Higgs Hunt at LEP 200 - Present and Future

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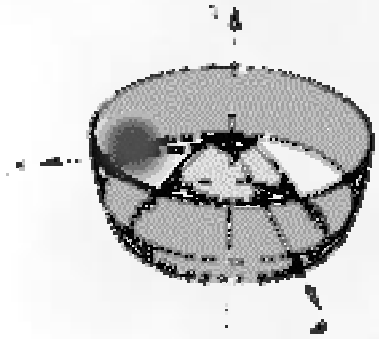
SUSY99 Fermilab



- Precision Measurements & Motivation
- Deriving a limit
- Standard Model Higgs search:
  Do we see the tip of the iceberg?
- 2 Doublet Higgs models
- Exploring the MSSM Higgs realm
- Prospects

Luminosities at E_{CM}=189 GeV

LEP 2: Year E_{CM}
Luminosity/Experiment

Year	E_{CM}	Luminosity/Experiment
1996	161	10 pb^{-1}
1996	172	10 pb^{-1}
1997	183	55 pb^{-1}
1998	189	175 pb^{-1}
1999	192	30 pb^{-1}
1999	196	?

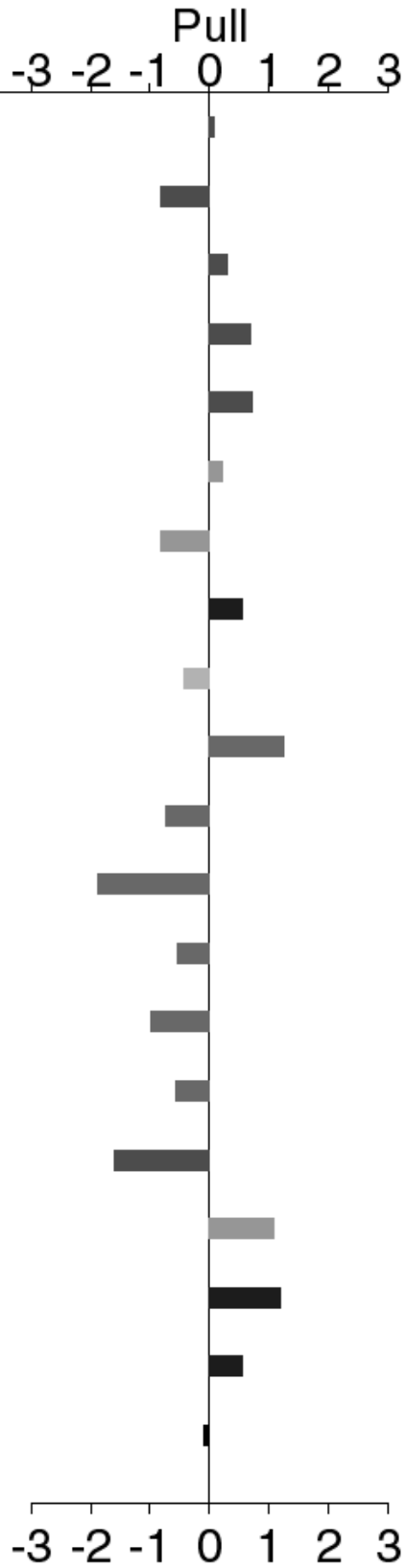
Detailed Luminosities

E_{CM}	189	192	196
• ALEPH:	170 pb^{-1}		
• DELPHI:	158 pb^{-1}		
• L3:	176 pb^{-1}		
• OPAL:	187pb^{-1}		

Desperately seeking for a Higgs boson

Moriond 1999

	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0021	.08
Γ_Z [GeV]	2.4939 ± 0.0024	-.81
σ^0_{hadr} [nb]	41.491 ± 0.058	.30
R_e	20.765 ± 0.026	.69
$A_{fb}^{0,e}$	0.01683 ± 0.00096	.71
A_e	0.1479 ± 0.0051	.23
A_τ	0.1431 ± 0.0045	-.81
$\sin^2\theta_{eff}^{lept}$	0.2321 ± 0.0010	.54
m_W [GeV]	80.350 ± 0.056	-.43
R_b	0.21680 ± 0.00073	1.26
R_c	0.1694 ± 0.0038	-.75
$A_{fb}^{0,b}$	0.0991 ± 0.0020	-1.88
$A_{fb}^{0,c}$	0.0712 ± 0.0043	-.53
A_b	0.908 ± 0.027	-.99
A_c	0.651 ± 0.030	-.56
$\sin^2\theta_{eff}^{lept}$	0.23109 ± 0.00029	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.07
m_W [GeV]	80.448 ± 0.062	1.20
m_t [GeV]	174.3 ± 5.1	.54
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02804 ± 0.00065	-.08



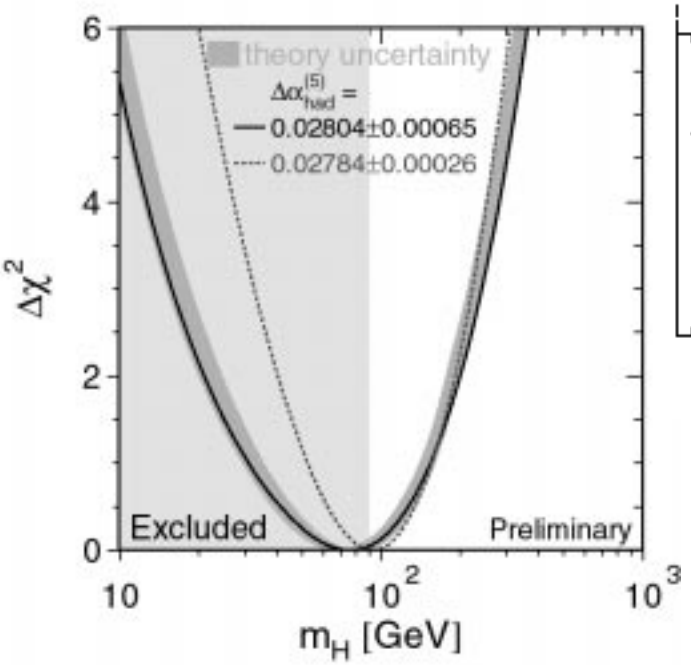
Fit to Electroweak PM

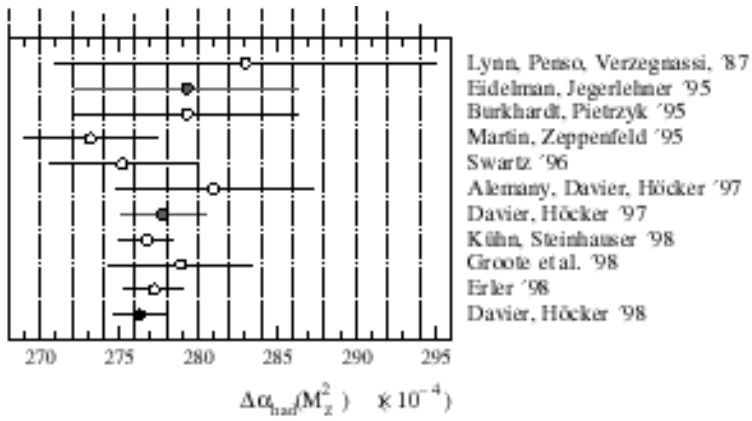
$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha_{lep}(s) - \underline{\Delta\alpha_{had}(s)}}$$

The leptonic contribution has been calculated to third order.

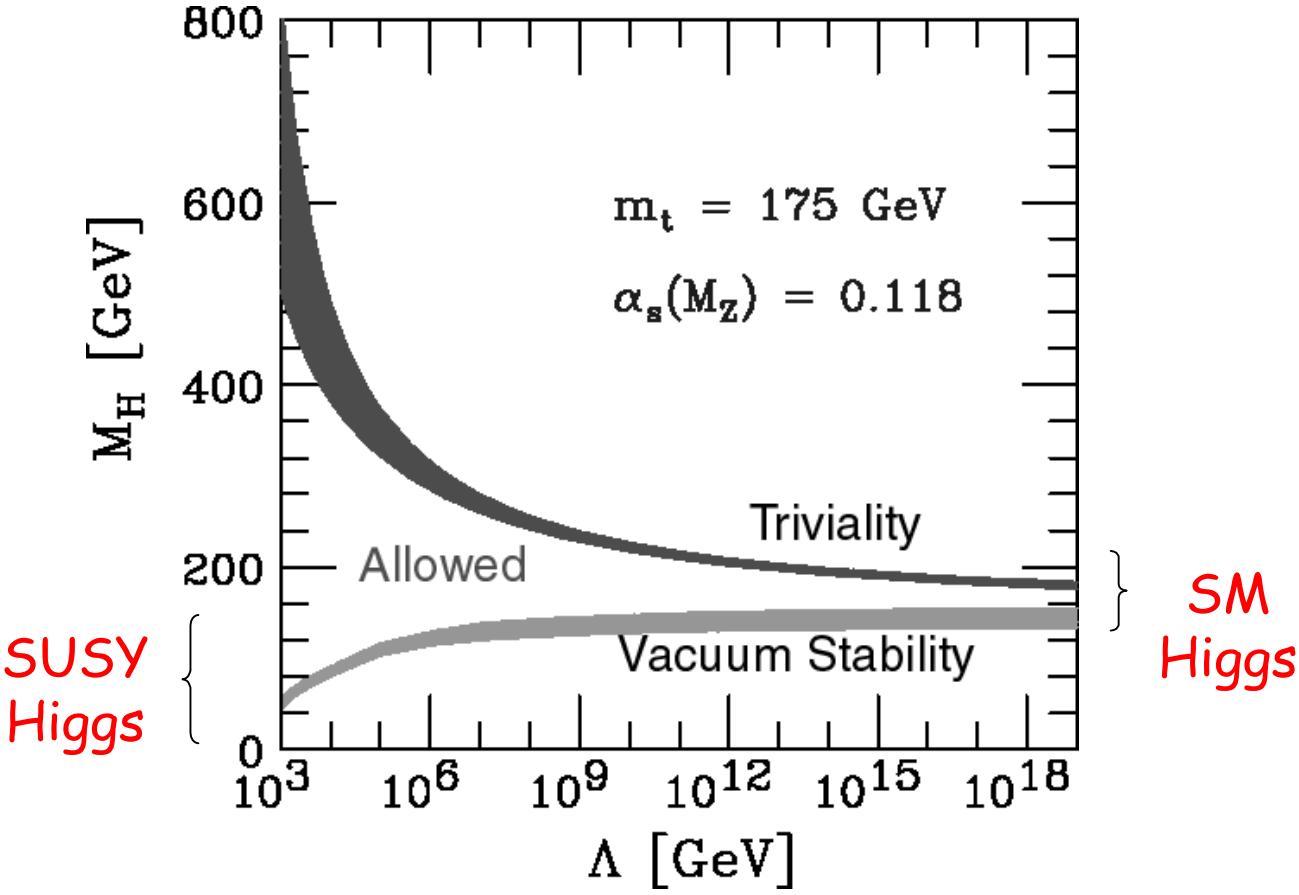
The 1995 evaluation of the hadronic contribution (Eidelman, Jegerlehner) based on experimental input is challenged (Davier, Hocker) by replacing some experimental data taken at low energies by precised QCD predictions that are tested in recent studies of hadronic decays

	$\alpha(m_Z^2)^{-1}$	$\Delta\alpha_{had}(m_Z^2)$	m_H	95% C.L. $m_H <$
Eidelman, Jegerlehner '95	128.878 ± 0.09	0.02804 ± 0.000615	76^{+79}_{-45}	234
Davier, Hocker '97	128.905 ± 0.036	0.02784 ± 0.00026	93^{+63}_{-41}	219





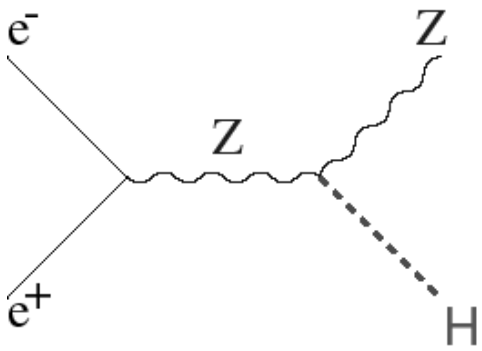
Do We Expect a Higgs Boson?
New Physics Around the Corner?



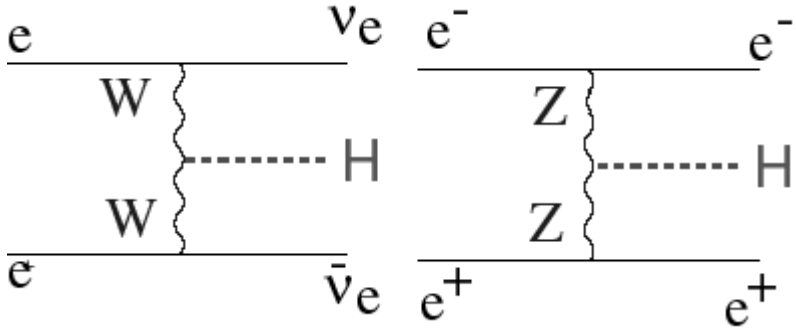
… If a Higgs is discovered at LEP
then there is New physics around the corner

SM Higgs Production

Bjorken-HiggsStrahlung



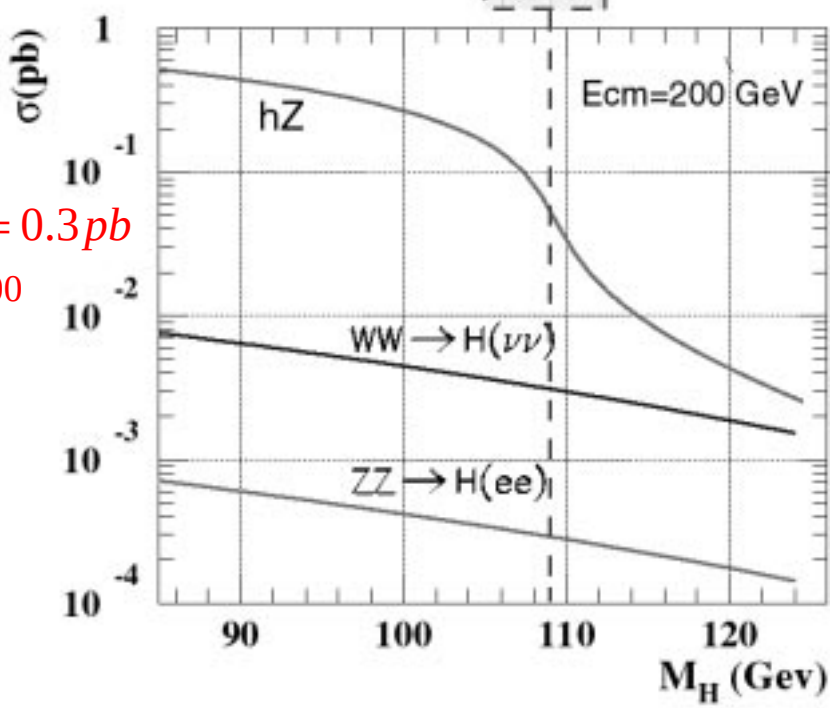
WW and ZZ fusion



m_H=109 GeV

$$\sigma\left(e^+e^- \rightarrow HZ\right) = 0.3\,pb$$

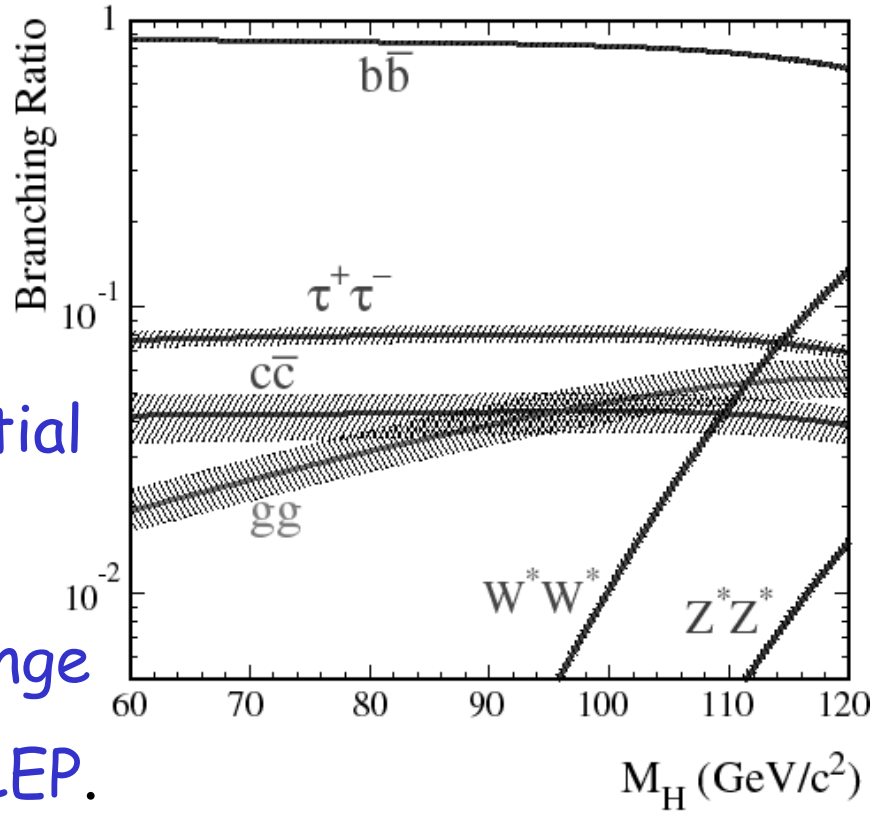
$$m_H = 95 @ E_{CM} = 200$$



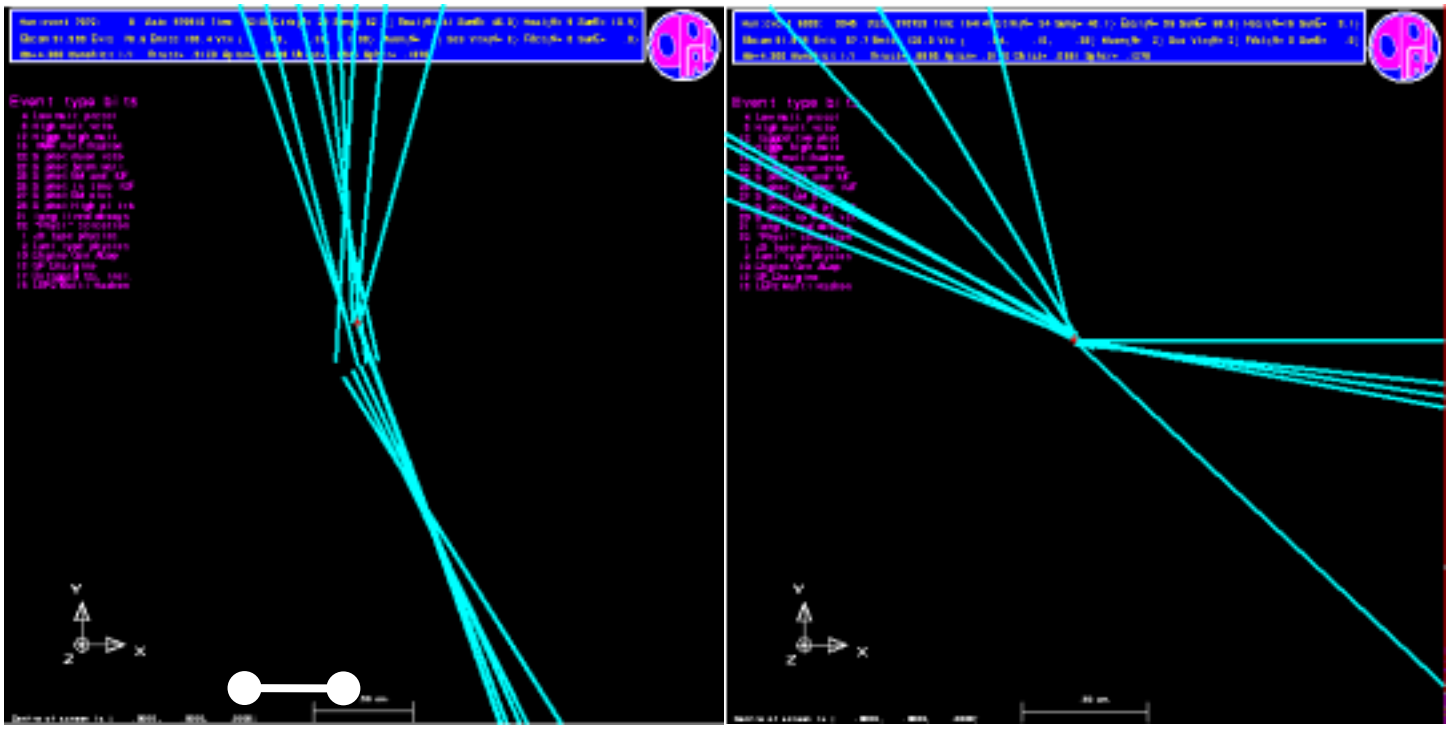
Cross section of fusion channels is (almost) hopeless. For a 125 GeV Higgs boson produced in the WW fusion channel,
2 events are expected with an integrated luminosity exceeding 1000 pb^{-1}

Higgs Decays to bottom quarks

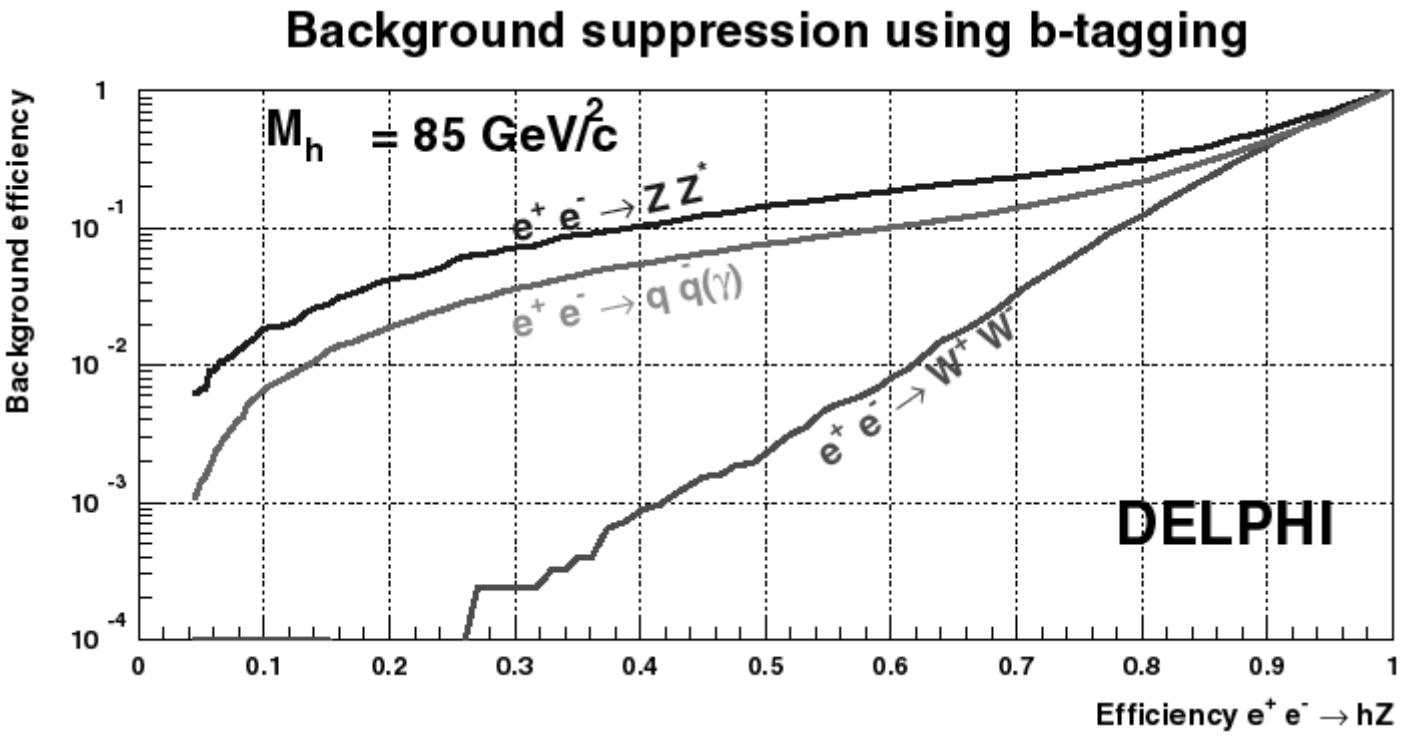
- A Higgs boson decays >85% to $b\bar{b}$
- B-tag is essential to tag Higgs in the mass range accessible at LEP.

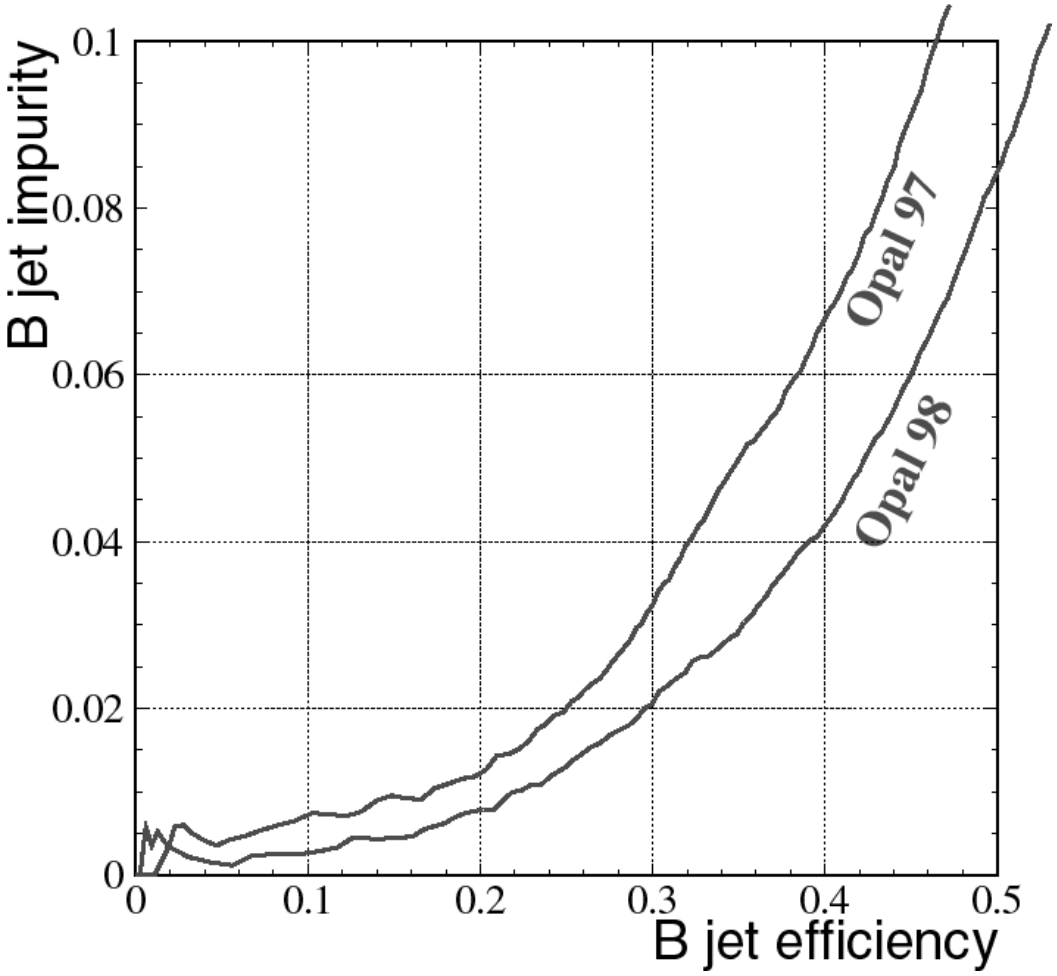


$$e^+e^- \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b} \qquad e^+e^- \rightarrow ZZ \rightarrow \nu\nu q\bar{q}$$



b-tag

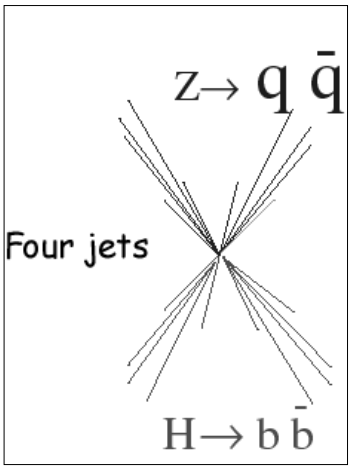

Background suppression using b-tagging
M_h = 85 GeV/c^2
$e^+e^- \to ZZ^*$
$e^+e^- \to q\bar{q}(\gamma)$
$e^+e^- \to W^+W^-$
DELPHI
Background efficiency
Efficiency $e^+e^- \to hZ$


B jet impurity
B jet efficiency
Opal 97
Opal 98

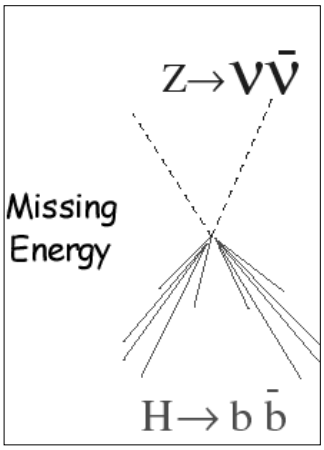
Search Topologies

- $H \rightarrow b\bar{b}(\sim 85\%), \tau^+\tau^-(\sim 8\%)$
- $Z \rightarrow q\bar{q}(70\%), \nu\bar{\nu}(20\%),$

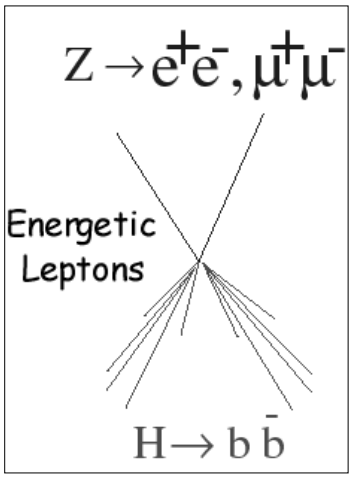
$$e^+e^- + \mu^+\mu^-(6.6\%), \tau^+\tau^-(3.3\%)$$



- Energy-momentum conservation
- The 2 most probable b-tagged jets recoil against a di-jet compatible with a Z-boson
- eff 30-40%

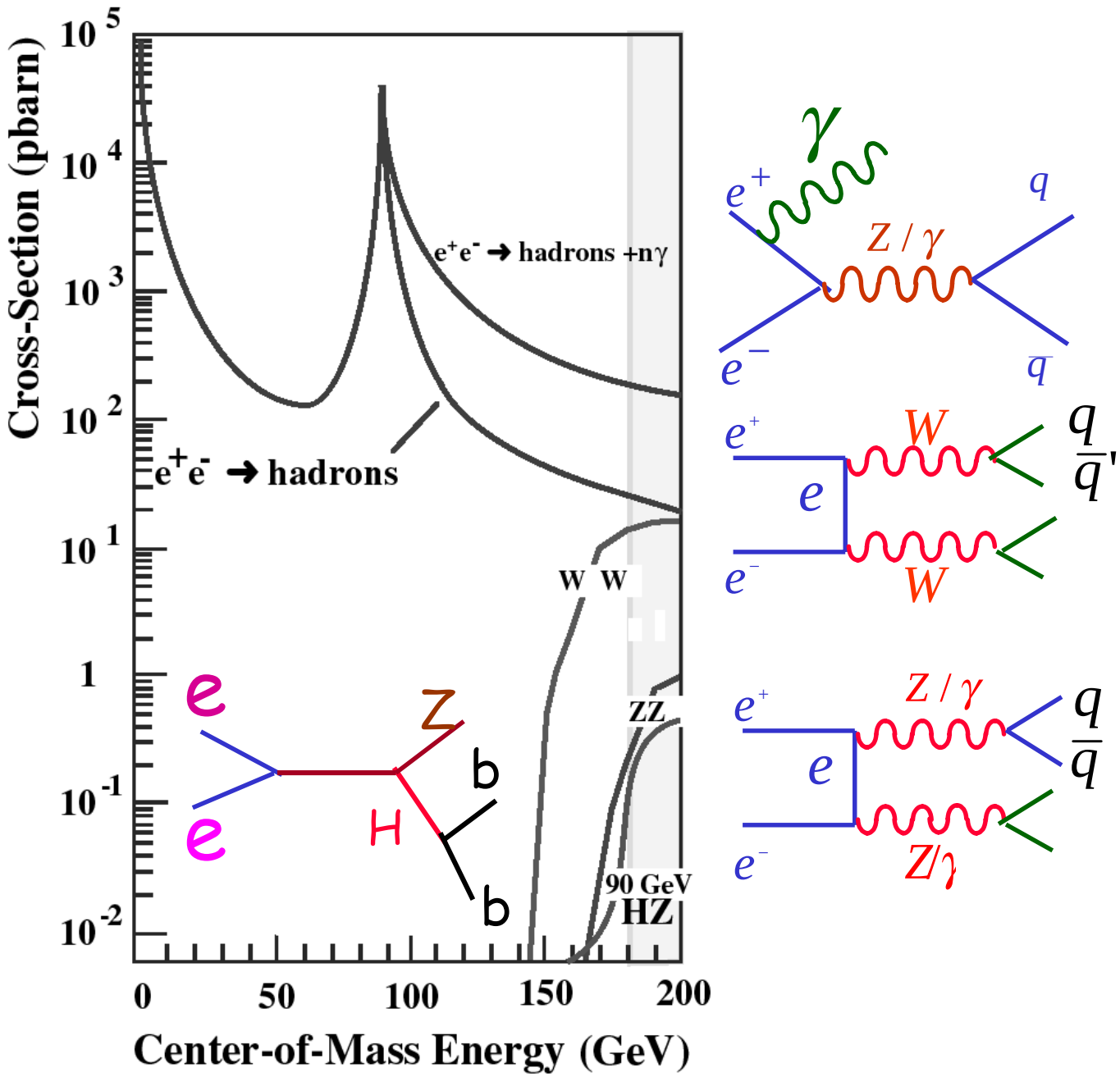


- The recoil mass of the 2 b-tagged jets is compatible with a Z boson
- eff 30-40%



- 2 high energetic leptons with a mass compatible with a Z boson recoil against 2 jets.
- Clean channel, high eff ~50-60%

Backgrounds: Z Z, W W & q q γ



- The most severe background is the 91 GeV Higgs-like irreducible ZZ production.
- Higgs decays to b-quarks >85% of the times. Only good b-tag will reduce ZZ and WW bg's.

$$Z \longrightarrow \bar{b}b = 15\%$$

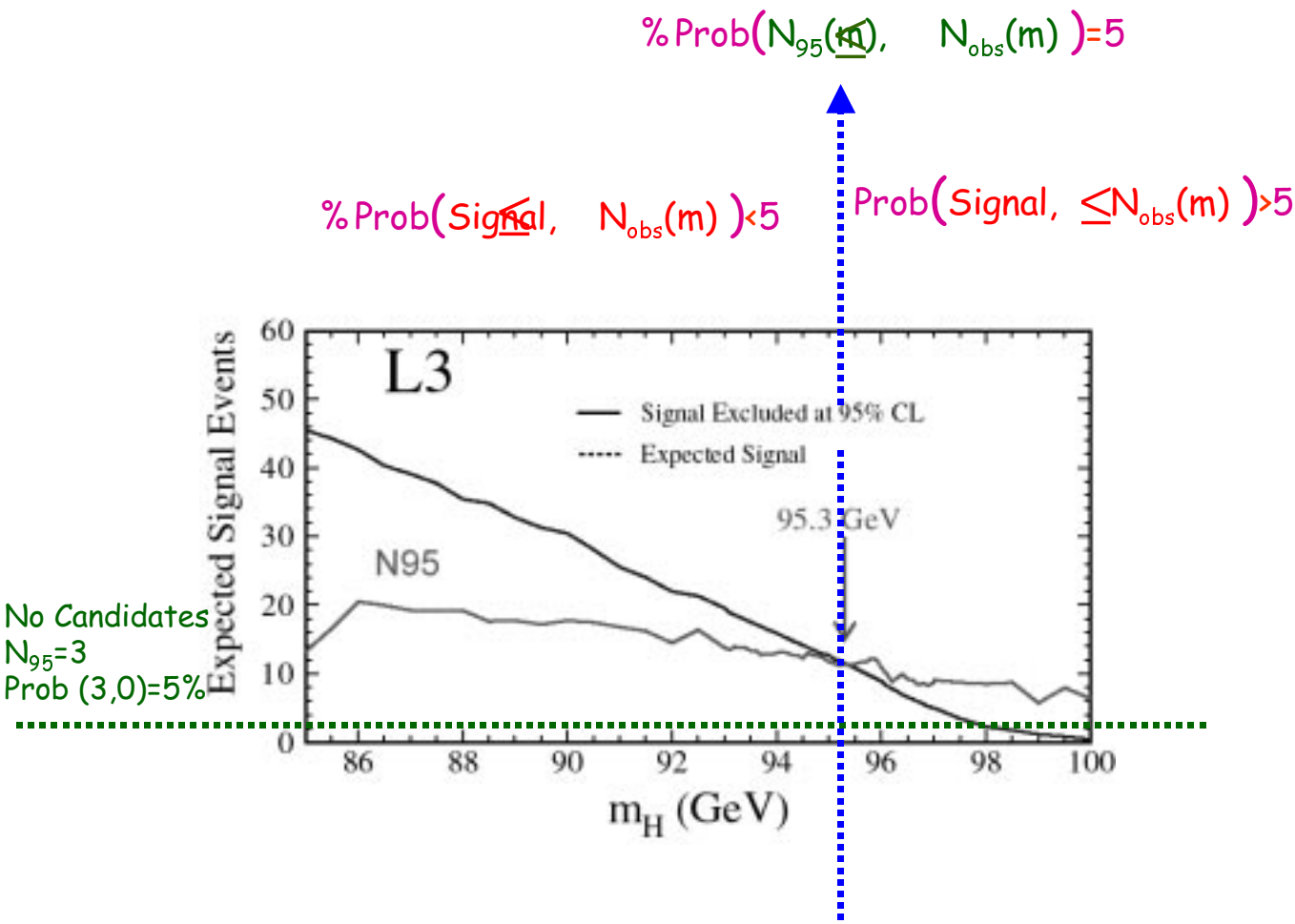
Deriving Limits - Classical Approach

- At a given mass m , we denote by $N_{95}(m)$ the number of expected events satisfying

  $Prob(N_{95}(m), \leq N_{obs}(m))=5\%$

- As a result, if $N_{exp}(m_H) \geq N_{95}(m)$,

  a Higgs boson with a mass $m \leq m_H$ is excluded at the 95% Confidence Level



Observed and Expected Limits

A simplified explanation

X = Test statistics which depends on Signal-Background Discriminators

$X = X(m_H; m_{reconstructed}, W_b, \ldots\ldots)$

Simplest example: Number of observed events

The Confidence ("CL") in the Signal hypothesis is related to the probability

$$CL_s \approx \Pr ob\,(X_{s+b} \leq X_{obs})$$

in signal+background experiments

A Higgs boson with a mass m_H is excluded if the probability $\Pr ob\left(X_{s+b}(m_H) \leq X_{obs}\right) \leq 5\%$

i.e. $CL_S(m_H) < 5\%$ or $CL = 1 - CL_s > 95\%$

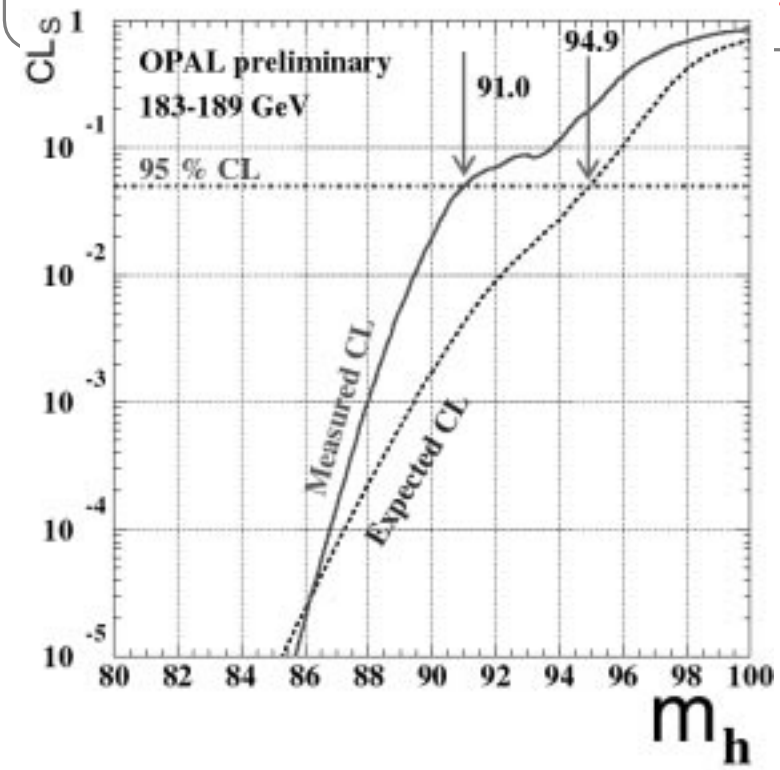
To estimate an experiment sensitivity to find the Higgs boson, one can generate gedanken background experiments and "measure" the CL for each.

The experiment's sensitivity is expressed in terms of m_H for which the **average CL**

$$\langle CL_s(m_H)\rangle \equiv \langle 1 - CL(m_H)\rangle = 5\%$$

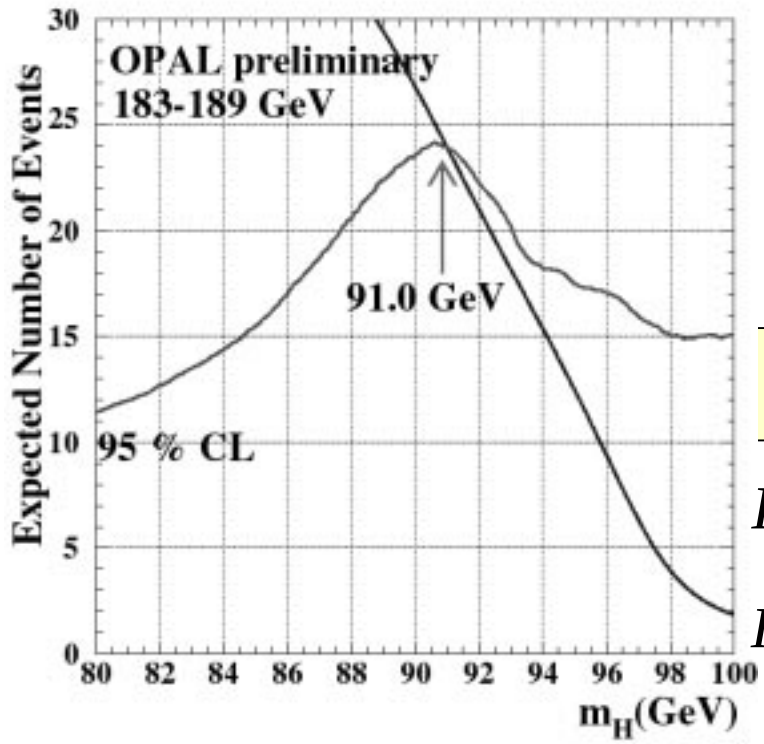
Note: m_H which satisfies $\langle CL_s(m_H)\rangle = 5\%$ is called the Expected Limit

OPAL SM Higgs Limit



m_H>91.0 (obs) 94.9 (exp)

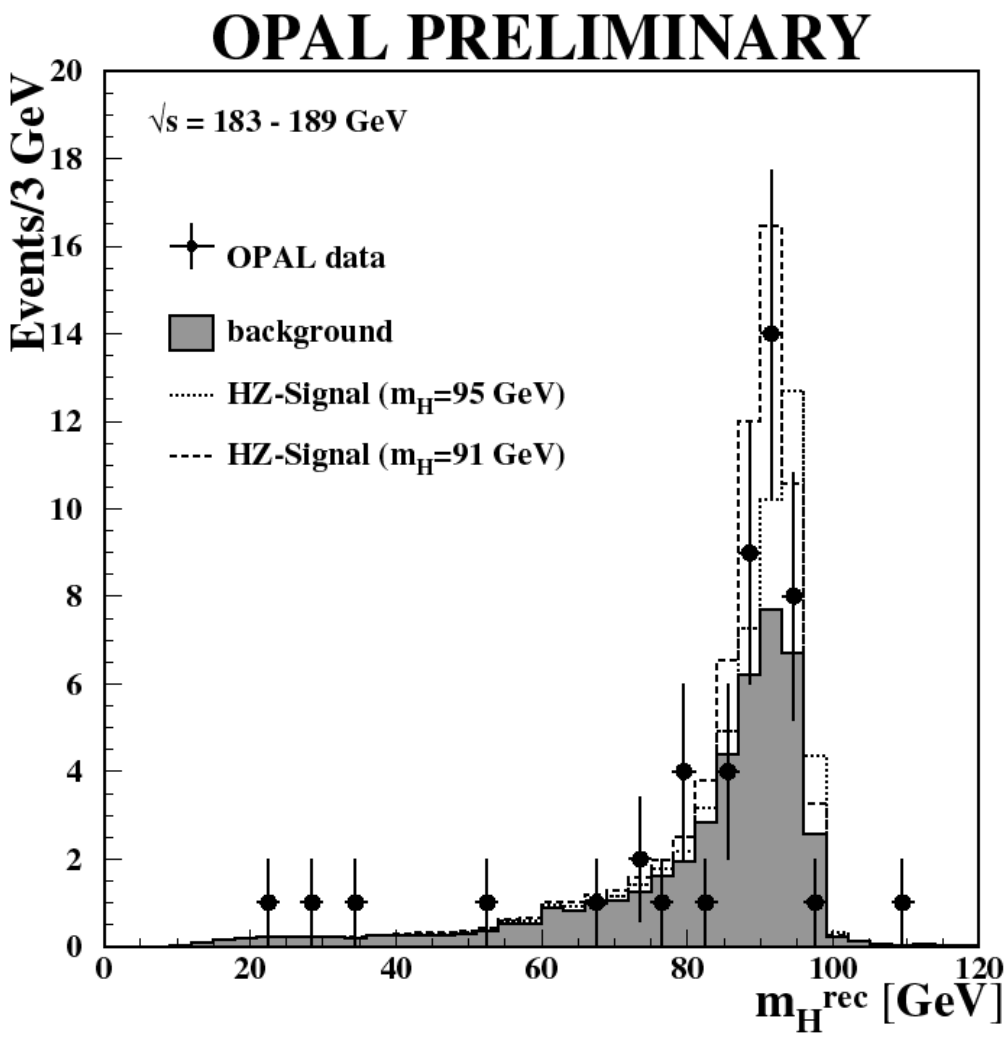
The Measured CL and the N_{95} shapes are "projections" of the candidate events. In this case they are typical to the ZZ irreducible background.



	eff m_H=95	BG	DATA
4j	47%	19.9*	24
$H\nu\bar{\nu}$	36%	6.9	10
$H\ell^+\ell^-$	~60%	4.7	4

* 10.4 of the expected background events are from ZZ and 90% of them contain a pair of $b\bar{b}$

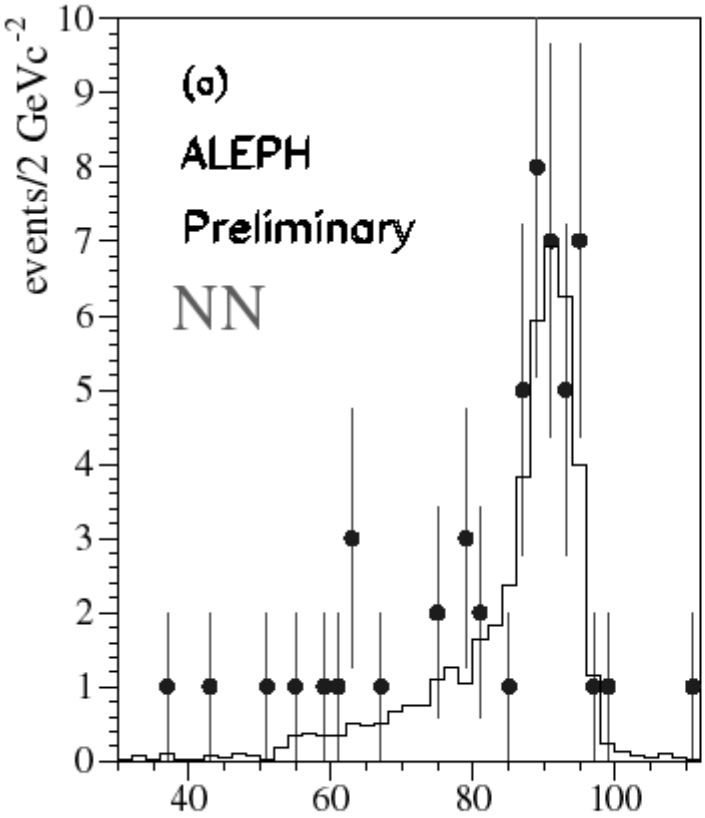
A Discovery?

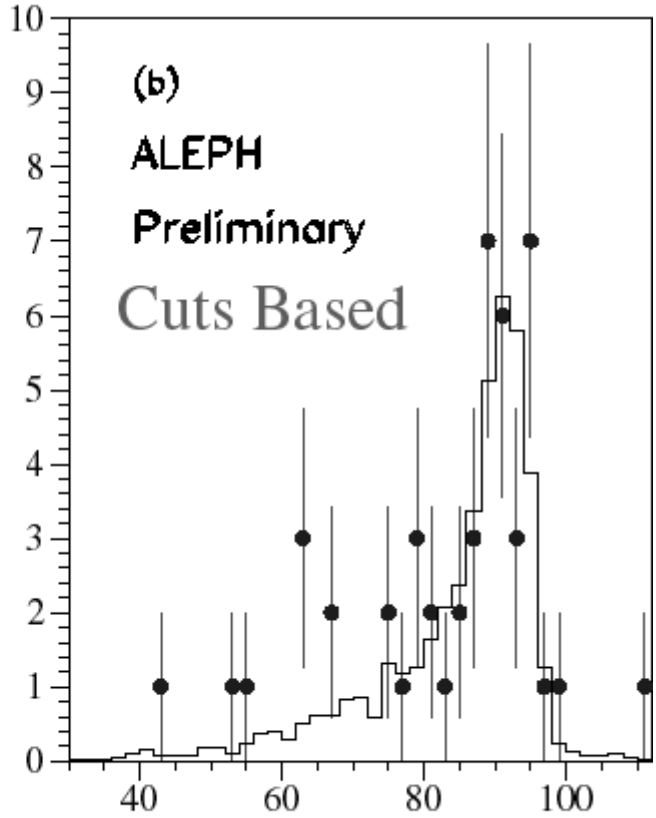


- This is exactly how a 91 GeV Higgs boson will look like with a 2σ significance. (However at least 5σ will be required for an "observation" effect).

ALEPH SM Higgs Search

$$\sqrt{s} = 189 \quad GeV$$





Expected 95.7 GeV
Observed 93.8 GeV

Expected 95.4 GeV
Observed 92.0 GeV

	4-jets Cuts	4-jets NN	Missing Energy Cuts	Missing Energy NN	leptonic
eff	46%	39%	29%	35%	77%
signal (m_H=95)	8.5	7.3	2.0	2.5	1.5
background	21.4	exp 19	3.1	exp 7.3	exp 14.4
DATA	28	obs 24	5	obs 8	obs 14

No smoking gun!

2 Doublet Higgs Models

- General 2-doublet, CP conserving:

  H_1^0, H_2^0 : Real parts mix with an angle $\alpha \rightarrow$ h,H

  Imaginary part (not eaten by Z) $\rightarrow$ A

  In total 5 Higgs bosons and two angles:

  $$H^{\pm}, h, H, A \qquad tg\beta = \frac{v_u}{v_d}, \alpha$$

  Higgs bosons produced via $e^+e^- \rightarrow hZ, hA$

  $$g_{hz}^2 + g_{hA}^2 = 1$$

- General 2-doublet, CP violating:

  Higgs bosons produced via $e^+e^- \rightarrow hZ, hA, AZ$

  $$g_{hz}^2 + g_{hA}^2 + g_{AZ}^2 = 1$$

- Minimal SuperSymmetric Model (MSSM):

  Tree level:

  2 pars (m_h,m_A) or ($tg\beta$, m_h) or ($tg\beta$, m_A)

  determines α and the mass spectrum:

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

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

The light MSSM Higgs boson mass

- Rad corrections ⟶ Max light Higgs mass depends on soft SUSY breaking parameters

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

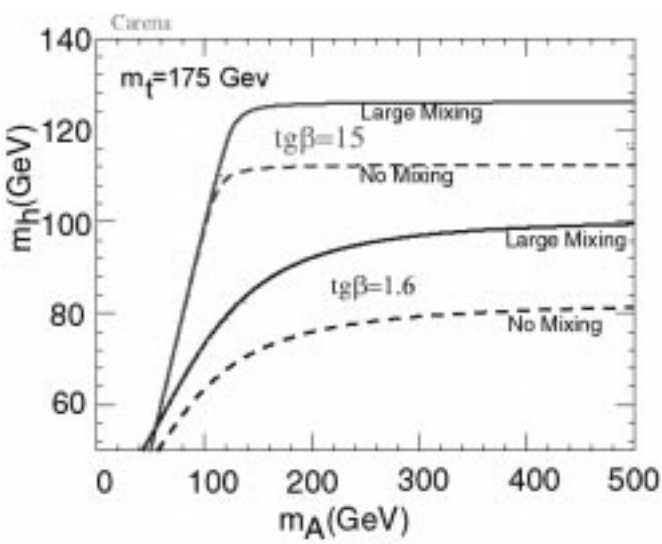
- The SUSY mass parameter related to the stop mass $\boxed{m_s = \sqrt{\frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{2}}}$

$\tilde{A}_t$ controls the mixing in the stop sector

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

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

- μ is the Higgs mass term $\mu \varepsilon_{ij} \hat{H}_1^i \hat{H}_2^j$
- A_t is the trilinear Higgs coupling $A_t g_{ht\bar{t}} \varepsilon_{ij} H_2^j \tilde{Q}^i \tilde{t}_R^*, \quad \tilde{Q} = \begin{pmatrix} \tilde{t}_L \\ \tilde{b}_L \end{pmatrix}$



Benchmarks:

$m_s = 1TeV, \mu = -0.1 m_s, M_2 = 1.6TeV$

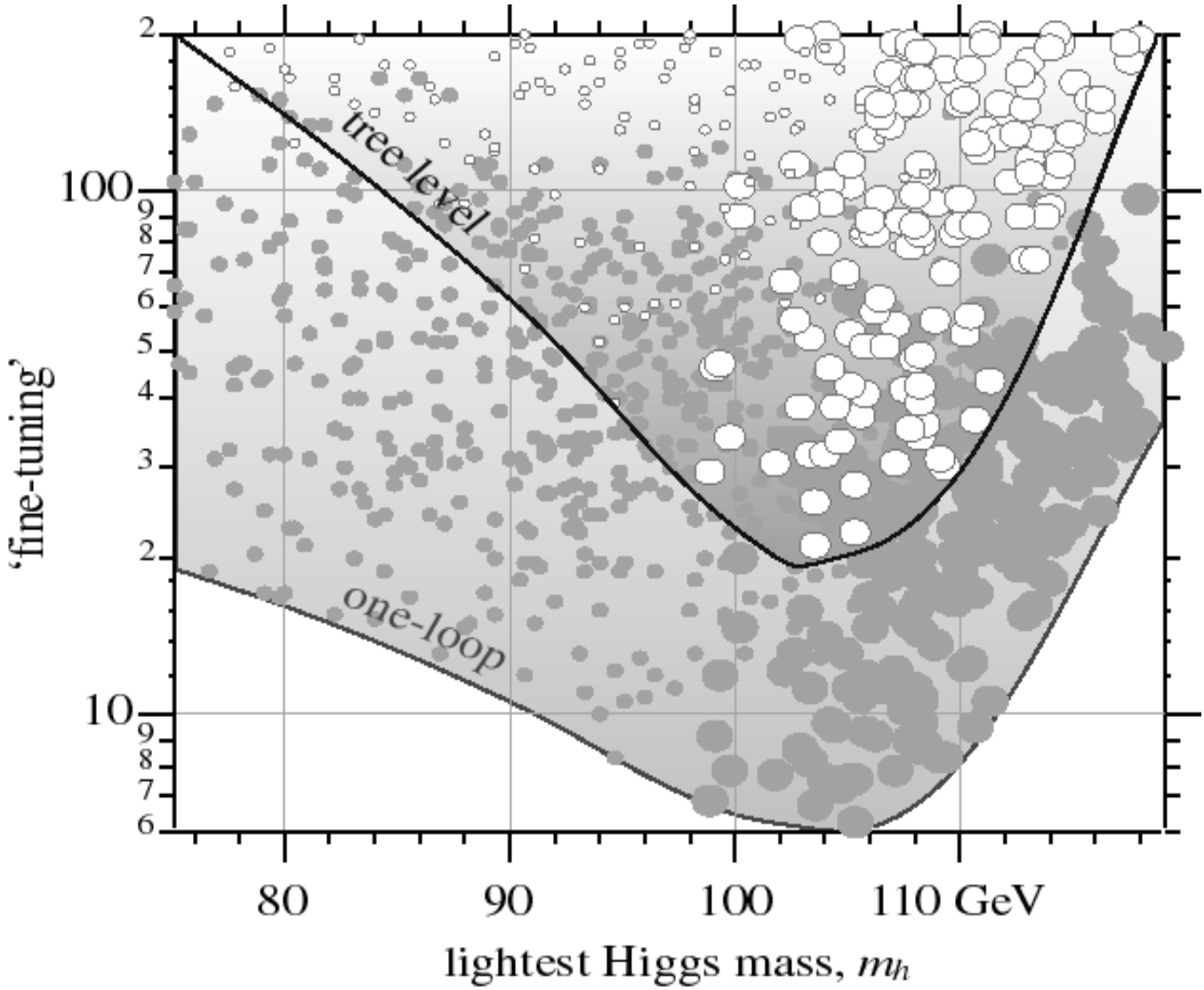
No Mixing in the stop sector:
$A_t = 0, \quad m_h < 115 \quad GeV$

Max Mixing in the stop sector:
$A_t = \sqrt{6} m_s, \quad m_h < 130 \quad GeV$

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

for small μ : $m_{H^\pm} > m_W$

SUSY Higgs is Around the Corner



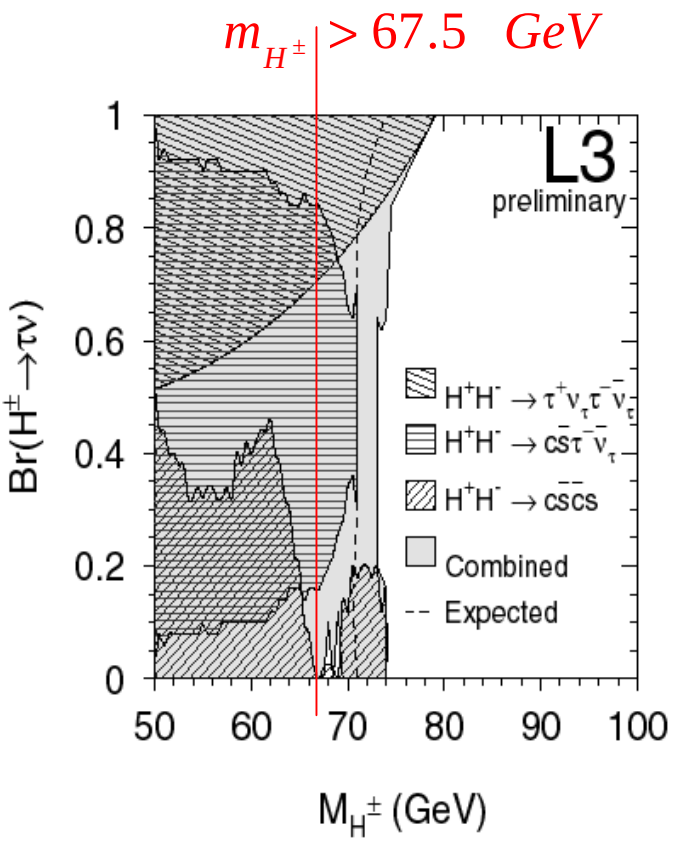
$$\Delta = \left| \frac{\mu^2}{m_Z^2} \frac{\Delta m_Z^2}{\Delta \mu^2} \right|$$

tree level: $m_Z^2 = -2\mu^2 + \dfrac{2m_{H_2}^2 \sin^2\beta - 2m_{H_1}^2 \cos^2\beta}{\cos 2\beta}$

Results: Charged Higgs

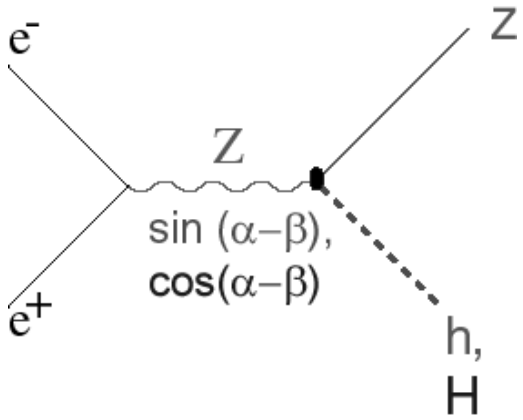
- In most of the SUSY parameters space $m_{H^\pm} > m_{W^\pm}$
- In principle LEP can kinematicaly probe the charged Higgs (with E_{CM}~190), however
  - Low cross section $\sigma(e^+e^- \to H^+H^-) \sim 0.15\,pb$ for $m_{H^\pm} = 80$ @ $E_{CM} = 190\ GeV$
  - Large BG: signature is $W^\pm$ alike, especially for heavier charged Higgses $H^\pm \to \tau^\pm\nu, c\bar{s}$

    large tgβ prefers $\tau^\pm\nu$ decays.
  - If a charged Higgs is discovered at LEP II, it will probably be lighter than that predicted byMSSM and it will indicate either physics beyond the MSSM or some obscure set of MSSM parameters.



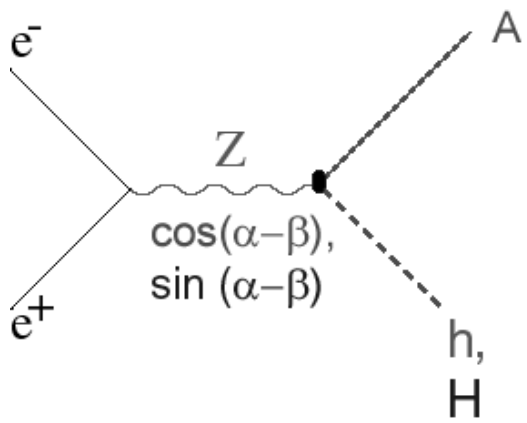
	Obs	Exp
ADLO 183	69.0	~68
DELPHI	65.1	69
L3	67.5	70
OPAL	68.7	67
ALEPH	62.5	68.5

Neutral Susy Higgs : Production & Decay



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

SM like topologies

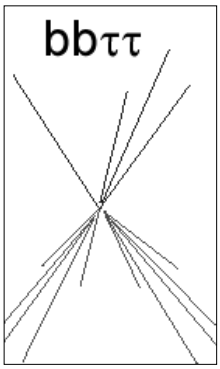


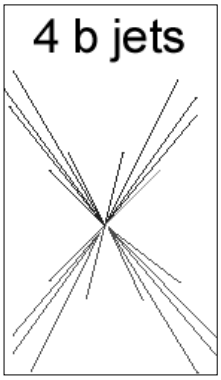
$$\sigma_{hA} = \sigma_{HZ}^{SM} \lambda \cos^2(\alpha - \beta)$$

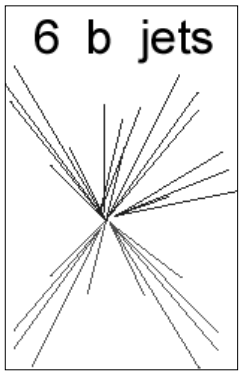
λ Kinematical factor

Complementarity

- h,A decay modes:
- Rad corrections $\Rightarrow$ possible $m_h > 2m_A \Rightarrow h \to AA$
- $g_{hb\bar{b},h\tau\tau} \sim \frac{\sin\alpha}{\cos\beta}$, $g_{Ab\bar{b},A\tau\tau} \sim tg\beta$ $\begin{cases} tg\beta > 1: h, A \to b\bar{b}\ (>85\%), \tau^+\tau^- \\ tg\beta < 1: h, A \to c\bar{c} \end{cases}$
- hA main search topologies:



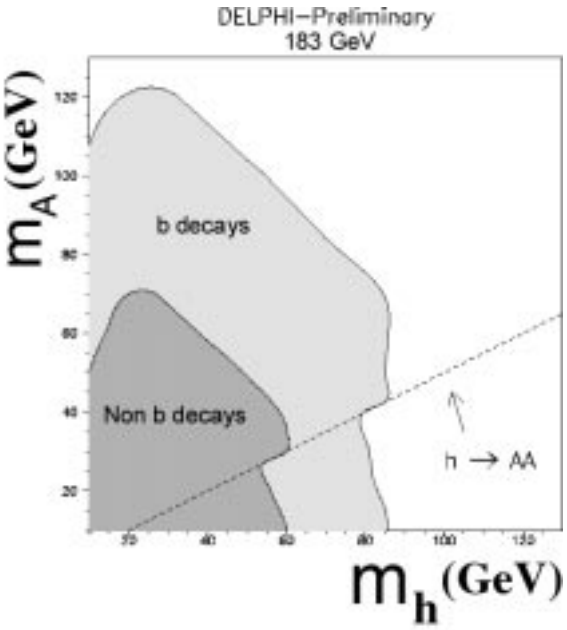




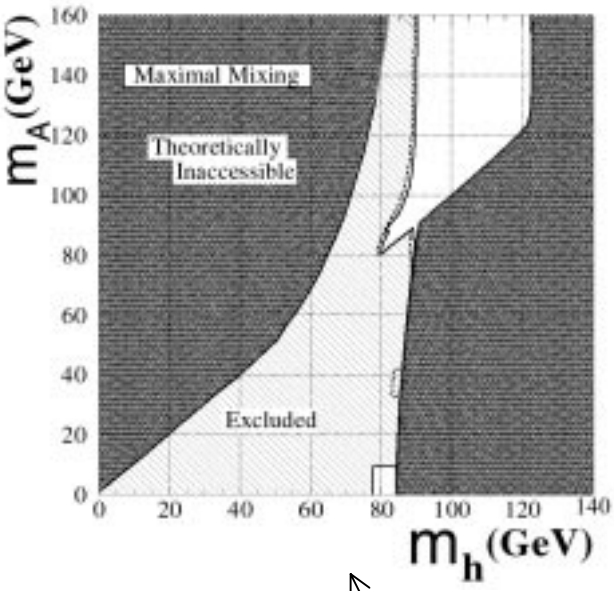
b tag essential

Results: General 2-Doublet Model

- Delphi (Similar results from OPAL)
- CP conserving case:



MSSM: ADLO 183 GeV

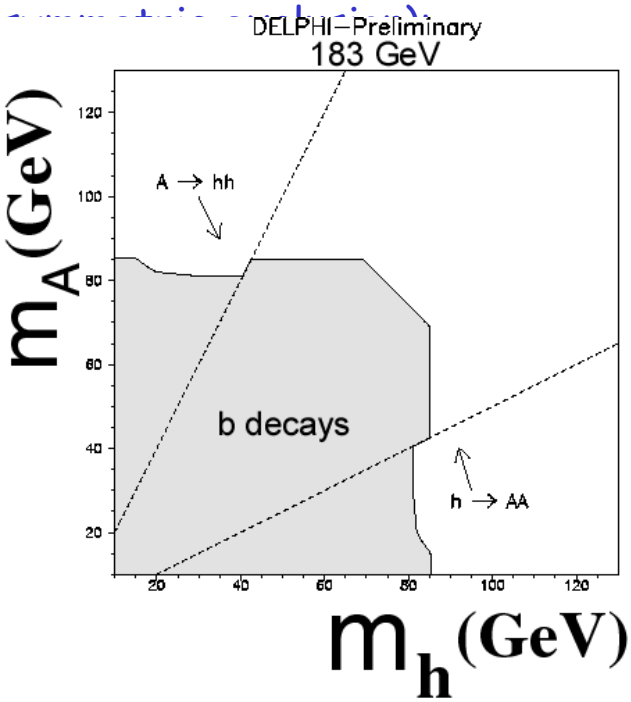


unexcluded area tgβ<1

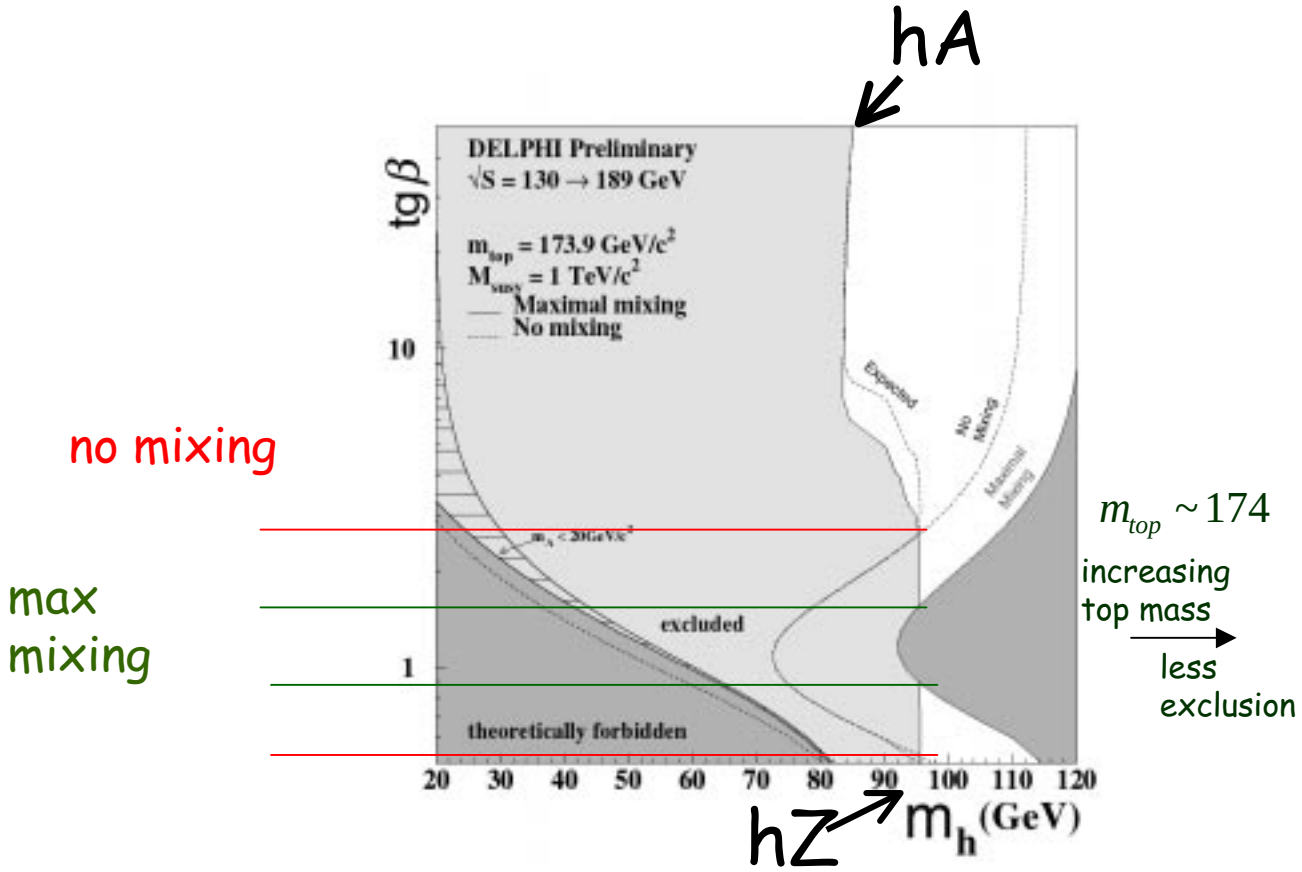
- CP violating case:

AZ production and the A → hh deacy should be considered

(leading to a



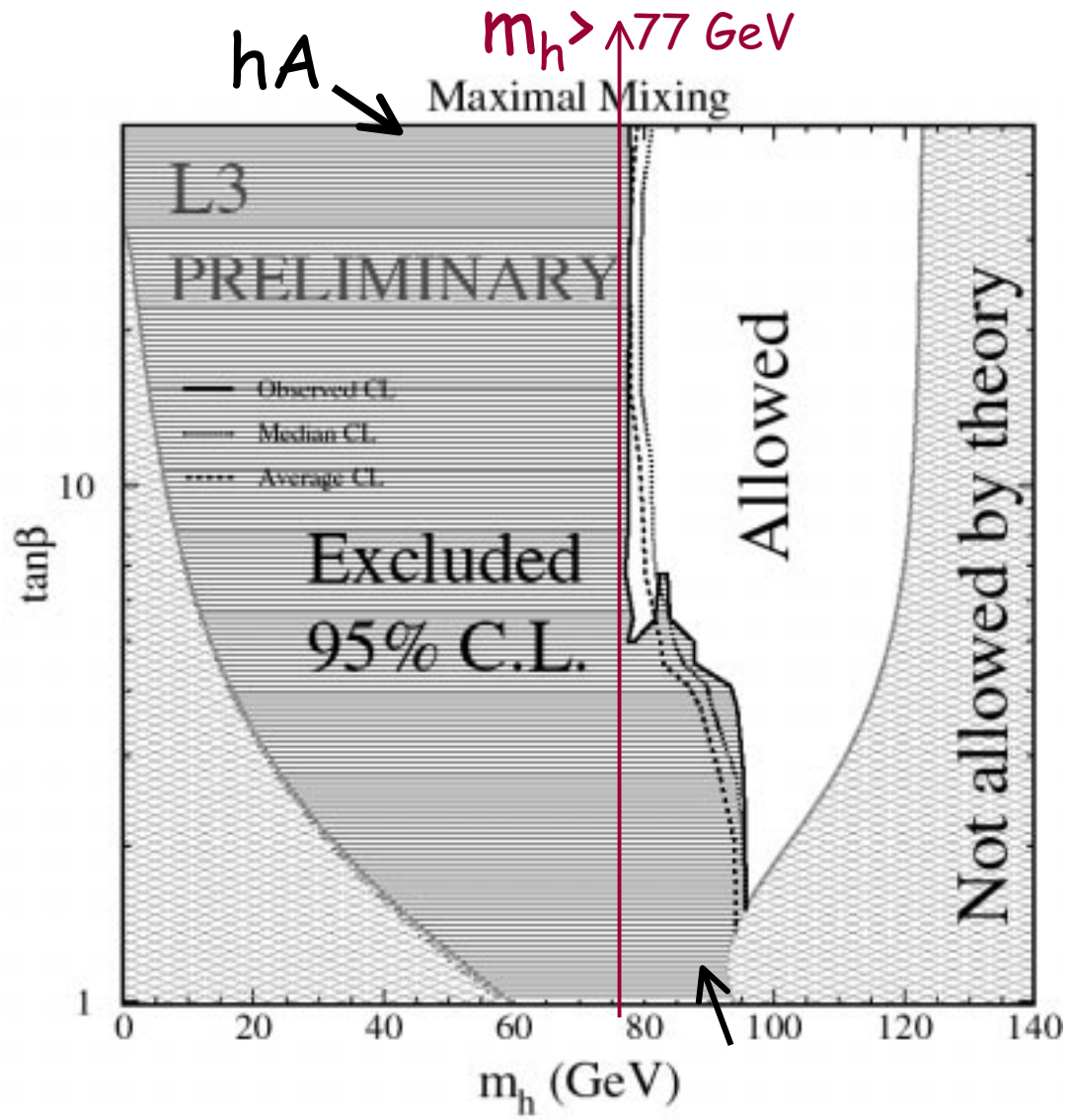
Results: Limits on tg β



• ADLO 183	0.8<tgβ<2.2	none	$(m_{top} \sim 175)$
• OPAL 189	0.8<tgβ<2.2	none	$(m_{top} \sim 175)$
• DELPHI 189	0.6<tgβ<2.6	0.9<tgβ<1.5	$(m_{top} \sim 174)$
• ALEPH 189	<tgβ<	none	$(m_{top} \sim 175)$
• L3 189	1.0<tgβ<2.6	1.0<tgβ<1.5	$(m_{top} \sim 175)$

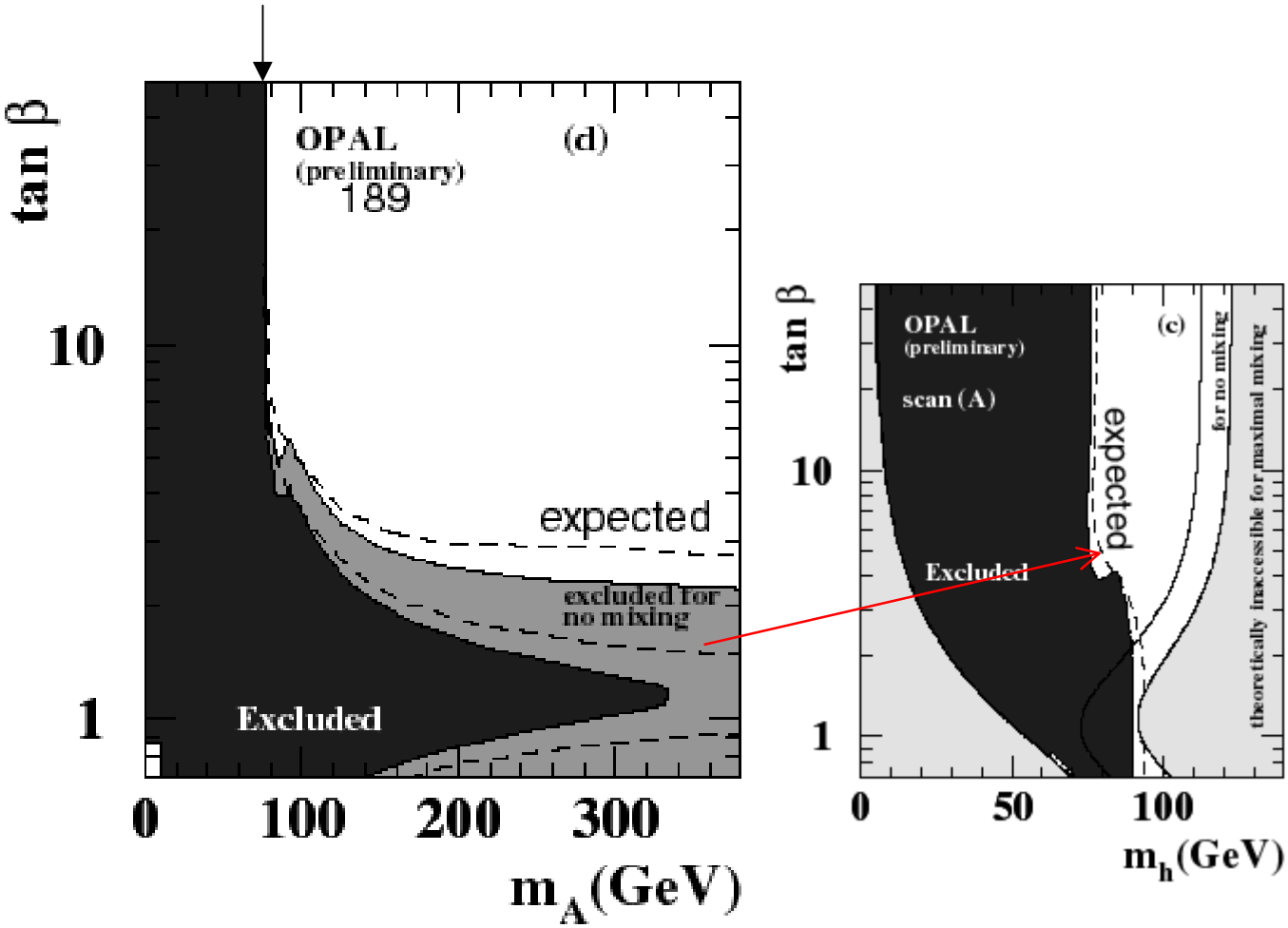
b-τ unification ⇒ h_t; $m_t = h_t v \sin\beta$ ⇒ $m_t(\mathrm{tg}\beta)$
m_t~174 GeV ⇒ IRFP solutions at low (1.5-2) and high (>40) tgβ. Low solutions on the edge of exclusion!
However, if the top mass is heavier and in particular for μ>0 the IRFP can still survive.

Results: Limits on m_h



- ADLO 183 m_h>79.6 (exp ~80.7) GeV
- ALEPH 189 m_h>81.2
- DELPHI 189 m_h>83.5 (exp 80.5) GeV
- OPAL 189 m_h>74.8 (exp 76.4) GeV
- L3 189 m_h> 77 (exp 77.8) GeV

Results: Limits on m_A



- ADLO 183 m_A>80.2 (expected ~81) GeV
- ALEPH 189 m_A>81.2 (expected) GeV
- DELPHI 189 m_A>84.5 (expected 81.6) GeV
- OPAL 189 m_A>76.5 (expected 78.2) GeV
- L3 189 m_A>78.0 (expected 77.9) GeV

Beyond the MSSM Benchmarks

- Why? To identify pathological points where e.g.
  - $\sin^2(\alpha-\beta)$ is very small; h is accessible kinematically, yet A is too heavy to be probed via hA production.
  - The $BR(h \to b\bar{b})$ is abnormally very small .
- Method: In addition to $(tg\beta, m_A)$ Scan over all SUSY parameters with $m_{top} = 165-175$ and find all (m_0, M_2, μ, A_t) physical nonexcluded points

(whenever applicable the heavier Higgs (H) production is considered):

  - SUSY constraints:

    No tachionic MSSM states, LSP is neutralino and masses of charginos and sfermions not excluded by SUSY searches.

    Limits on invisible Higgs are considered.
  - All model independent experimental constraints on $\sin^2(\alpha-\beta)$ and $\cos^2(\alpha-\beta)$ as well as PM (Γ_Z from LEP 1). ($b \to s\gamma$ not used yet)
  - $H^{\pm}$ is not excluded by direct searches.
  - No charge color breaking (CCB) minima in the MSSM lagrangian: (OPAL exclusive) $A_t^2 + 3\mu^2 < x(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2); \quad x = 7.5$

Invisible Higgs Decays

- MSSM R_p conserved $h \to \tilde{\chi}_1 \tilde{\chi}_1$

  or nearly invisible (OPAL)

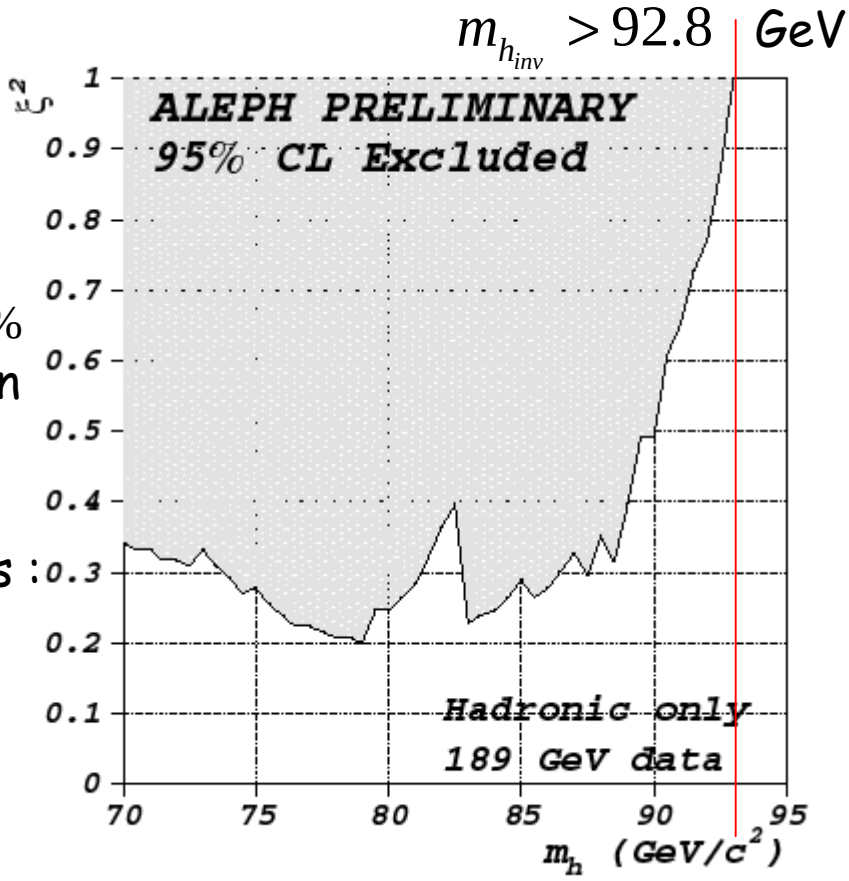
  $h \to \tilde{\chi}_2 \tilde{\chi}_1 \to \tilde{\chi}_1 \tilde{\chi}_1 + Z^* / \gamma$ with very small Δm

- R_p violating $h \to JJ$;J is a Majoron (Goldstone Boson via SSB of Lepton # U(1)) which couples only to ν_R

$$\xi^2 \equiv \frac{\sigma_{h_{inv} Z}}{\sigma_{h_{SM} Z}}$$

If the $BR(h \to inv) = 100\%$ and if the cross section is SM like than the excluded m_h (in GeV) is :

ALEPH	92.8
DELPHI	91.6
L3	
OPAL	84
OPAL (n.i.)	87

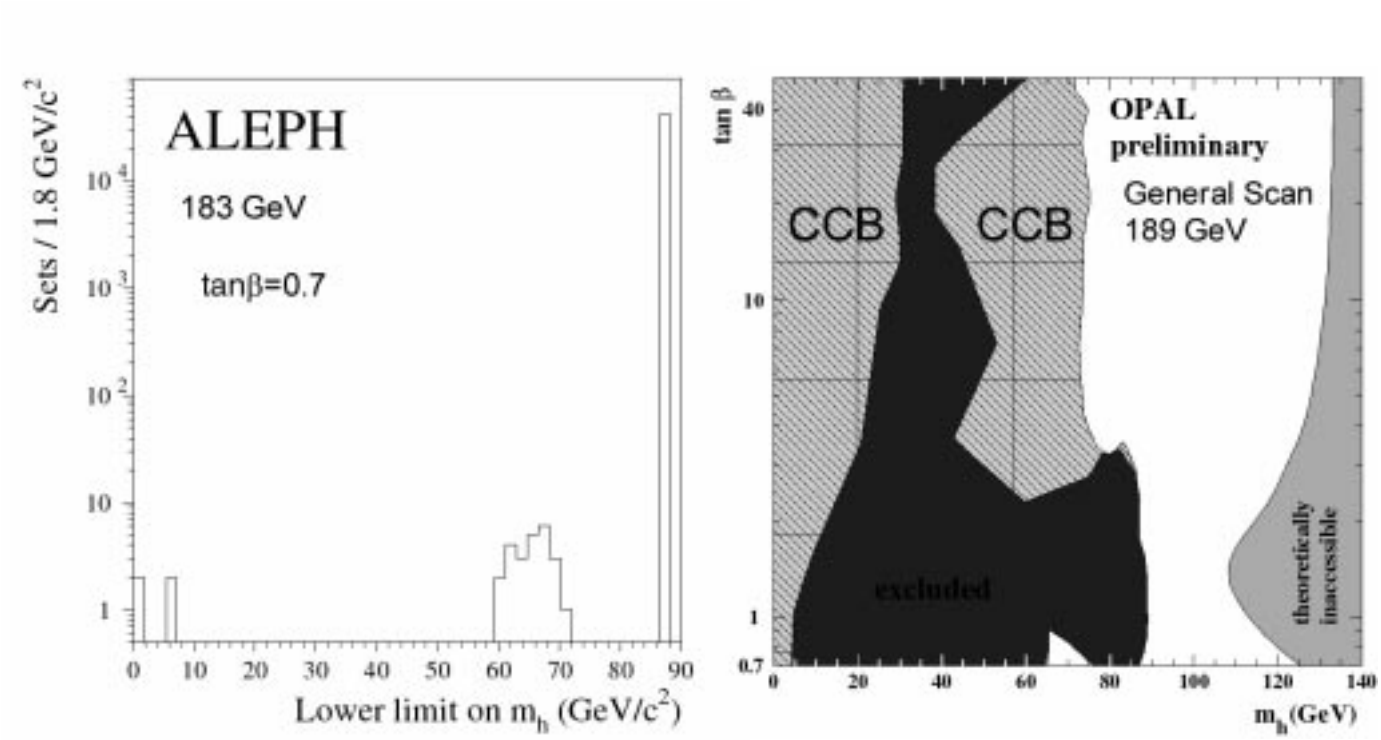


Results: General MSSM Scan

All masses in TeV

	m_{top}	$tg\beta$	m_A	m_0	M_2	$\lvert\mu\rvert$	$\lvert A_t\rvert$
ALEPH	.170-.180	0.7-32	0.0-2	0-2	0-2	0-2	0-4
OPAL	.165-.185	0.7-50	.005-2	0-1	0-2	0-2	0-2.5

Up to 8,000,000 sets of points were tested per experiment!

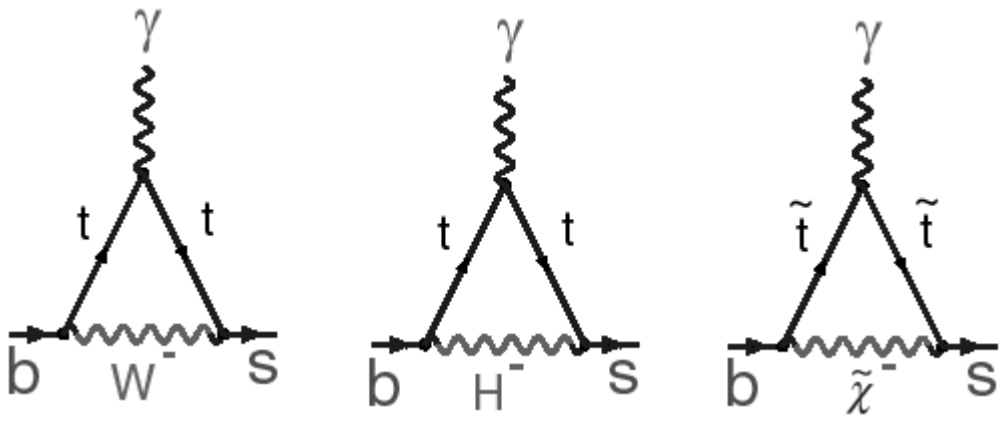


Level of pathological points $<10^{-3}$
Most are CCB type.

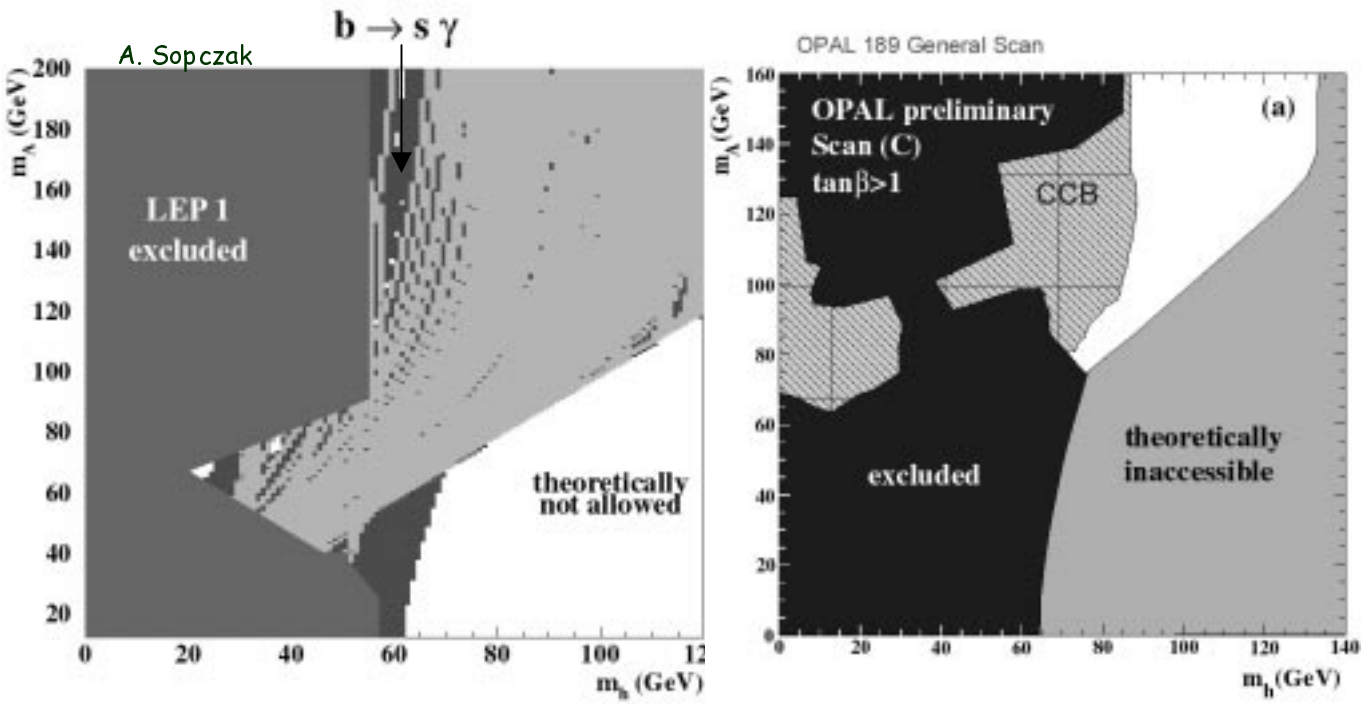
MSSM Scan
$m_h>72.2$
$m_A>76$ GeV

Maximal Mixing
$m_h>74.8$
$m_A>76.5$ GeV

PM: b ⟶ s



- NLO paper: NPhys. B534 (1998) 3
- CLEO: (3.15+/-0.54) * 10e-4 from CLEO CONF 98-17 (1998).
- Not too much is gained by $b \to s\gamma$

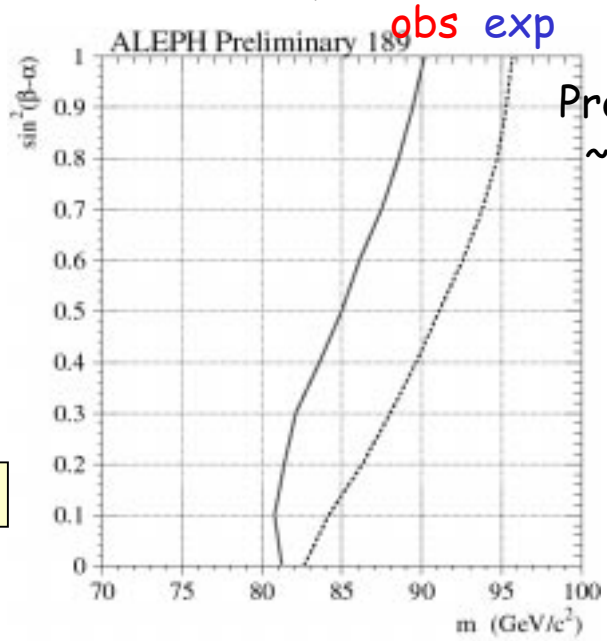


Back to ℵ SM Higgs Search

With HZ analysis
m_H> 95.7 92.0
exp obs

hZ+hA analysis → $\sigma_{hz} = \sigma_{HZ}^{SM} \sin^2(\alpha-\beta)$

$\sin^2(\alpha-\beta)=1 \Rightarrow m_H$> 90.2 (95.7)
obs exp



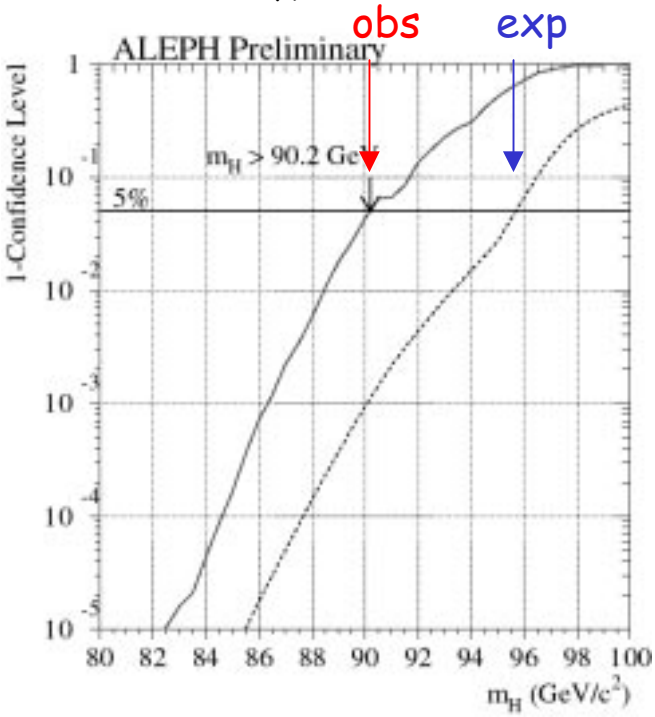
Prob ~1%

In principal hA (4b's) searches have some sensitivity to hZ 4-jets final states.

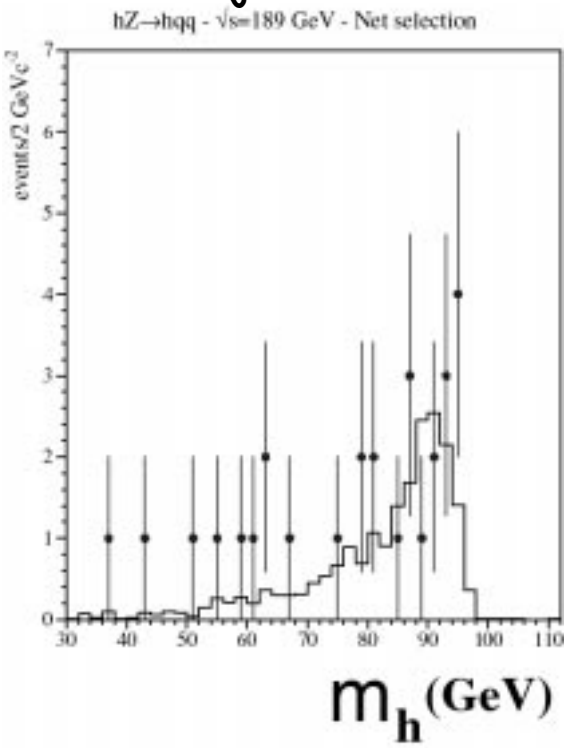
	m_H=95 hZ	BG	DATA
hZ	6.6	18.9	24
hZ+hA	1.9	2.6	4
hA	0.1	2.4	3

The hZ+hA is a statistically independent analysis which has higher weight (S/BG) than the HZ~hZ+(hZ+hA) analysis so the 4 candidate events have more significance
(than they had in the NN based standalone SM analysis).

m_H> 90.2 (95.7)
obs exp



4-jets



LEP SM Higgs Limits

	Luminosity	$m_H >$ Expected	Observed	Prob(%)*
ALEPH	171	95.7	90.2	~1%
Delphi	158	94.8	95.2	
L3 63%	176	93.7	95.3	
OPAL	187	94.9	91.0	4%
ADLO 183	220 (combined)	90.2	89.7	
ADLO 189	691 (combined)	97.2*		
ADLO 200	600 (combined)	108.5*		

*Prob= prob to set a limit lower

*Predicted

Prospects for Higgs Search at LEP 2

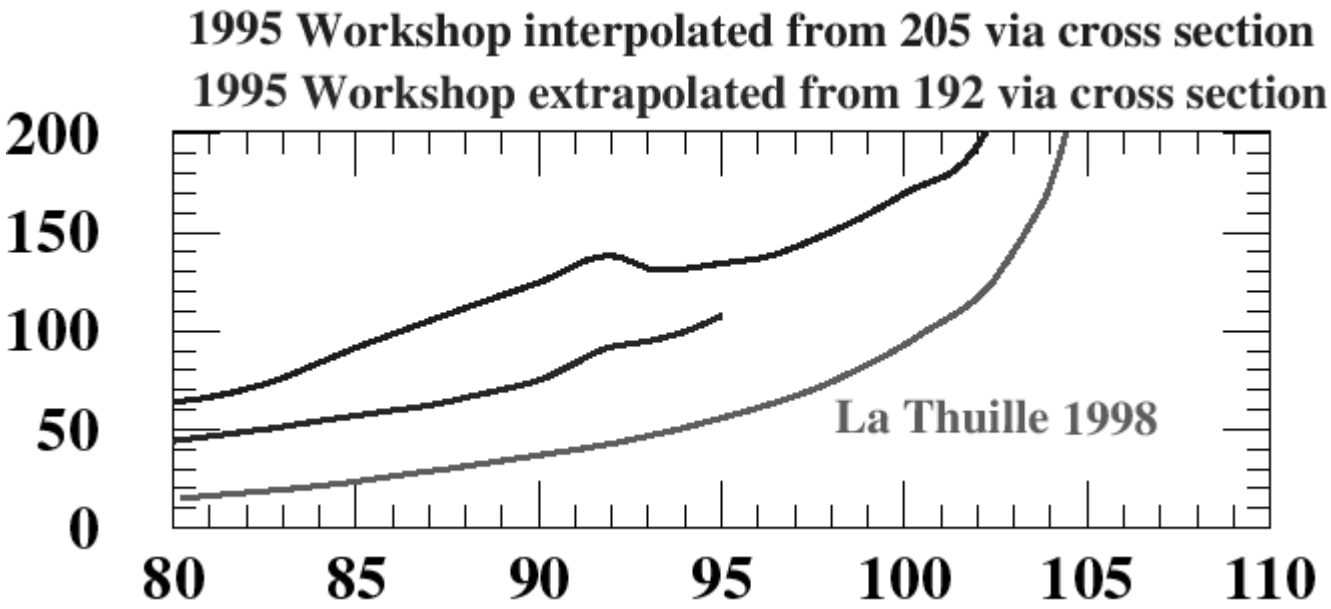
CERN 96-001

Physics at LEP 2
1995
Workshop

First attempt to predict LEP Higgs search sensitivity was made in 1995

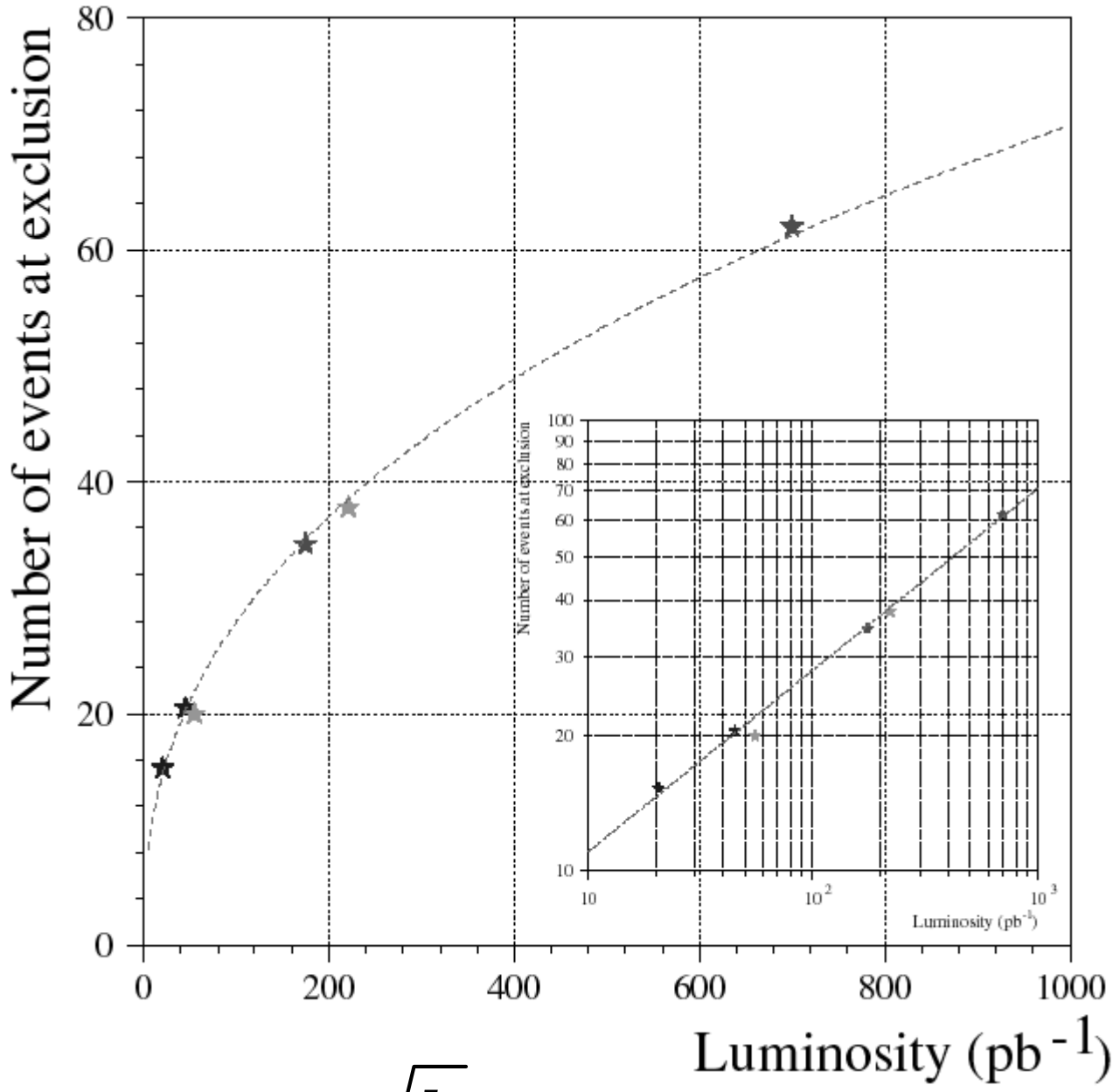
It was based on LEP 1 experience and turned out to be pessimistic

A second attempt (based on LEP @ 183 and 172) was done for
La Thuile 1998 by E.G. and A. Read



Most recently (Chamonix, January 1999) P. Janot presented an easy way to extrapolate LEP performance

Prospects: Chamonix 1999



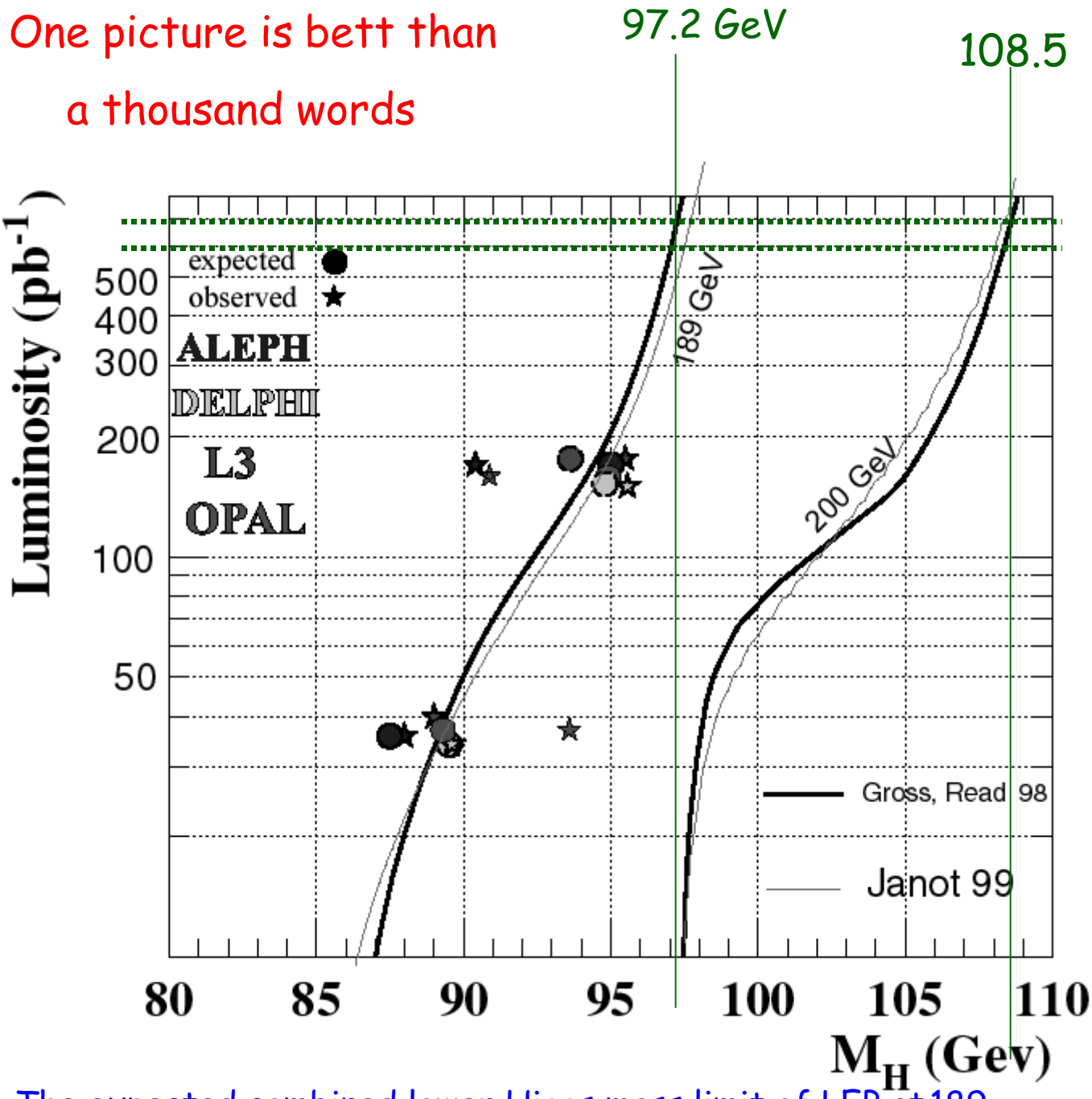
$$s/\sqrt{b} = 2$$

$$N(m_h^{limit}) \propto \sqrt{L}$$

$$N(m_h^{limit}) = (\sigma_0 L)^{0.404} \quad \sigma_0 = 38.2\,pb$$

Predictions and Observations

One picture is bett than a thousand words



- The expected combined lower Higgs mass limit of LEP at 189 GeV is 97.2 GeV.
- With 150 pb^{-1} per experiment (600 pb^{-1} total) at 200 GeV the expected final exclusion sensitivity of LEP is around 108.5 GeV (close to kinematical limit)
- Excellent agreement between Janot's and our predictions

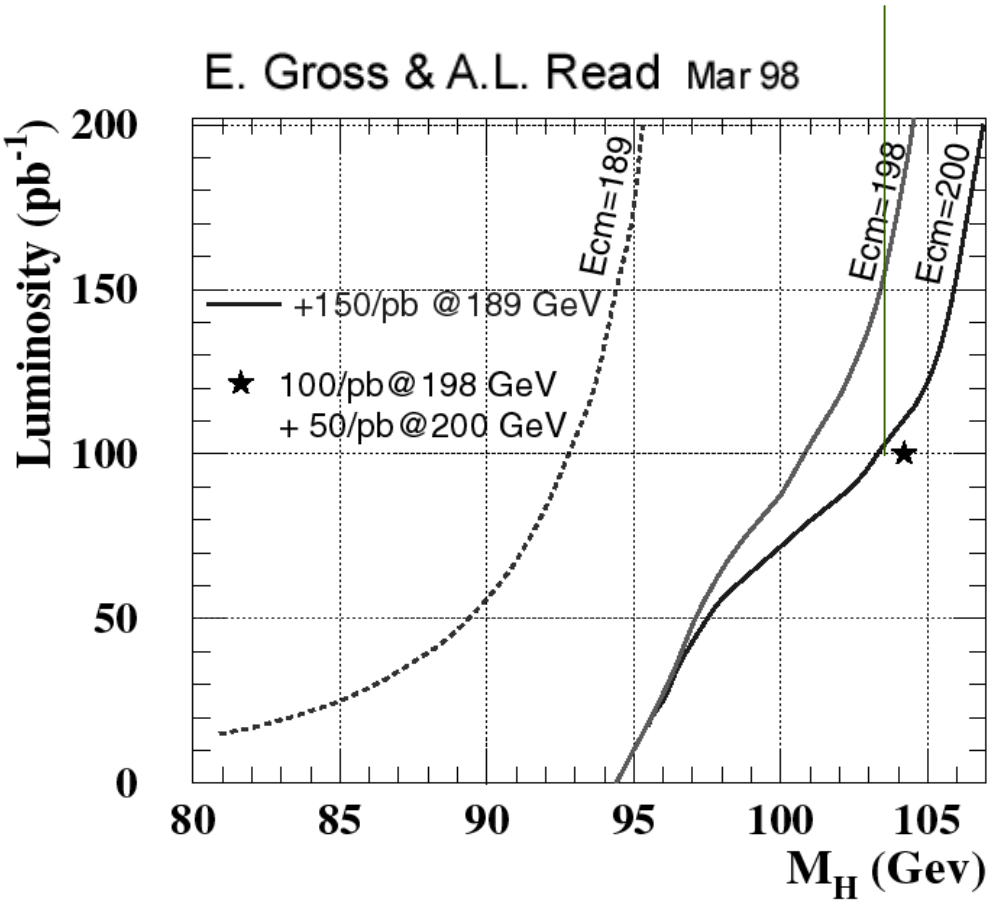
Discovery Sensitivity

The discovery sensitivity is defined as the value of m_H for which 50% of signal+background experiments are expected to have a significance of 5s or better.

The fraction of $s(m_H)+b$ MC experiments with $1\text{-}CL_b = \text{Prob}(Xb > Xobs) < 5 \cdot 10^{-7}$ $> 50\%$

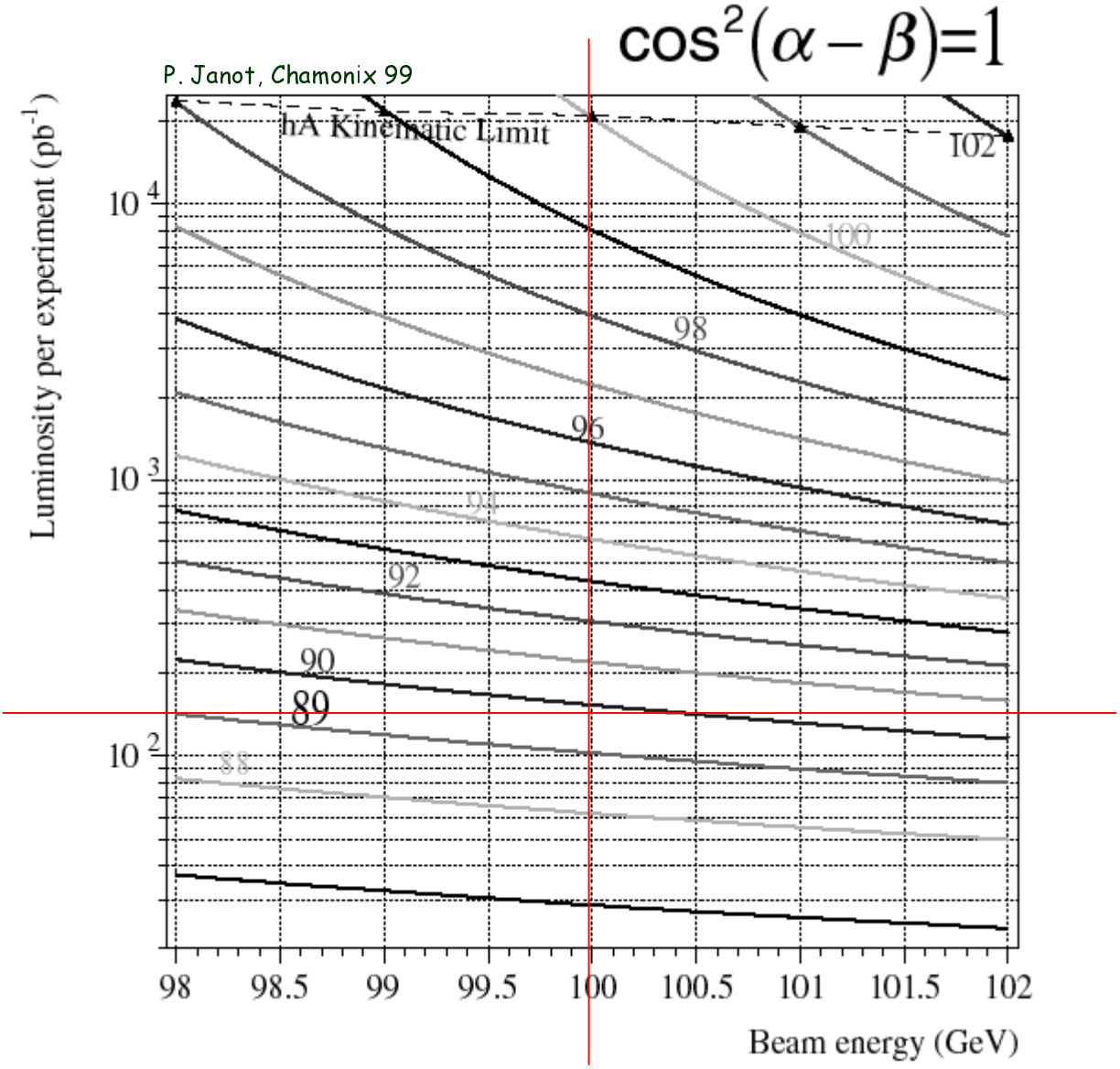
Discovery Prospects

The discovery sensitivity is defined as the value of m_H for which 50% of signal+background experiments are expected to have **a significance of 5s or better.**



- With 100 pb^{-1} per experiment at E_{CM}=200 GeV, LEP combined discovery sensitivity reaches 103.5 GeV
- There is a trade-in between Luminosity and Energy e.g. an increase of 2 GeV in energy pays only if the luminosity decrease is less than 50%...

MSSM Higgs Prospects at LEP



- With ~150 pb^{-1} at E_{CM}=200 GeV (per experiment), the combined sesitivity of LEP is for a light SUSY Higgs with a mass smaller than ~90 GeV
- About 20 fb^{-1} per experiment are needed to reach the kinematical hA limit.....

Conclusions

- LEP has performed remarkably well at E_{CM}=189,192 GeV.
- The Standard Model Higgs boson should be heavier than 90-95.5 GeV with an expected combined LEP limit of around 97 GeV!

m_H>90-95 GeV

- A light SUSY Higgs is excluded if it is lighter than 80 GeV

m_h>80 GeV. Also excluded 0.9<tgβ<1.5

- LEP is expected to reach an energy of 200 GeV and increase its exclusion power to a Higgs boson of 108 (~90) GeV for a SM (MSSM) Higgs (with an integrated luminosity of 150 pb^{-1} per experiment). This is almost at the kinematical wall for the SM Higgs..
- Theory predicts a SM Higgs boson around the corner. Vacuum stability set the corner way above LEP sensitivity (>160 GeV), however a light SUSY Higgs is still on the theoretical map.
- LEP collected 30 pb^{-1} (per exp) at E_{CM}=192 GeV and is collecting data at E_{CM}=196 GeV now... And on our way to 200 GeV!

If god is on our side, let the Higgs appear this year,

Amen