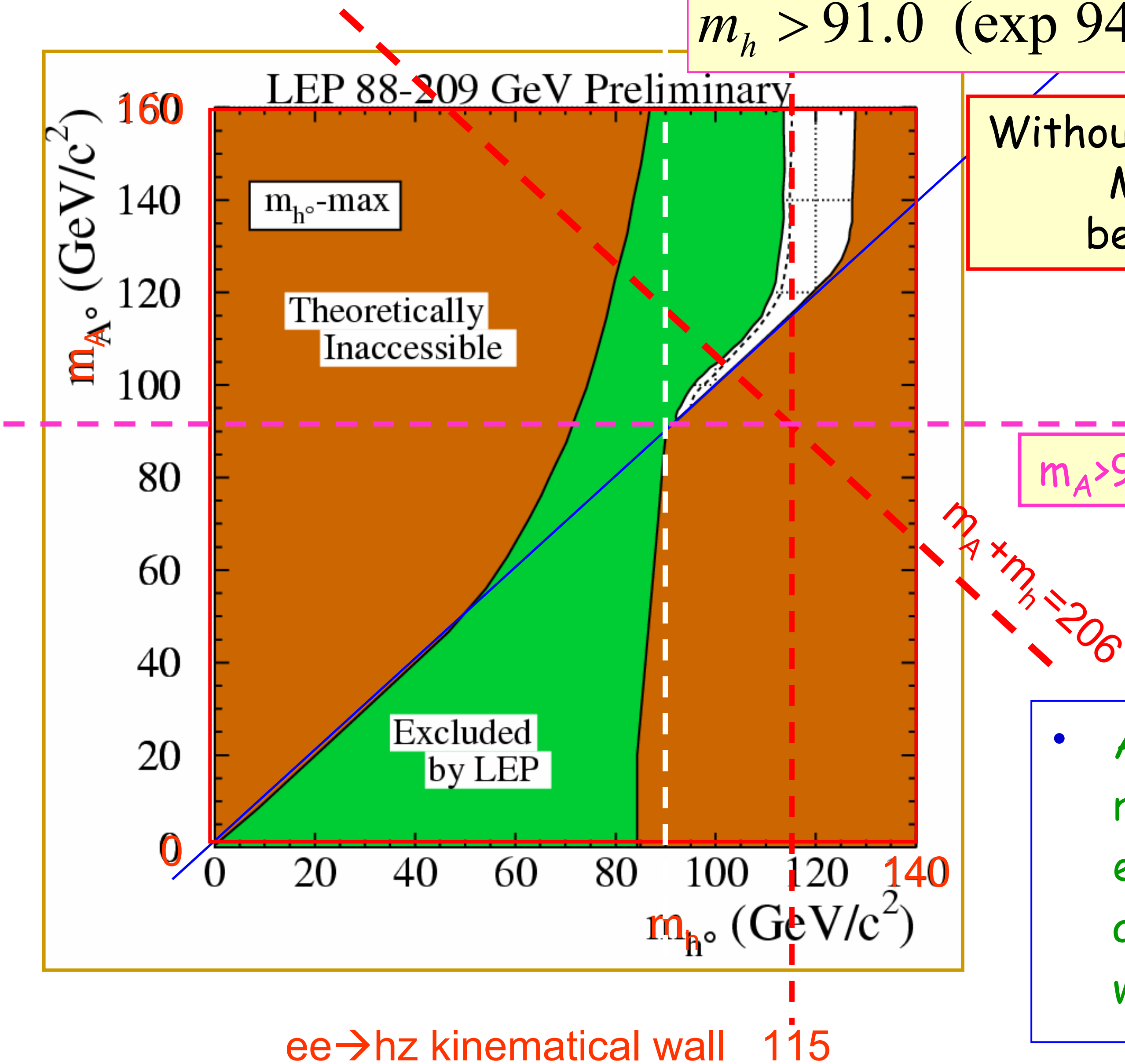




- With the flavour independent searches the all pre-LEP II defined region is now excluded!

Maximal m_h

$$m_h > 91.0 \ \ (\text{exp } 94.6)$$

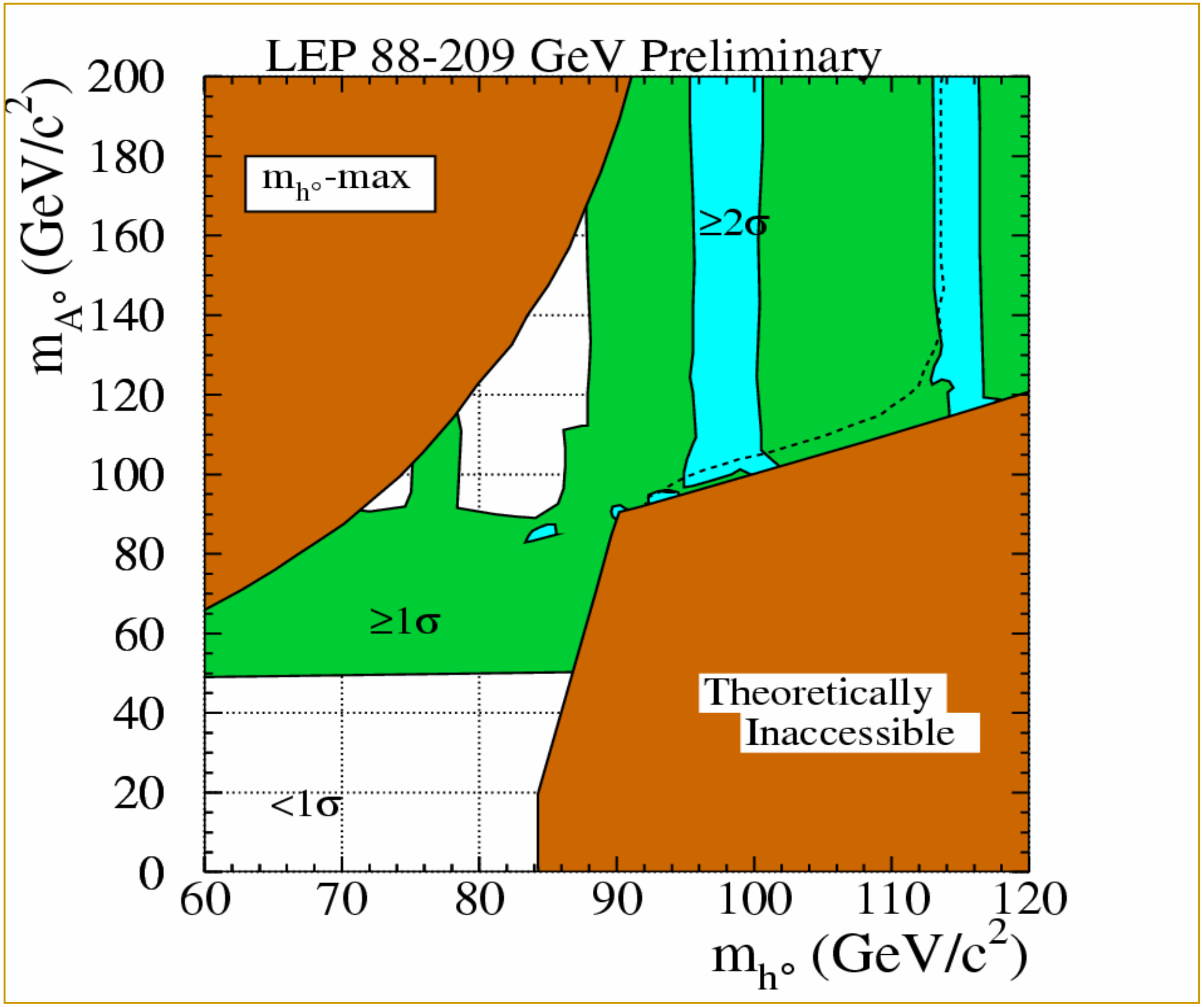


Without Radiative Corrections MSSM would have been widely excluded

$m_A > 91.9$ (exp 95.0) GeV

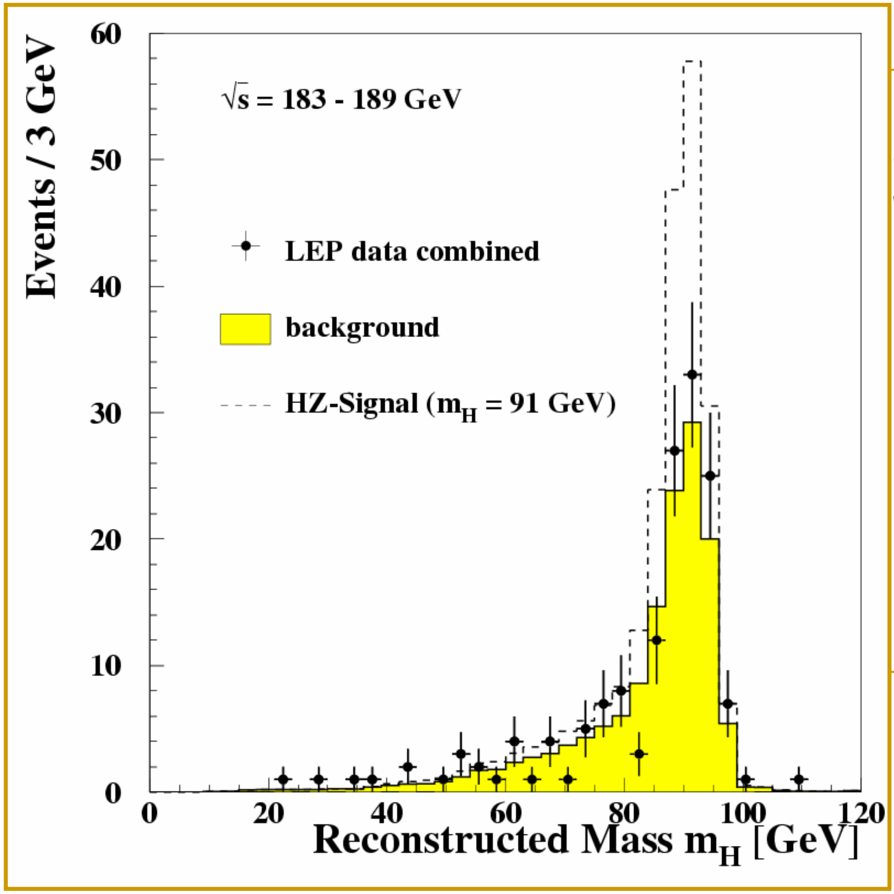
- Almost all accessible region is excluded, except near the hZ and hA kinematical wall!

Mh-Max Scenario - A Closer Look

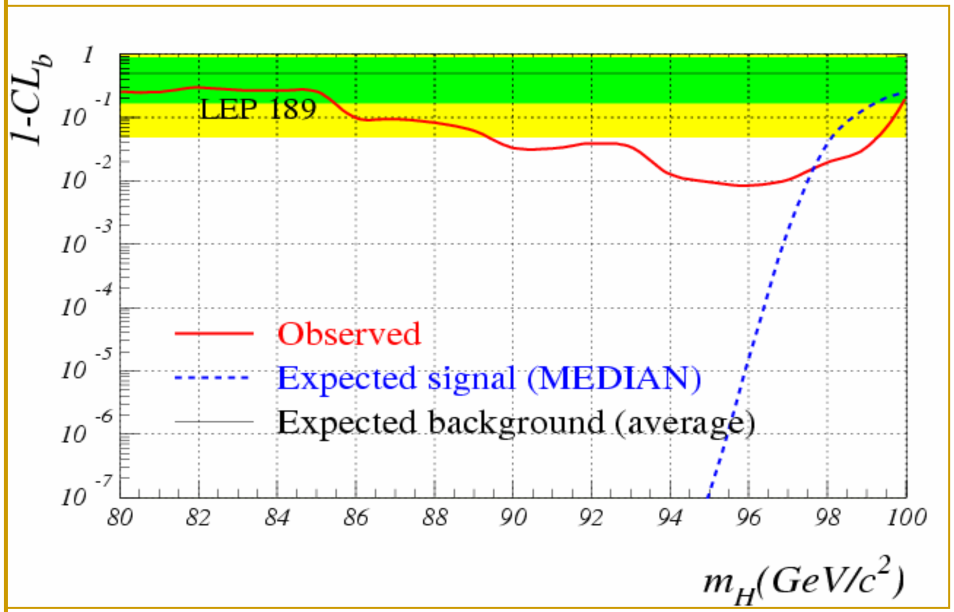


- Exclusion at the 2σ level does not mean there cannot be an excess at the 2σ level!
- You see something but its not what you excpect from your model!
- Excess in LEP 189 (at ~97 GeV) and LEP 206 (~115) is seen

Excess 189

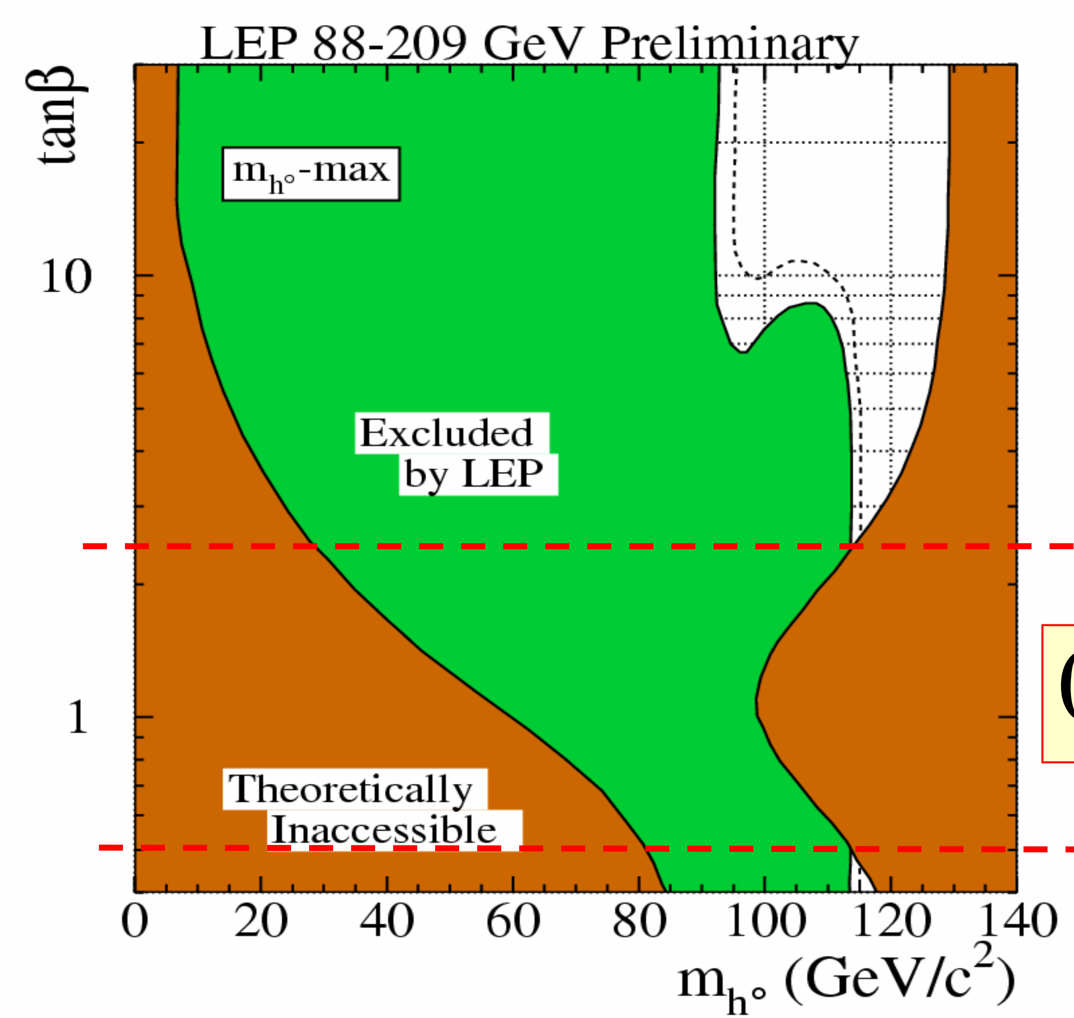


Events / 3 GeV
√s = 183 - 189 GeV
LEP data combined
background
HZ-Signal (m_H = 91 GeV)
Reconstructed Mass m_H [GeV]



$1-CL_b$
LEP 189
Observed
Expected signal (MEDIAN)
Expected background (average)
$m_H(GeV/c^2)$

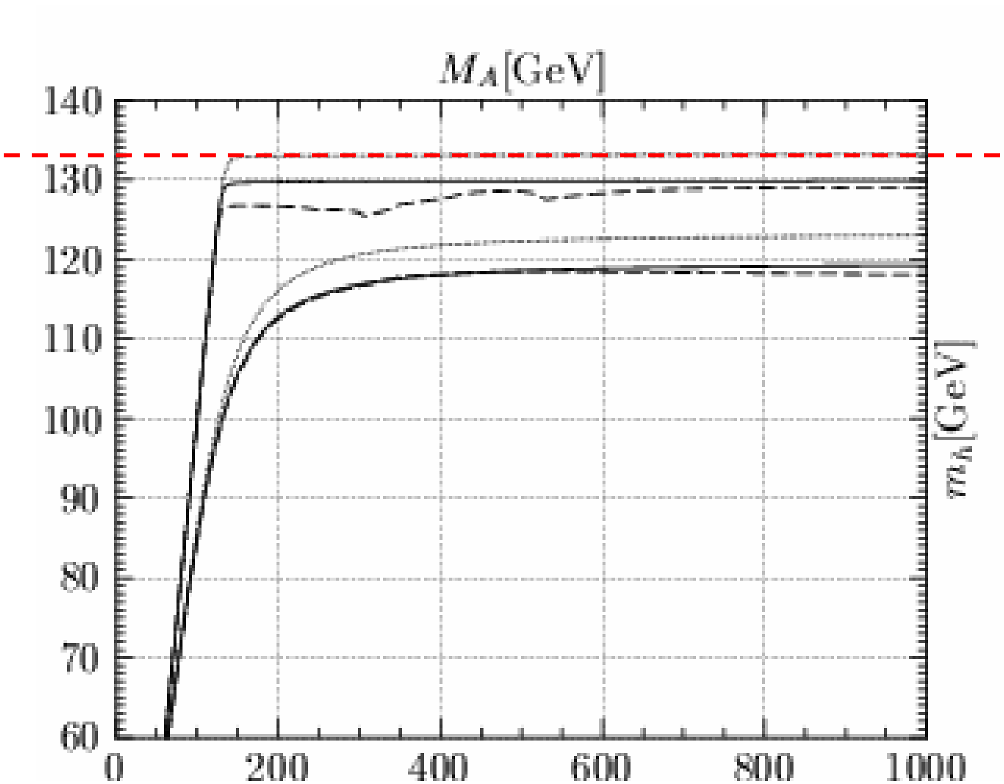
Maximal m_h



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

$$0.5 < tg\beta < 2.4$$

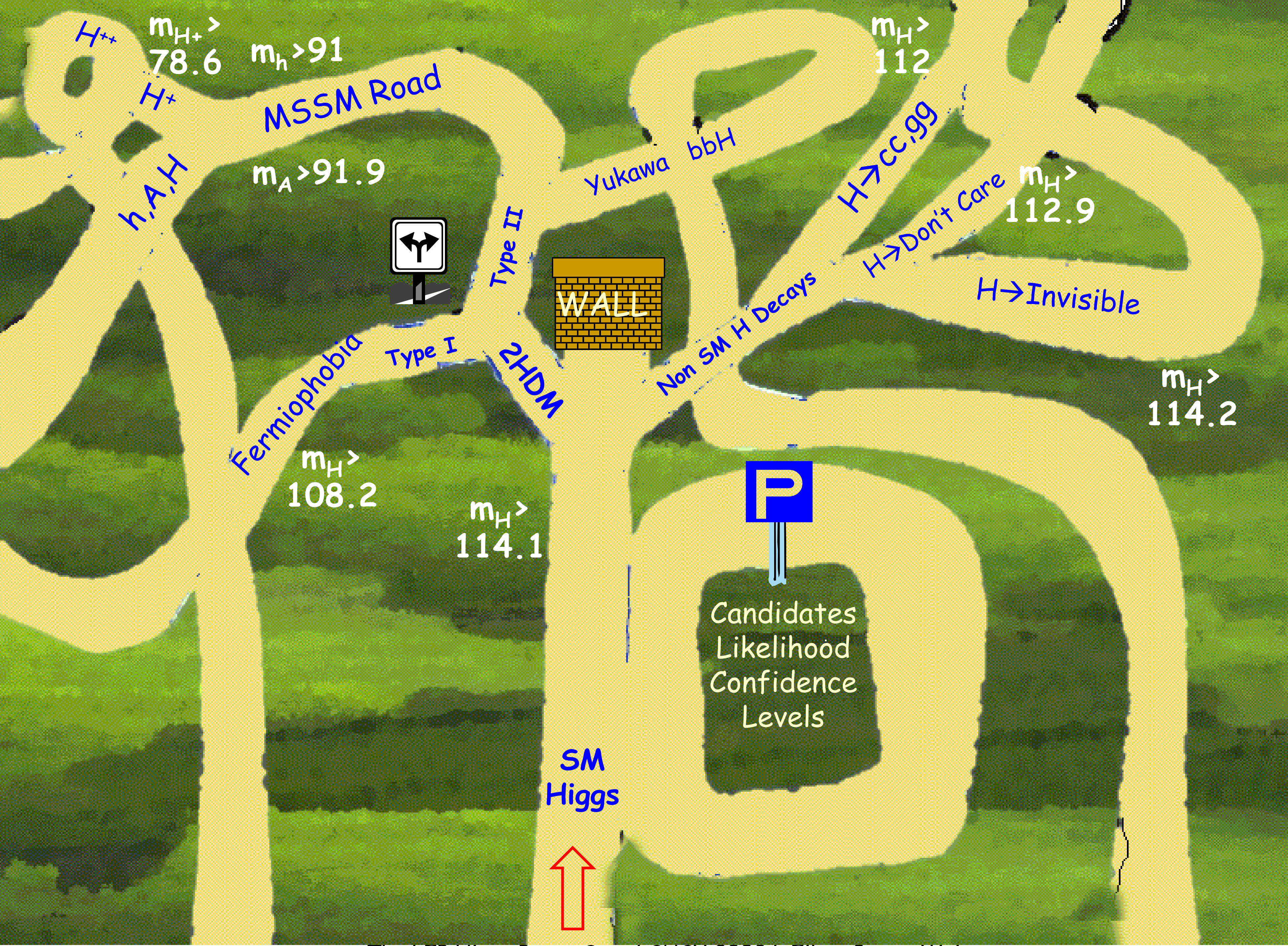
Casting Doubts!



A new version of Feynhiggs including $O(\alpha_t^2)$ 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 ~134 GeV, which weaken LEP limits on tgβ!

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



H++
m_{H^+}>
78.6
m_h>91
H+
MSSM Road
m_H>
112
h,A,H
m_A>91.9
Yukawa bbH
H→cc,gg
m_H>
112.9
Type II
H→Don't Care
WALL
H→Invisible
Non SM H Decays
Fermiophobia
Type I
2HDM
m_H>
114.2
m_H>
108.2
m_H>
114.1
P
Candidates
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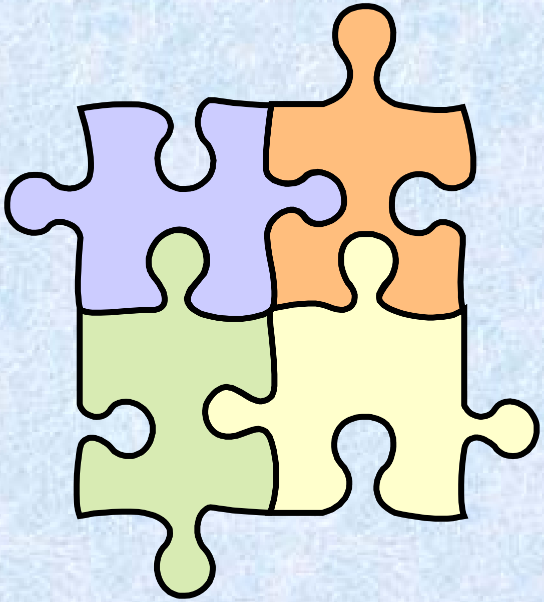
Higgs

Coclusions

- 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
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- & to Peter Zerwas for giving me the opportunity and pleasure of preparing this talk

Conclusions

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