Higgs Searches at LEP

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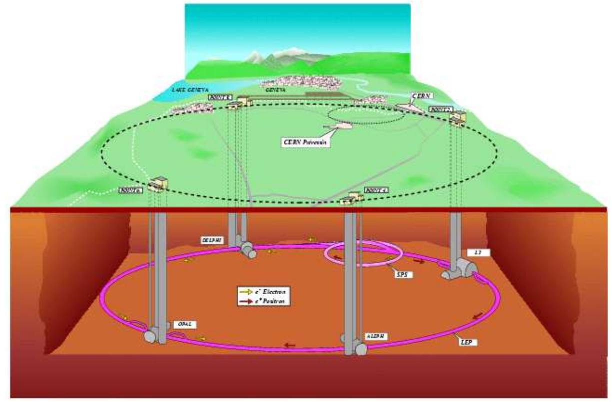
...for the LEP-Higgs working group...

increasing model-dependence

- **Decay-Mode independent Higgs Search**
- **Flavour-independent Higgs Search**
- **Standard Model Higgs Search**
- **2HDM Higgs Searches**
  - **general 2HDM Scan**
  - **MSSM Higgs Searches**
  - **Search for charged Higgs Bosons**
  - **Fermiophobic Higgs Searches**
  - **Yukawa Production of a light Higgs**
- **... and beyond ...**

...only selected topics shown ...

Introduction



Higgs Field	El.magn. field	Weak fields
Complex scalar doublet (4 degrees of freedom)	$U(1)$ symm.	$SU(2)_L$ symm.
Φ^+ Φ^0	B	W^+ W^0 W^-

Higgs mechanism : 3 degrees of freedom from Higgs fields

$\Rightarrow$ Longitudinal polarization of W^+, W^-, Z^0

$\Downarrow$

Massless γ, massive $W^\pm$ and Z^0 bosons

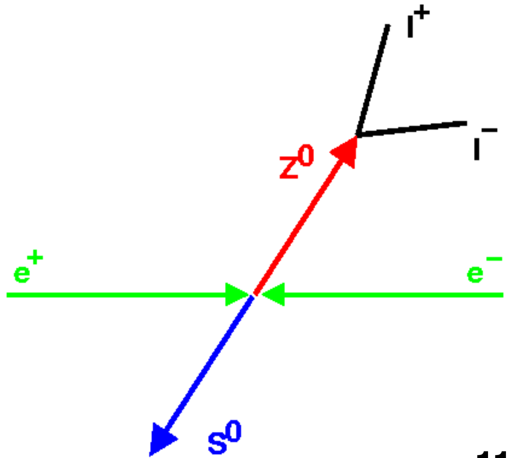
Remaining degree of freedom ...
H^0 neutral scalar boson

Higgs boson mass m_H ... free parameter ... if known
Higgs phenomenology (production/decay) fully determined

as example: OPAL numbers

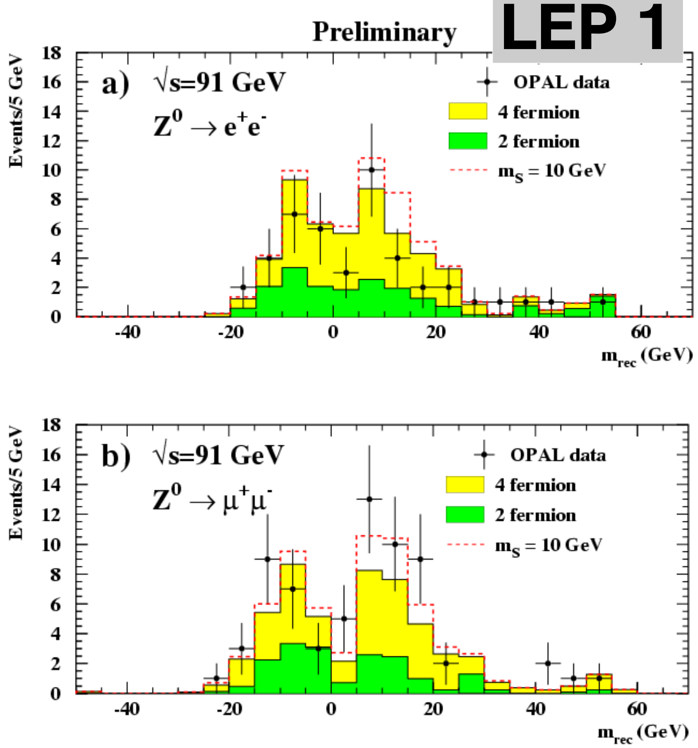
Stage	$\sqrt{s}$ (GeV)	Year	$\int \mathcal{L}$/exp. (pb^{-1})
LEP1	≈ 91	1989-95	175
LEP1.5	130-140	1995	5
LEP2	161-172	1996	20
	183	1997	55
	189	1998	180
	192-202	1999	230
	202-209	2000	220

Decay-Mode Independent Higgs Search



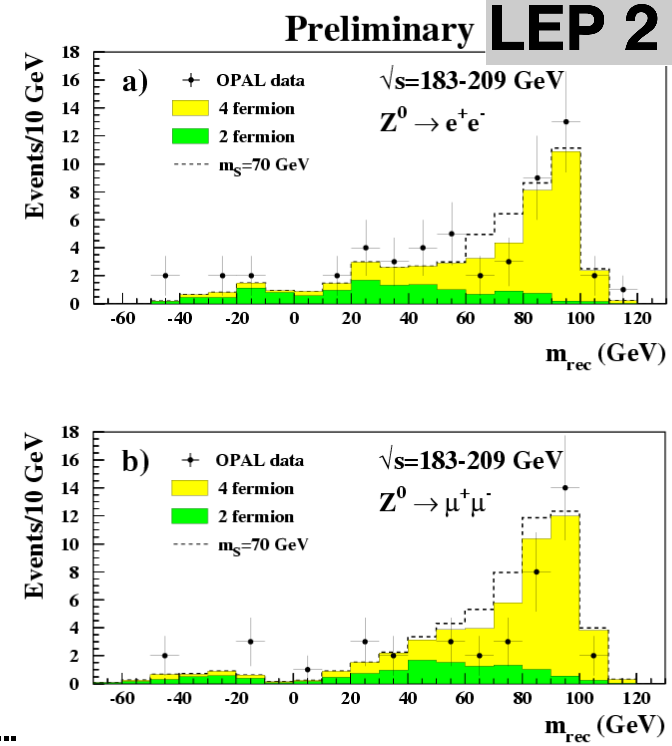
- select events on Z^0 -> di-lepton$^{(+/-)}$ signature
- be independent of recoiling S^0 decay products ...
- compare observed recoil mass spectrum with expectation for a S^0 signal ...
- minimum efficiency channel for exclusion

115.4 pb^{-1} **LEP 1**



LEP 1:	electron	muon
data	45	66
backgrd	55	54
LEP 2:		
data	54	43
backgrd	47	52

662.4 pb^{-1} **LEP 2**



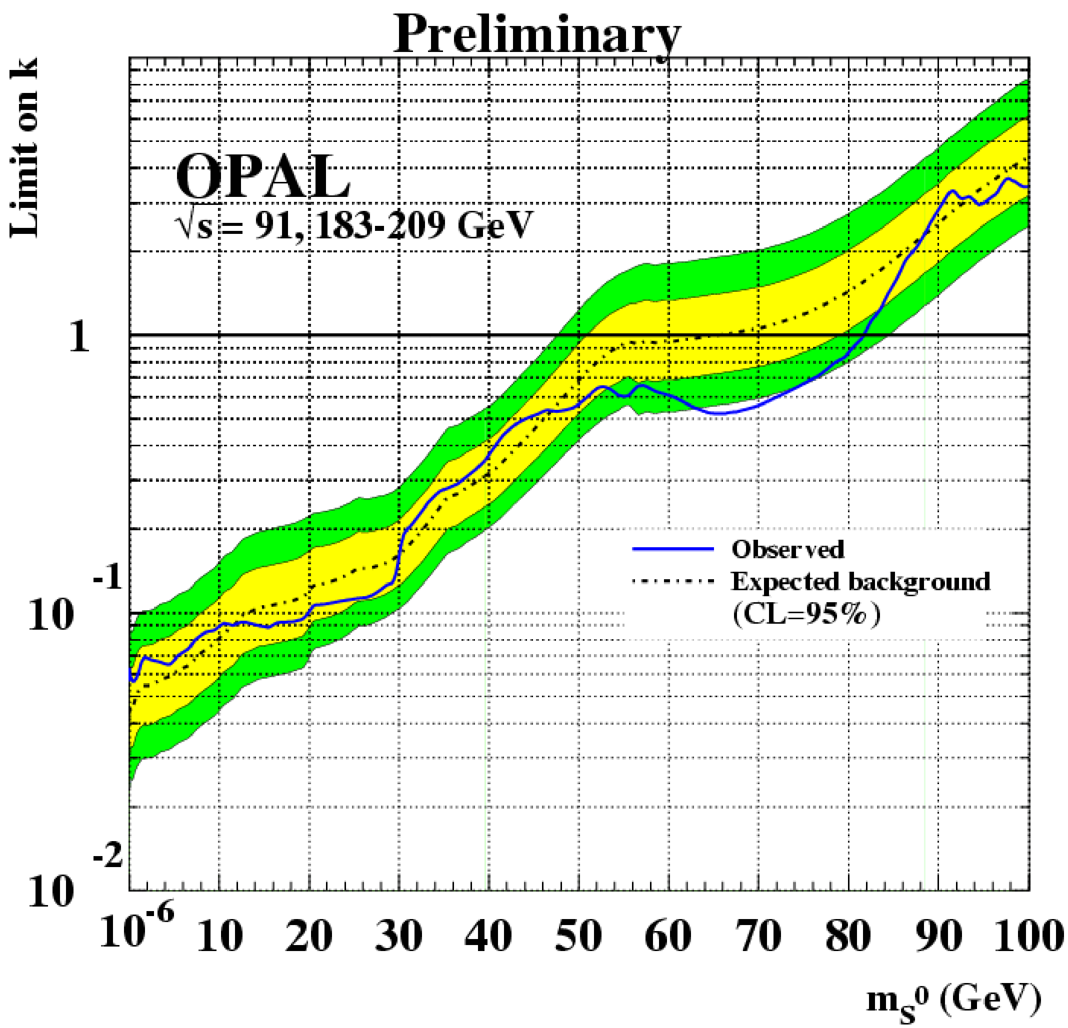
...repeated for TESLA benchmark study on Higgs...

Decay-Mode Independent Higgs Search

$$\sigma_{S^0Z^0} = k \cdot \sigma_{H_{SM}Z^0}$$

set 95% CL exclusion limit on production cross-section wrt. SM cross-section

only assume $\sqrt{s}$ -dependence as SM Higgs production cross-section ...



cross-section exclusions$_{(95\% \text{ CL})}$:

k<0.1 @ 1 keV < m_{S^0} < 19 GeV

k<1 @ m_{S^0} < 81 GeV

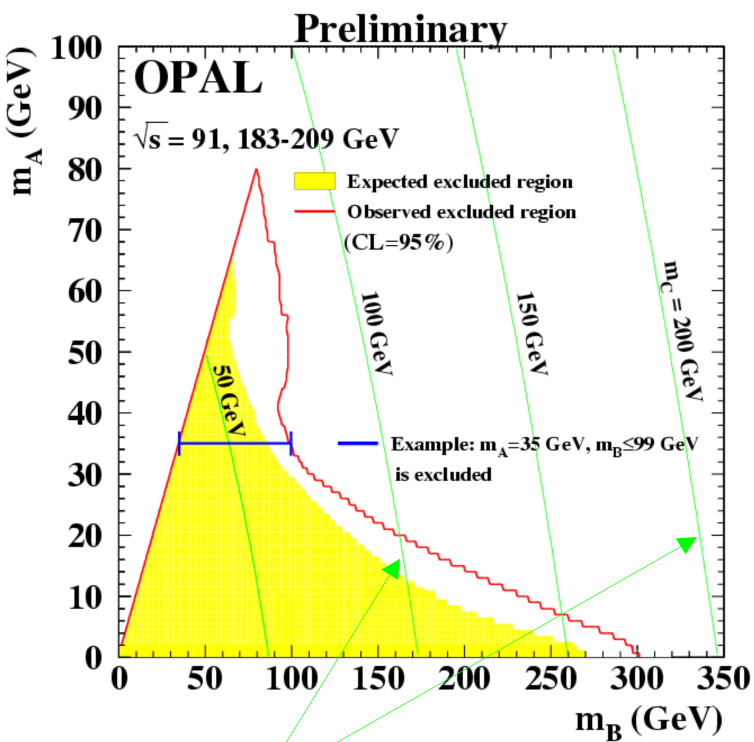
absolute mass limit for SM coupling strength

This result will be included in future model interpretations...

Decay-Mode Independent Higgs Search

Uniform Higgs scenario :

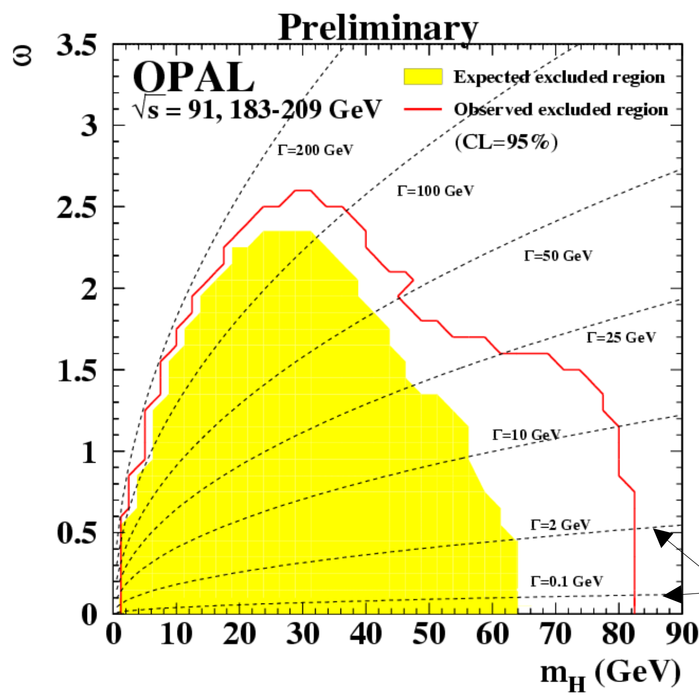
- spectrum of Higgs states H_i in $m_A < m_{H_i} < m_B$
- for normalised coupling density $\Rightarrow$ obtain mass limits



perturbative mass scale
in normalisation condition

Stealthy Higgs scenario (Binoth, van der Bij):

- prediction of additional $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields (Phions)
- no strong/electro-weak interaction, only coupling ω to Higgs
- Higgs width can become large, depending on coupling ω and number of singlet fields



resulting Higgs width

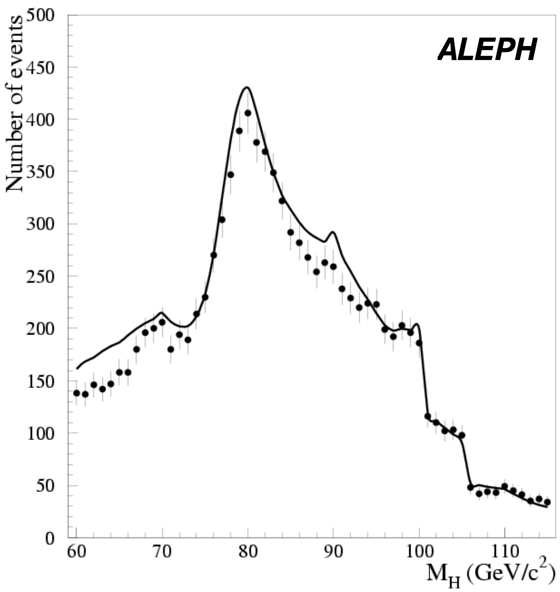
Flavour Independent Higgs Search

- physics beyond Standard Model could have modified H-b coupling
- Higgs might only couple to gluons (bosons) (see 2HDM-type I)
- ...

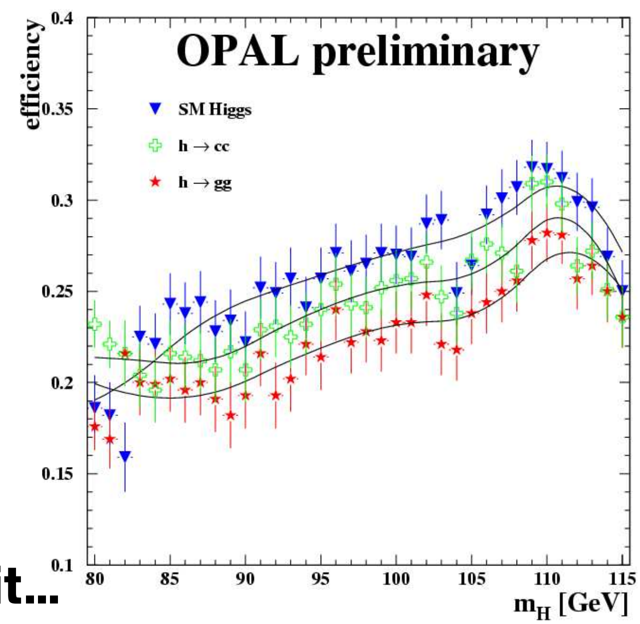
$\Rightarrow$ **Search for $e^+e^- \to Z^0H^0$ with $H \to$ Hadrons (qq or gg)**

most powerful background suppression mechanism (b-tag) gone
search in qqqq, $qq\nu\nu$, qqll in a mass window $\Delta m_h \approx \sigma\ (m_h)$

$\rightarrow$ correlated mass bins



...use minimum efficiency for conservative limit...

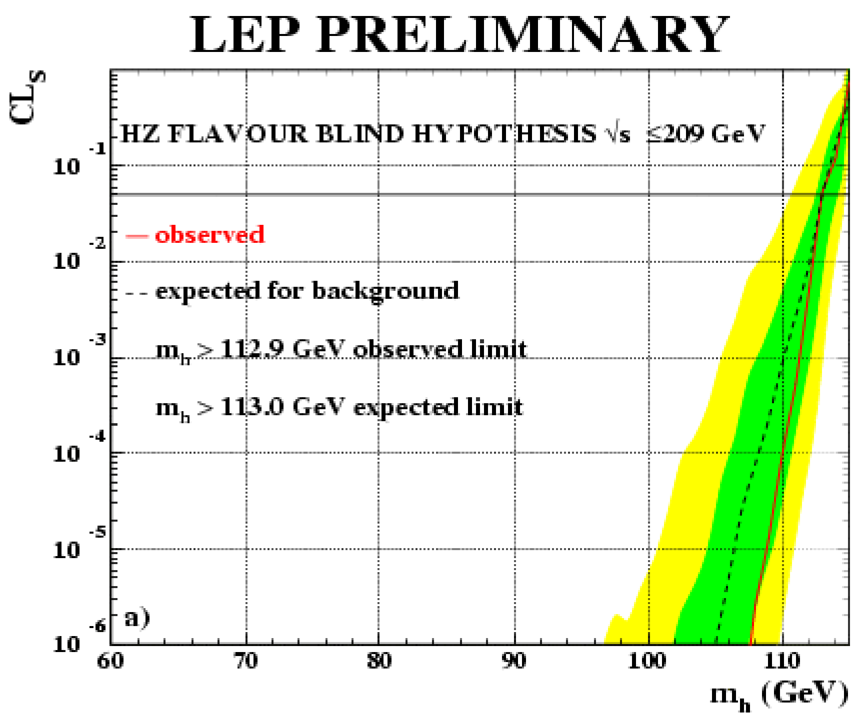


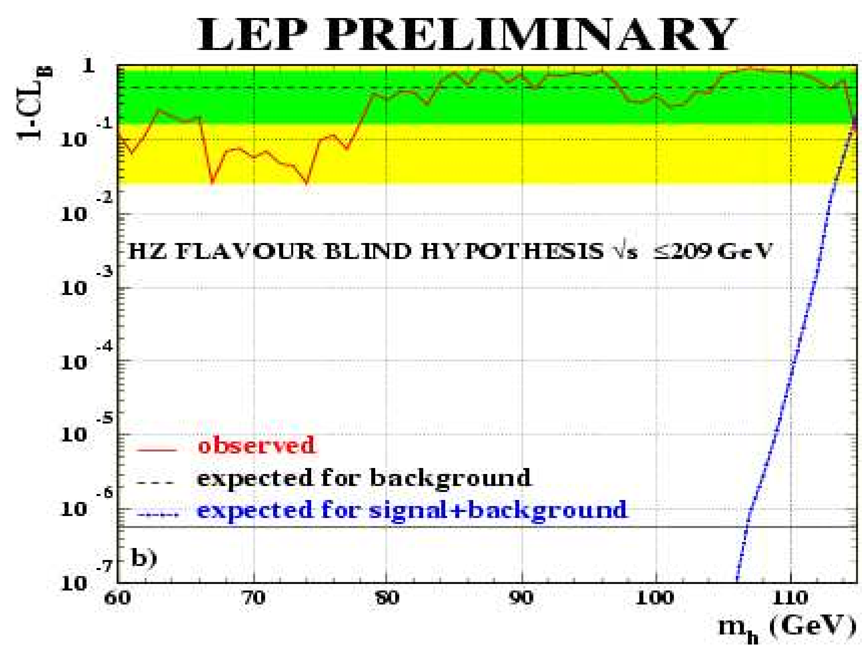
hep-ex/0107034

Flavour Independent Higgs Search

assuming :
- $\sigma_{HZ} = \sigma_{HZ}^{SM}$
- $Br(h \to \text{hadrons}) = 1$

- strong cross-section limit
- close to SM sensitivity
- good agreement with SM





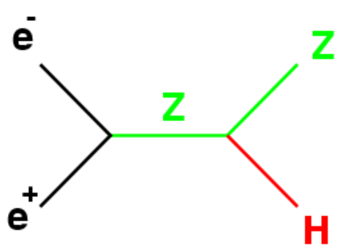
95% CL mass limits:
$m_H > 112.9$ GeV (obs.)
$m_H > 113.0$ GeV (exp.)

...will be used further in model interpretations (2HDM, MSSM, ...)

Standard Model Higgs Search

Higgs-Strahlung

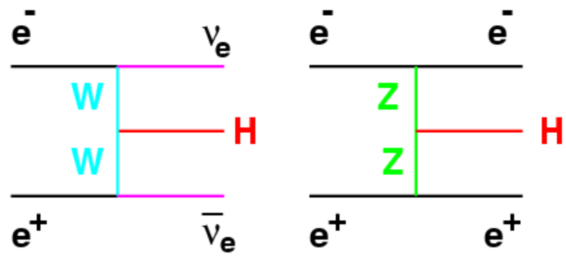
(dominant mode)



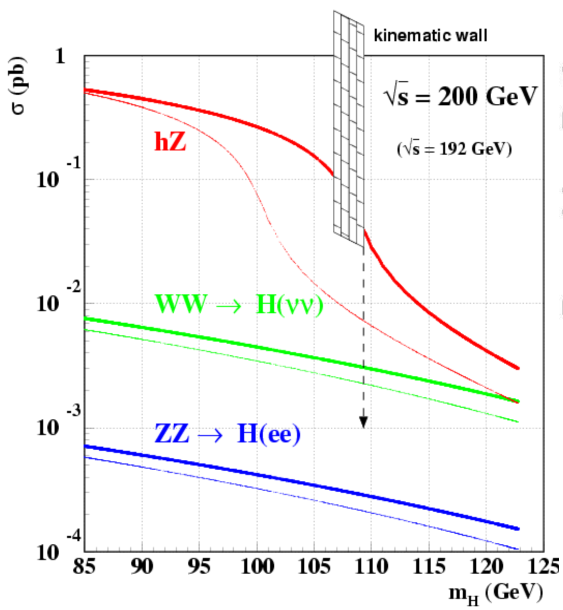
$m_h \simeq \sqrt{s} - m_Z$

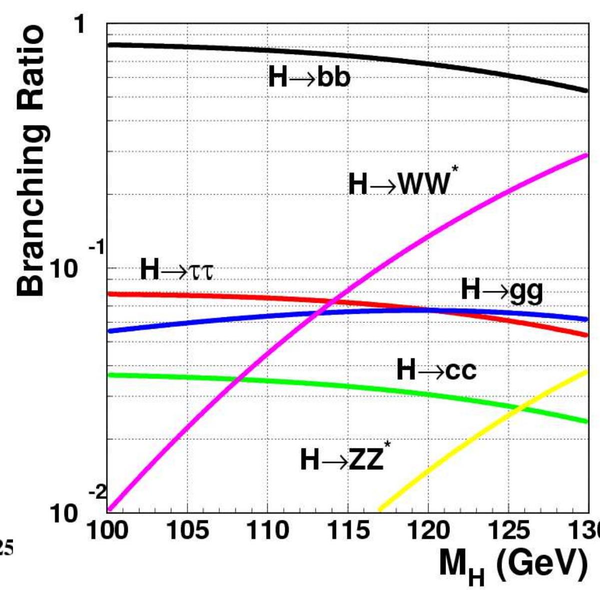
WW and ZZ fusion

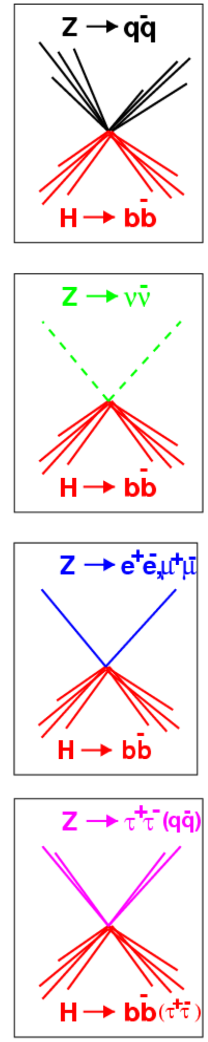
(small contribution)



Possibility to go beyond kinematic limit





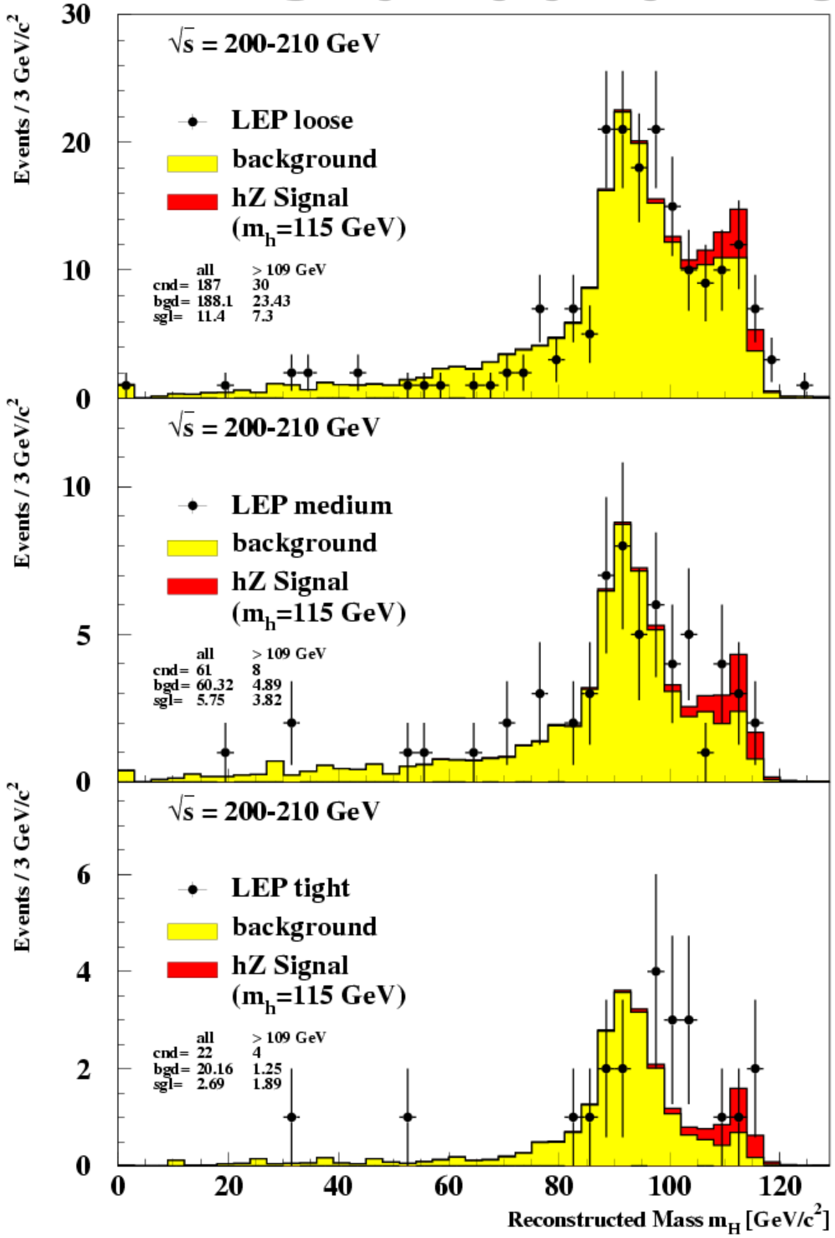


- **Four Jets :** (58% in SM)
  - ▷ Energy-momentum conservation
  - ▷ The 2 most probable b-tagged jets recoil against a di-jet compatible with a Z-boson
  - ▷ eff 40-50 %
- **Missing Energy :** (17% in SM)
  - ▷ The recoil mass of the 2 b-tagged jets is compatible with a Z-boson
  - ▷ eff 30-40 %
- **Leptons :** (6% in SM)
  - ▷ 2 high energetic leptons with a mass compatible with a Z-boson recoil against 2 jets
  - ▷ eff 50-60 %, clean channel
- **τ's :** (10% in SM)
  - ▷ 2 low multiplicity jets compatible with a Z-boson and 2 b-tagged jets
  - ▷ eff 35 %

H → bb dominant in LEP mass range...

combination
Budapest 2001

Standard Model Higgs Search



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

for m_h=115 GeV:

	Exp. sig.	Exp. bgd	Data
Loose	11.4	188.1	187
Medium	5.75	60.32	61
Tight	2.69	20.16	22

E_{CM}>189 GeV: 2465 pb^{-1}
E_{CM}>206 GeV: 542 pb^{-1}

Standard Model Higgs Search

N	number of observed candidates
$\tilde{s}_i$	expec. nr. of sgl events in local bin of (mass, discriminant)
$\tilde{b}_i$	expec. nr. of bgd events in local bin of (mass, discriminant)
s	total number of expected signal events
b	total number of expected background events

"likelihood ratio method"

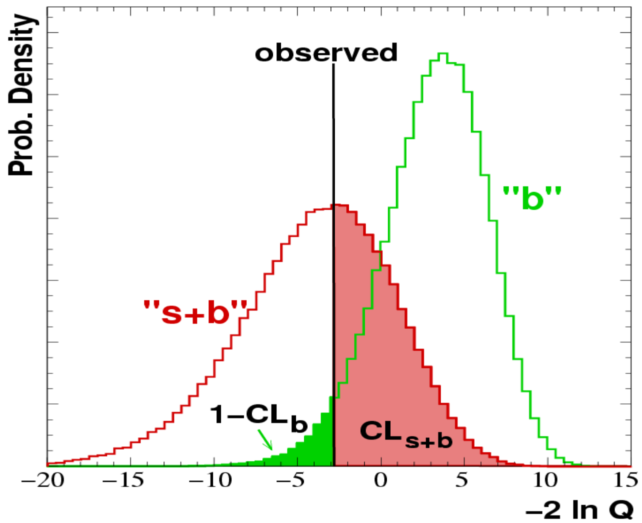
Likelihood for signal + background hypothesis

$$L_{s+b} = \frac{(s+b)^N}{N!} e^{-(s+b)} \prod_{i=1}^{N} \frac{(\tilde{s}_i + \tilde{b}_i)}{s+b}$$

Likelihood for background only hypothesis

$$L_b = \frac{b^N}{N!} e^{-b} \prod_{i=1}^{N} \frac{\tilde{b}_i}{b}$$

$$Q = \frac{L_{s+b}}{L_b} = \frac{e^{-(s+b)}}{e^{-b}} \prod_{i=1}^{N} \left(\frac{\tilde{s}_i + \tilde{b}_i}{\tilde{b}_i} \right) = e^{-s} \prod_{i=1}^{N} \left(1 + \frac{\tilde{s}_i}{\tilde{b}_i} \right)$$



$$\Rightarrow \boxed{\begin{array}{l} -2\ln Q = 2\left(s - \sum_{i=1}^{N} \omega_i\right) \\ \text{with weight } \omega_i = \ln\left(1 + \frac{\tilde{s}_i}{\tilde{b}_i}\right) \end{array}}$$

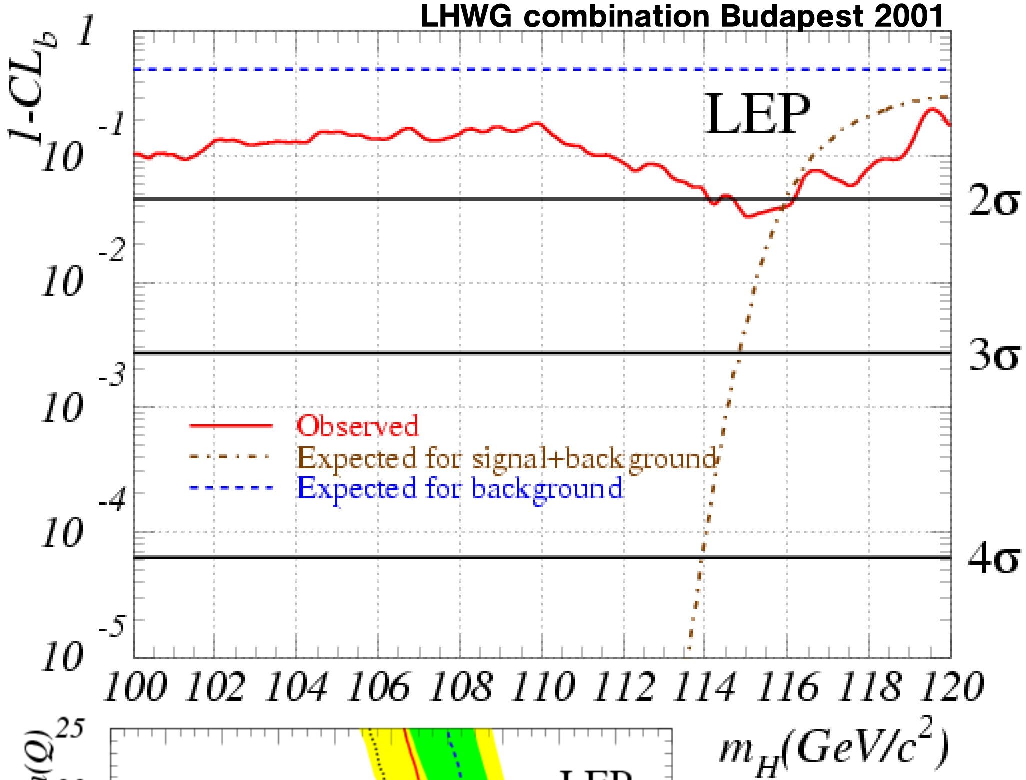
$1\text{-}CL_b$ ... a measure of compatibility with b

CL_{s+b} ... a measured of compatibility with s+b

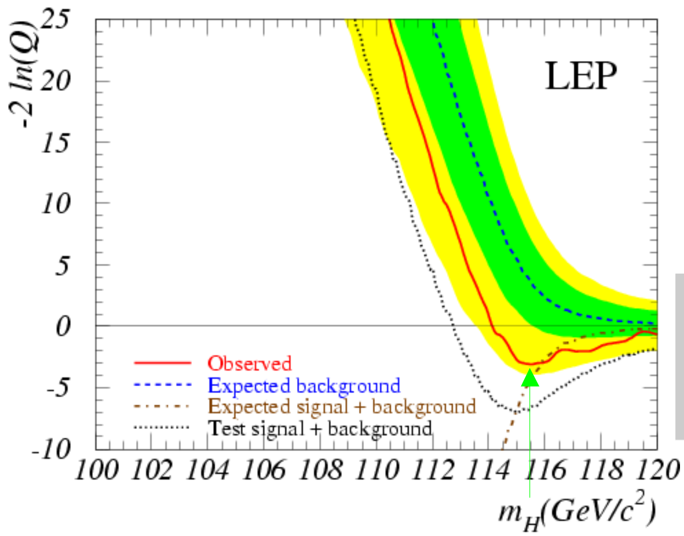
exclusion limits: $CL_s = CL_{s+b} / CL_b$

Standard Model Higgs Search

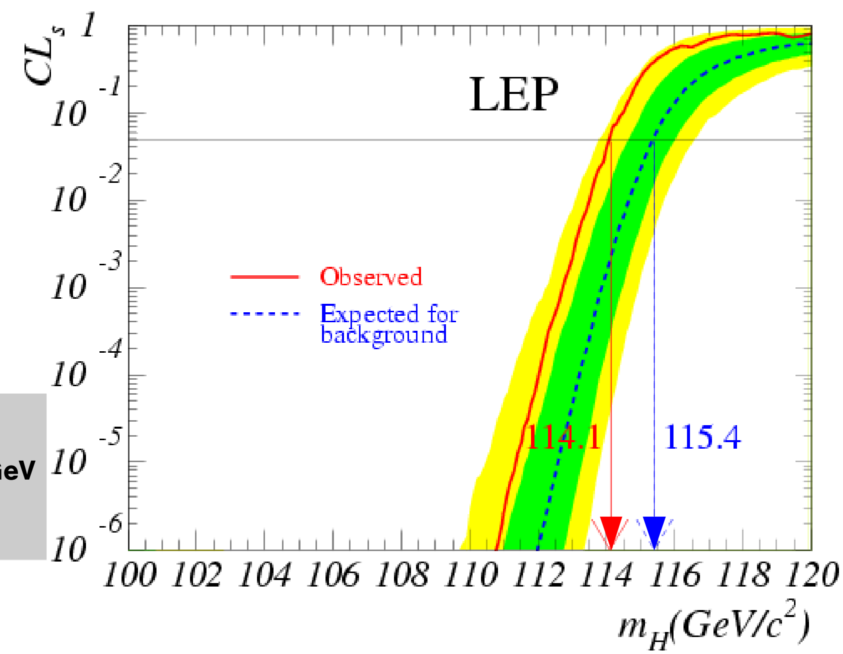
CERN-EP/2001-055
LHWG combination Budapest 2001



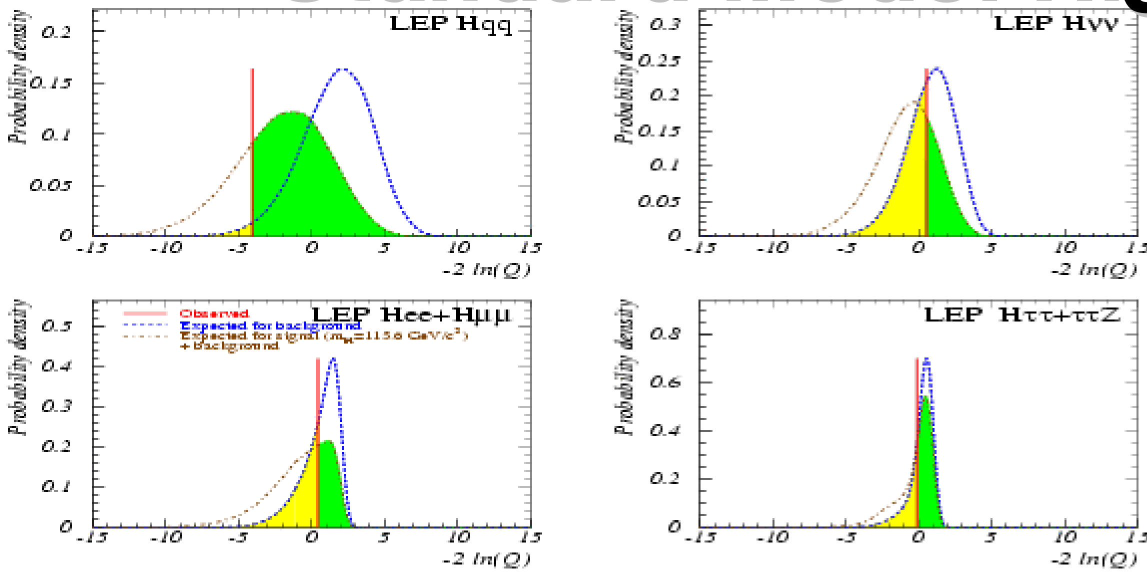
- **maximum likelihood occurs at**
  $m_h \approx 115.6$ GeV
- **LEP-combined result (Budapest '01) corresponds to 2.1σ over backgrd**
  (backgrd fluctuation prob. $1-CL_b = 3.4\%$)
- **at the 95% CL:**
  $m_h > 114.1$ GeV (obs.)
  $m_h > 115.4$ GeV (exp.)



- **kinematic edge @ 116 GeV**
- **mass resolution σ (m_H) ≈ 3.5 GeV**
- **test signal (here) for 115 GeV**

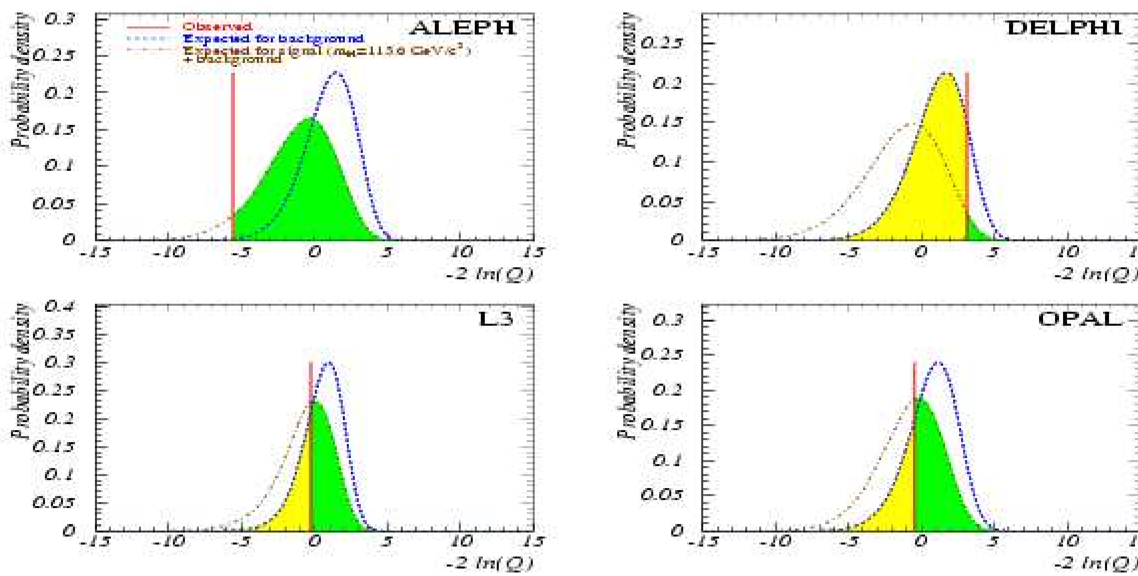


Standard Model Higgs Search



4-jet signal-like
νν background-like

ALEPH signal-like
DELPHI background-like



ALEPH	PLB 495 (2000) 1
ALEPH	PLB 526 (2001) 95 (Dec. 2001)
DELPHI	PLB 499 (2000) 23
L3	PLB 495 (2000) 18
L3	PLB 517 (2001) 319 (June 2001)
OPAL	PLB 499 (2000) 38
LHWG	CERN-EP/2001-055

- DELPHI and OPAL working towards final SM publication (summer 2002)
- then final LEP-Higgs Working Group combination …

2 Higgs Doublet Models

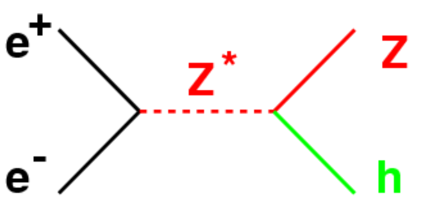
Two Higgs Doublets $\mathcal{H}_1, \mathcal{H}_2$ and 5 physical states

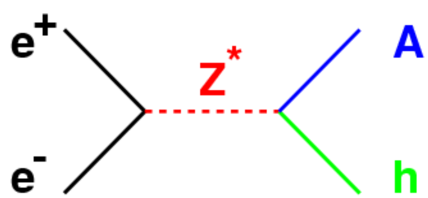
$$\mathcal{H}_1 = \Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}; \qquad \mathcal{H}_2 = \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

2 CP-even neutral Higgses	$\mathrm{h^0, H^0}$	$\mathrm{m_h < m_H}$
1 CP-odd neutral Higgs	$\mathrm{A^0}$	
2 charged Higgses	$\mathrm{H^\pm}$	
Free parameters:	$\tan\beta = v_2/v_1$	(VEV ratio)
	α	(mixing angle of h, H)
	μ	Higgs mass parameter
	A_0	common trilinear Higgs-sfermion coupling
tree level:	$\mathrm{m_h < m_Z < m_H}$	
rad.corrected:	$\mathrm{m_h <}$ 130 GeV	

couples to	type I	type II	type III	type IV
‘d-type’ leptons	Φ_2	Φ_1	Φ_2	Φ_1
‘u-type’ quarks	Φ_2	Φ_2	Φ_2	Φ_2
‘d-type’ quarks	Φ_2	Φ_1	Φ_1	Φ_2

for example: MSSM





“Higgsstrahlung”

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

- largest at small $\tan\beta \approx 1.4$
- SM topologies
- recycle SM searches

“Associated Production”

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

- largest at $\tan\beta > 15$
- typically $\mathrm{m_A \approx m_h}$
- new topologies
- dedicated searches:

$\mathrm{hA \to b\bar{b}b\bar{b}, hA \to \tau^+\tau^- b\bar{b}}$

- also $\mathrm{h^0 \to A^0A^0}$ and $\mathrm{h^0, A^0 \to \chi^0\chi^0}$ (invisible)

$g_{hff} \propto \cos\alpha$

$\Rightarrow$ fermiophobic for $\alpha=\pi/2$

i.e. might couple only to bosons, not to fermions

Parameter Scan in General 2HDM

parameter scan in 2HDM:

$1 \leq m_h \leq 120$ GeV

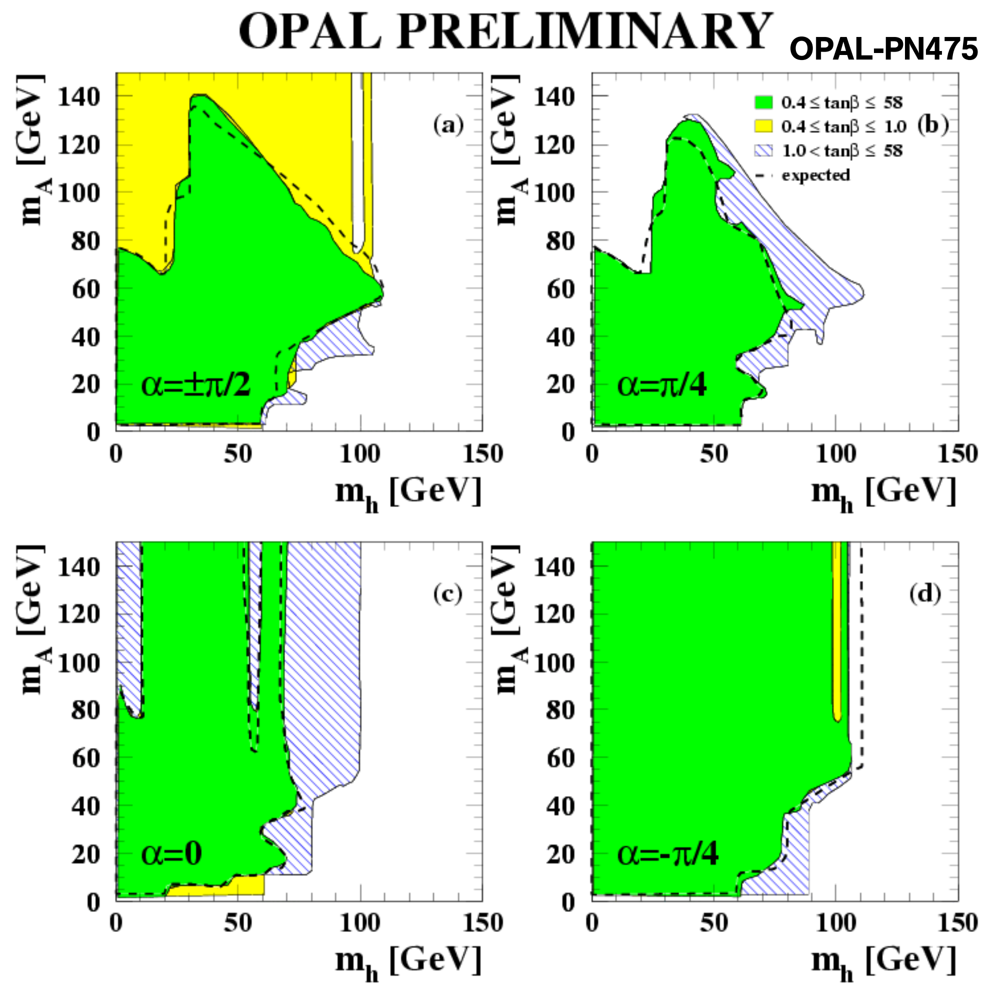
$3 \text{ GeV} \leq \mathrm{m_a} \leq 2 \text{ TeV}$

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

$\alpha = +\pi/2, +\pi/4, 0, -\pi/4, -\pi/2$

m_{H^+} and m_H above the kinematically accessible region

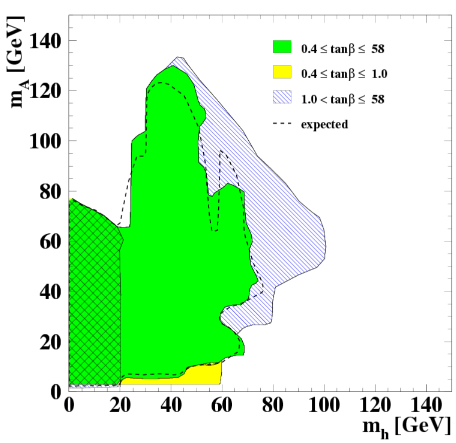
OPAL-PN475



$h^0 Z^0$ and $h^0 A^0$ channels with and without b-tagging

constraint by non-standard contribution to

Z^0 width $\Delta\Gamma_{inv}$



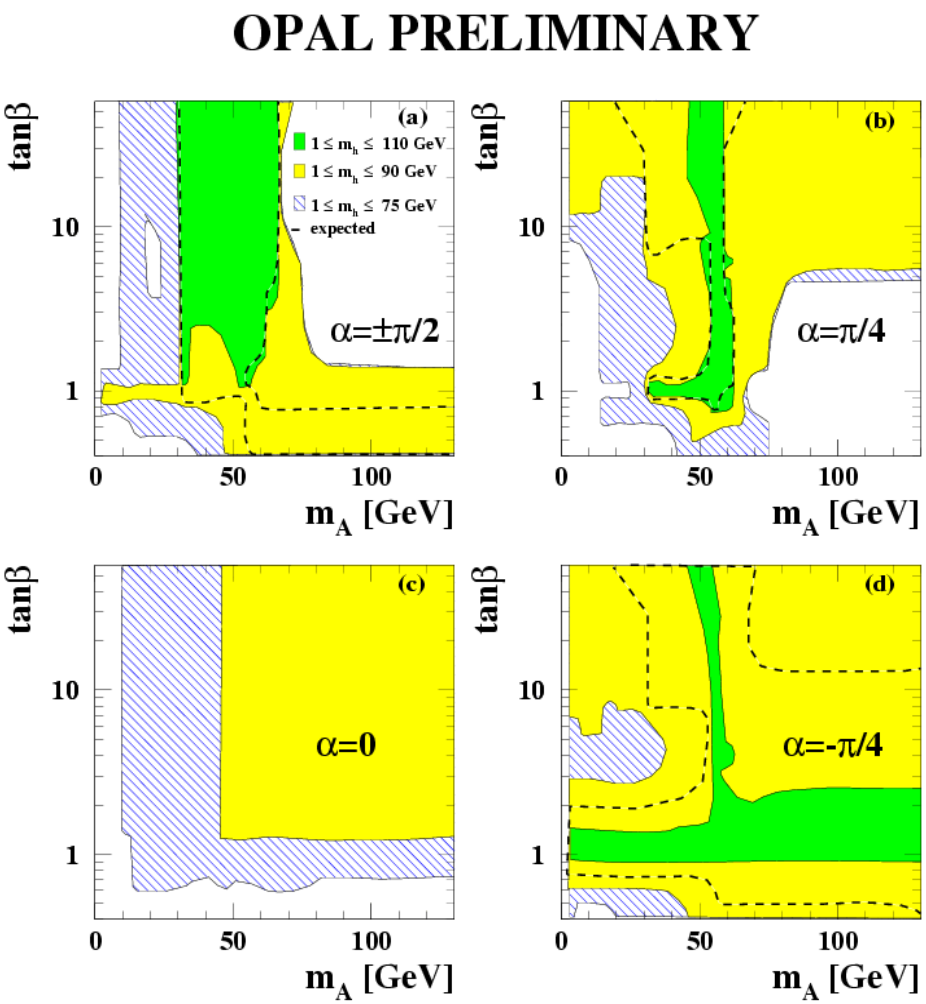
...exclusion for any α ...

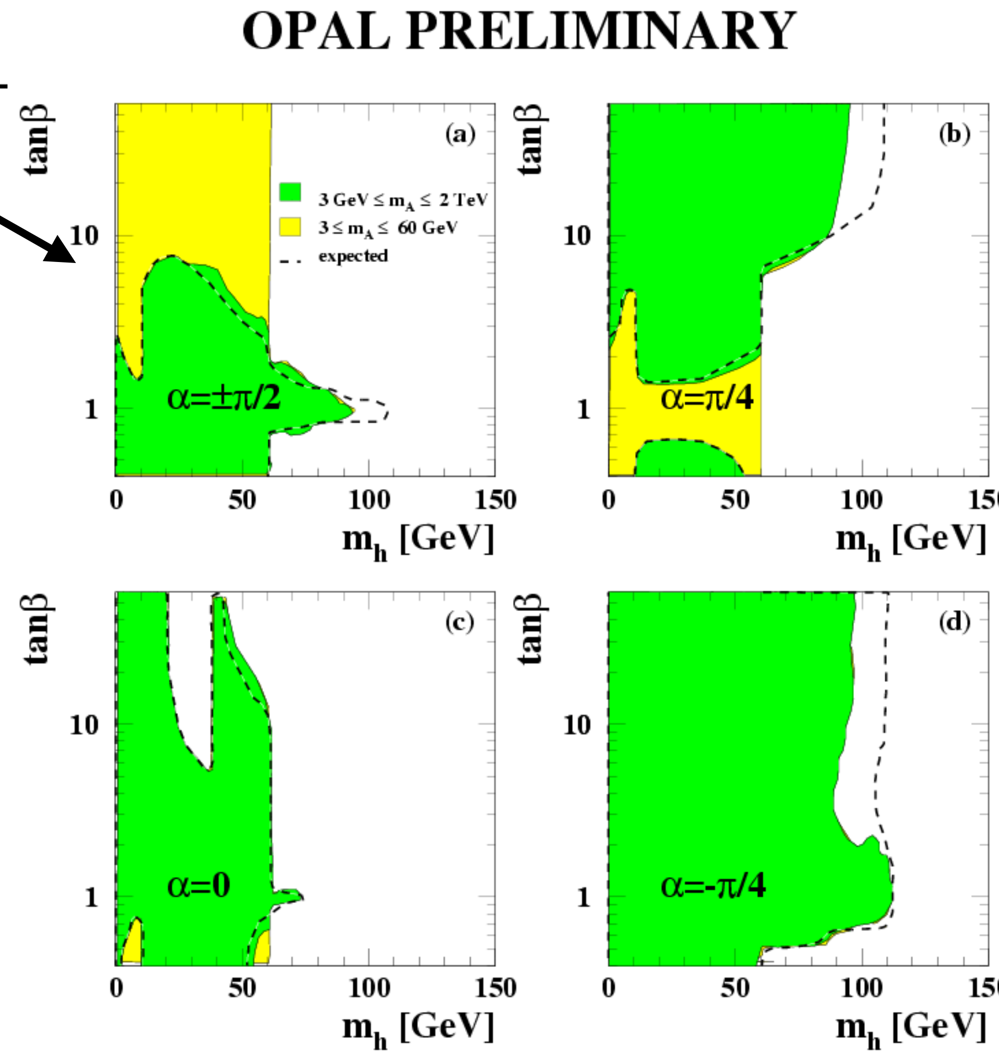
Parameter Scan in General 2HDM

...the other two projections ...

A particular $(m_h, \tan\beta, \alpha)$ point is excluded at 95% CL

if it is excluded for all scanned values of m_A

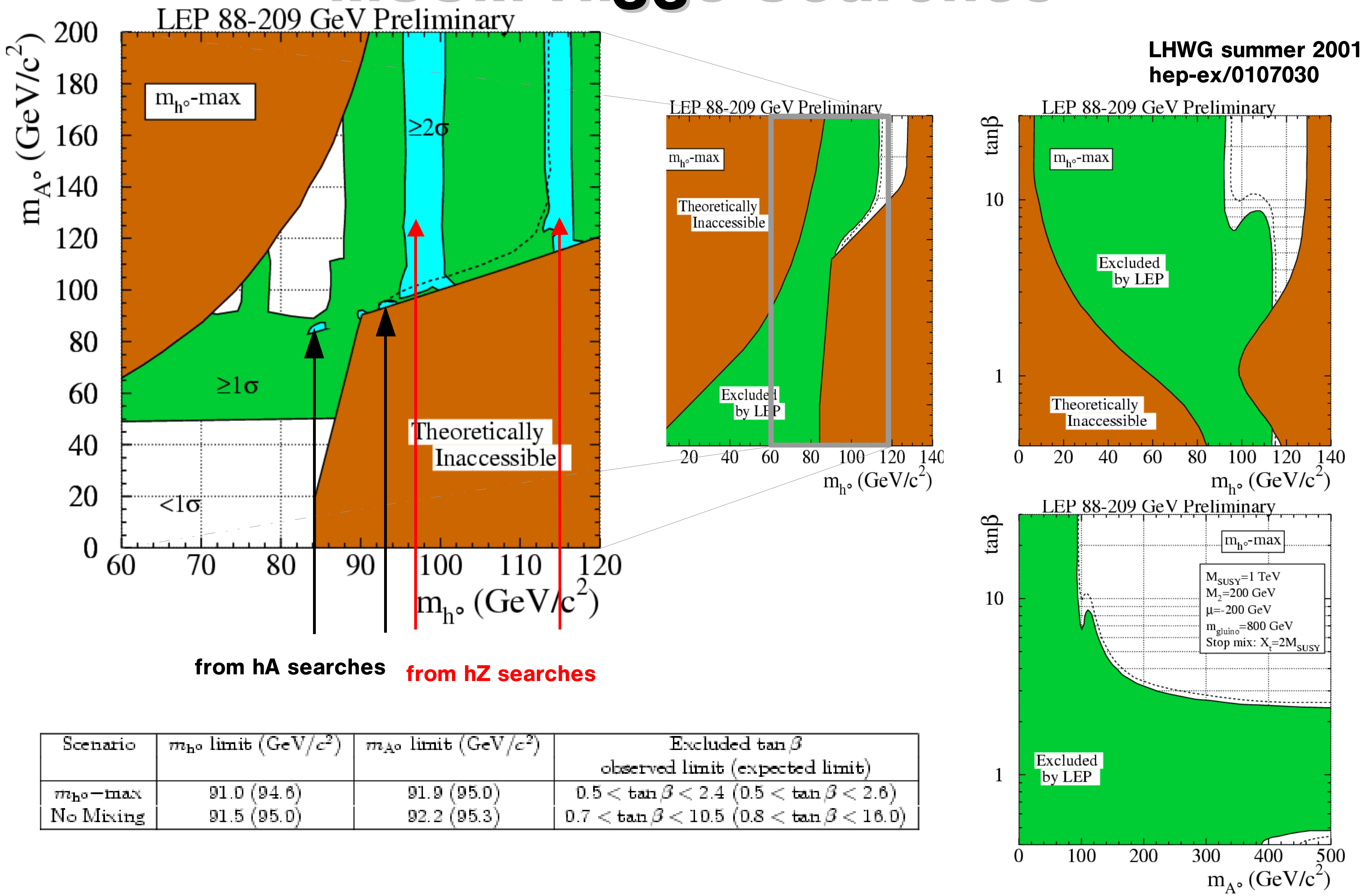




...scan will be done for LHWG combination when all inputs available (summer 2002 ?)...

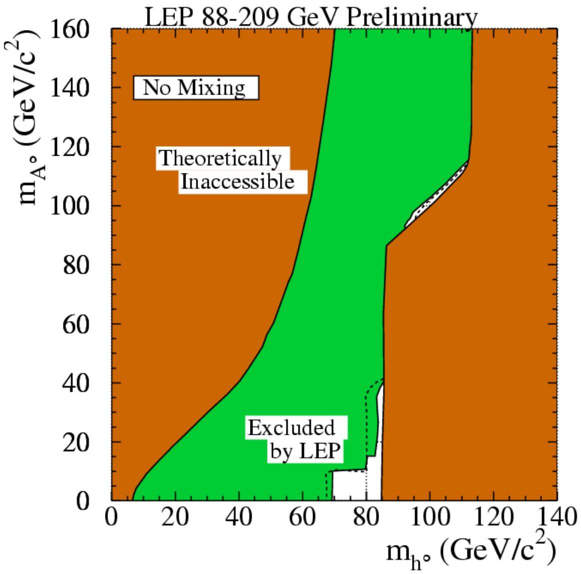
MSSM Higgs Searches

LHWG summer 2001
hep-ex/0107030



Scenario	m_{h^0} limit (GeV/c^2)	m_{A^0} limit (GeV/c^2)	Excluded $\tan\beta$ observed limit (expected limit)
m_{h^0}−max	91.0 (94.6)	91.9 (95.0)	$0.5 < \tan\beta < 2.4$ ($0.5 < \tan\beta < 2.6$)
No Mixing	91.5 (95.0)	92.2 (95.3)	$0.7 < \tan\beta < 10.5$ ($0.8 < \tan\beta < 16.0$)

MSSM Higgs Searches

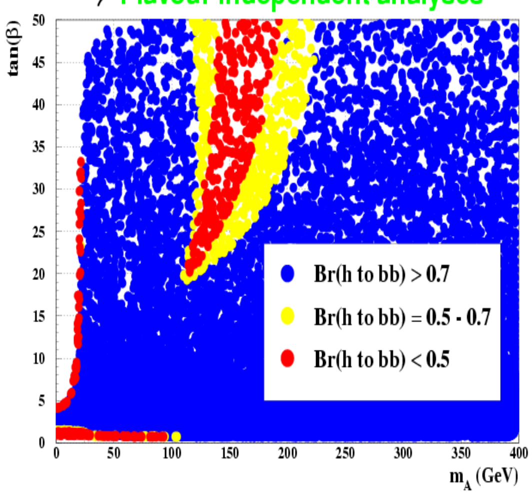


- **no mixing scenario almost entirely excluded...**
- **large-μ scenario:**
  completely excluded with flavour-indep. searches

(C) 'Large μ'

... pathological points with $Br(h \to b\bar{b}) \ll 1$

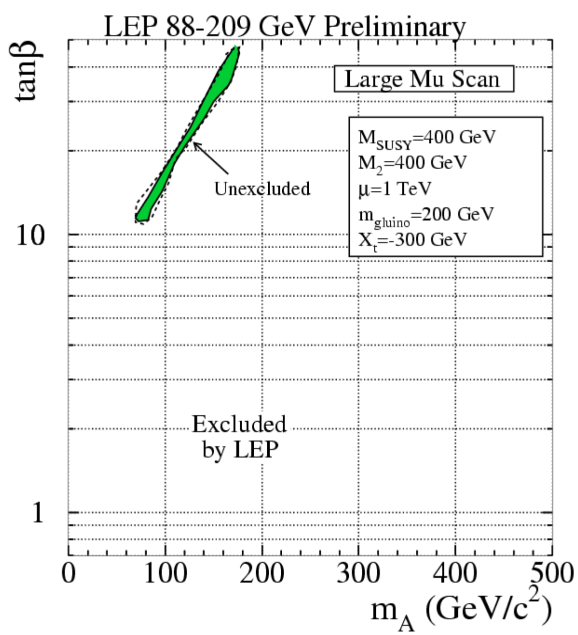
$\Rightarrow$ Flavour independent analyses



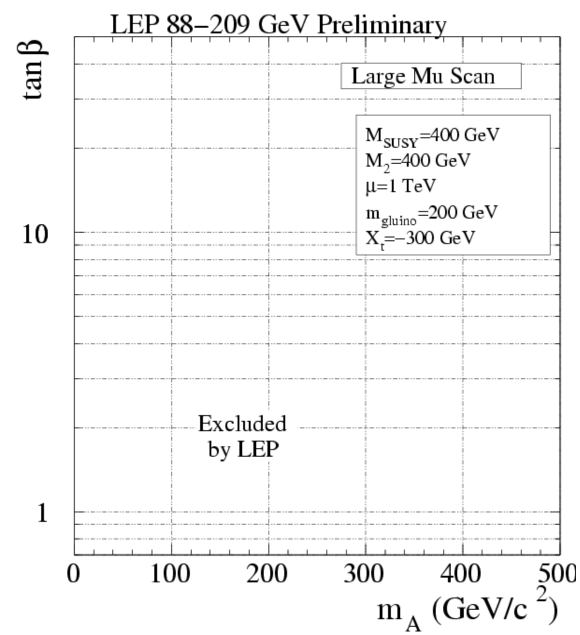
M. Carena,
S. Heinemeyer,
C. Wagner,
G. Weiglein

(hep-ph/9912223)

Theorie



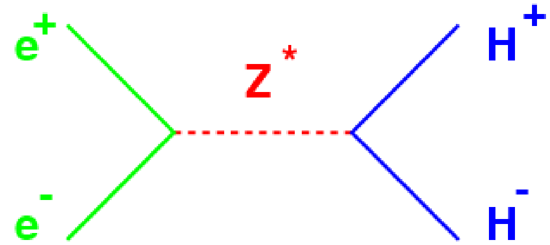
LHWG-March 2001



LHWG-July 2001

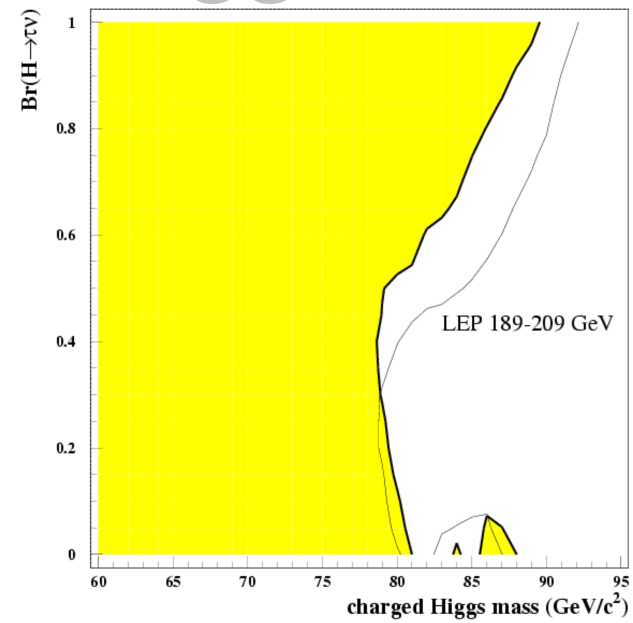
Search for Charged Higgs

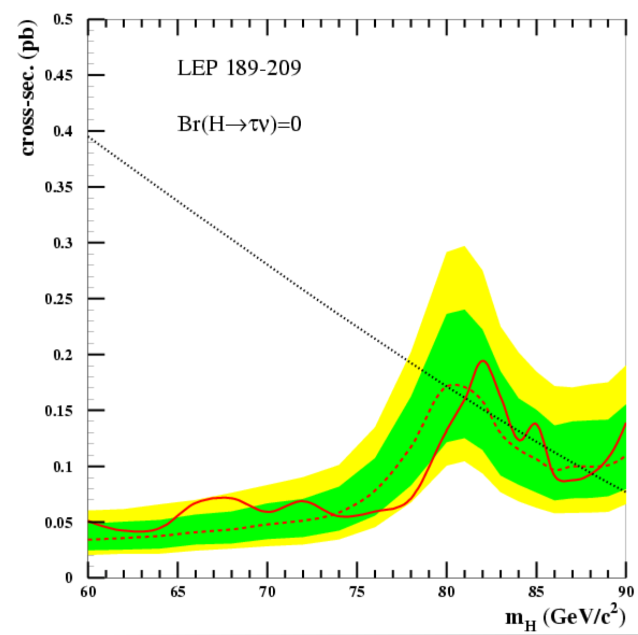
- Two Higgs Doublet Models - Type II ...
  down / up fermions couple to $\mathcal{H}_1$ / $\mathcal{H}_2$



- in the MSSM at tree-level: $\mathrm{m_{H^\pm}} > \mathrm{m_{W^\pm}}$
- rad. corrections can yield $\mathrm{m_{H^\pm}} < \mathrm{m_{W^\pm}}$
- decays to $\mathrm{H}^\pm \to \tau^\pm\nu, \mathrm{c\bar{s}}$
- Background from $e^+e^- \to W^+W^-$
- Assume: $Br(H^+ \to \tau\nu_\tau) +$
  $Br(H^+ \to c\bar{b}) = 1$

at 95% CL for any Br ($H^+ \to \tau^+\nu$):
$m_H^{+-} > 78.6$ GeV (obs)
$m_H^{+-} > 78.8$ GeV (exp.)





...further investigations and comparisons ongoing ...

OPAL-PN472

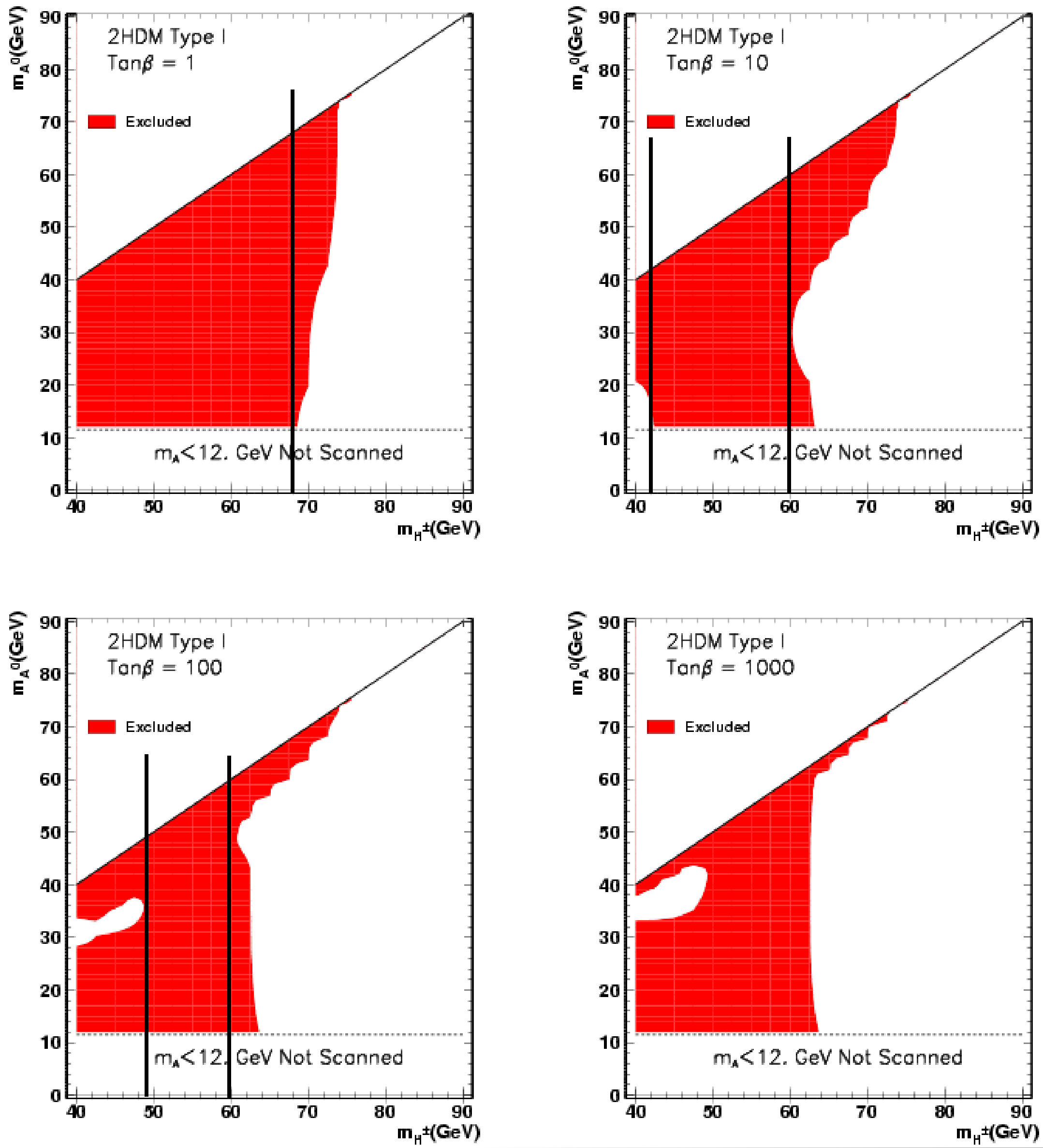
Search for $H^{+-} \to W^{*}A$

OPAL preliminary

In 2HDM type I:

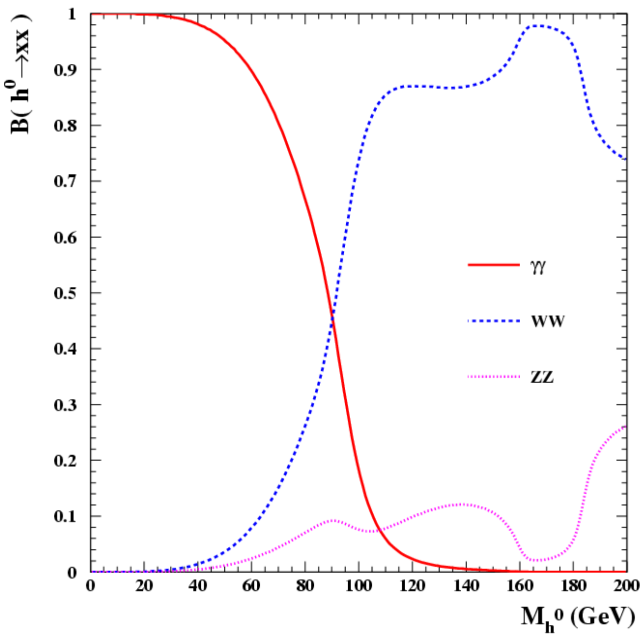
$H^{+-} \to W^{*+-}A^{0}$ dominates
- for tan β>1
- if kinematically allowed

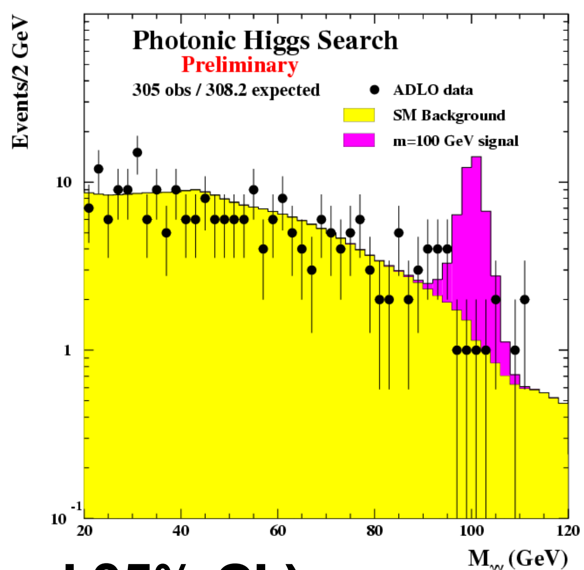
- search in LEP2 data for
  $H^{+}H^{-} \to W^{*}A \; W^{*}A \to$ qqbb qqbb
  $H^{+}H^{-} \to W^{*}A \; W^{*}A \to l\nu$bb qqbb
  $H^{+}H^{-} \to \tau\nu \quad W^{*}A \to \tau\nu$ qqbb



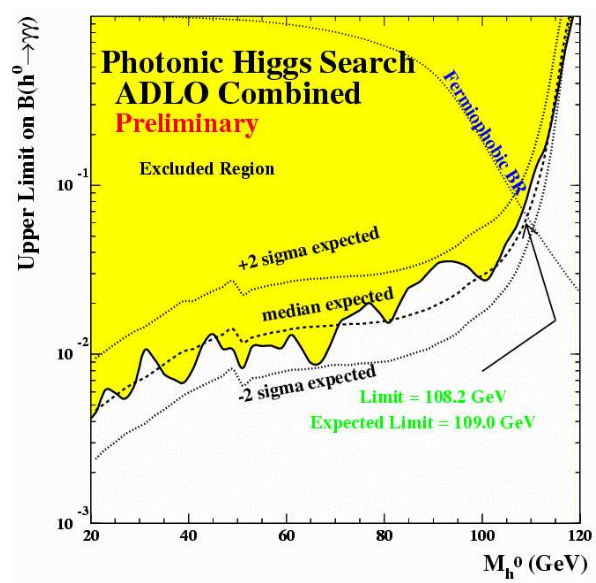
Fermiophobic Higgs Searches

- In 2HDM - type I Higgs coupling to fermions can go to zero ($\rightarrow$ `fermiophobic higgs')
- increase of bosonic Higgs decays (Br(H$\rightarrow\gamma\gamma$)$\approx$0.1% for m_h=90 GeV)





LHWG-summer 2001
hep-ex/0107035



At SM production rate (and 95% CL):

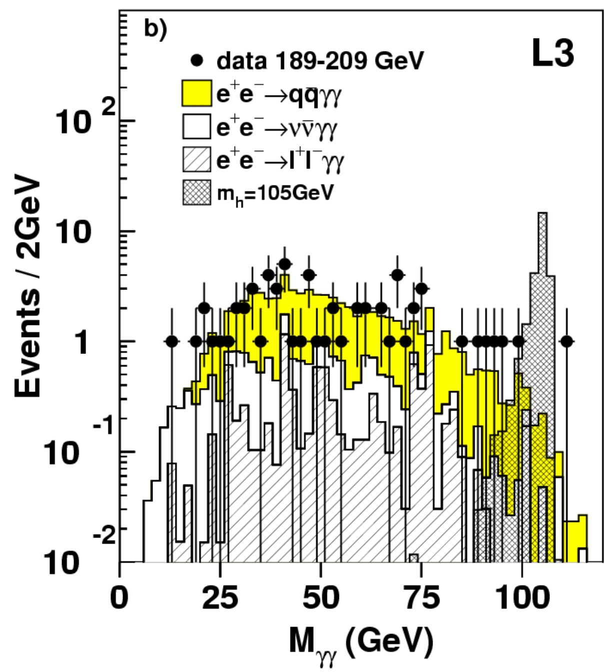
m_h > 108.2 GeV (obs.) and Br(h $\rightarrow \gamma\gamma$) < 6%

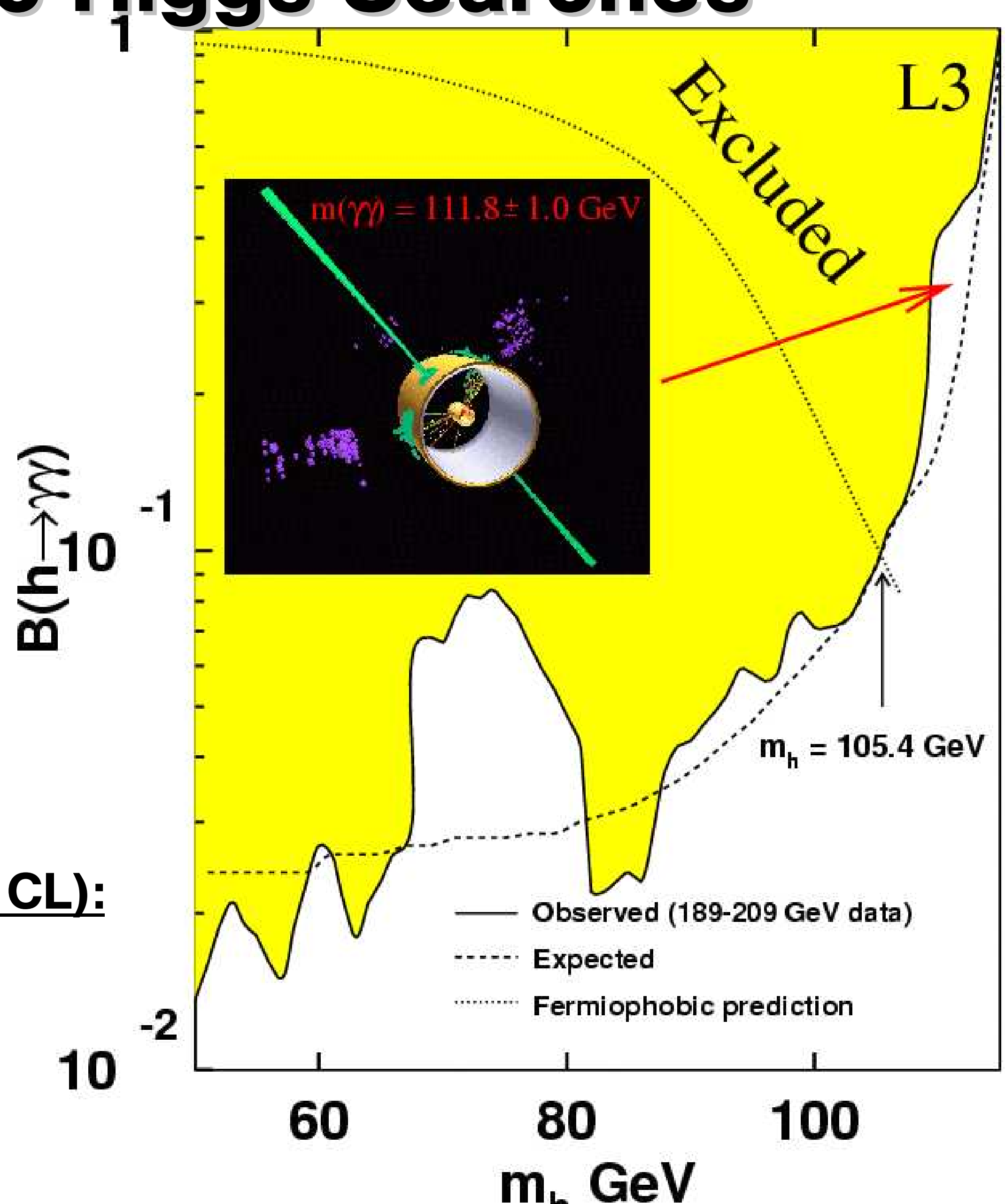
m_h > 109.0 GeV (exp.)

Fermiophobic Higgs Searches

L3 final publication

CERN-EP/2002-010
submitted to PLB





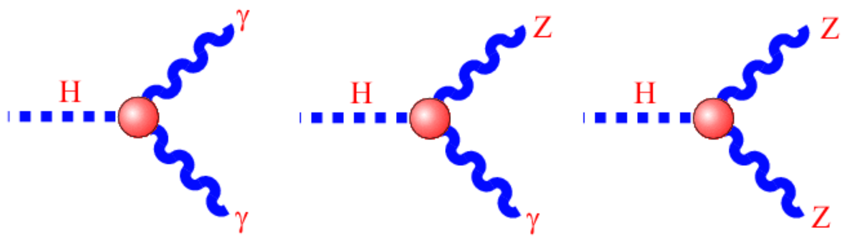
At SM production rate (and 95% CL):

m_h > 105.4 GeV (obs.)

m_h > 105.3 GeV (exp.)

Anomalous Higgs Couplings

L3 note 2698 on LEP2 data:
studying H $\rightarrow \gamma\gamma$ events limits on d, d_B Δg_1^Z, $\Delta\kappa_\gamma$, $\Gamma(H \rightarrow \gamma\gamma)$ and $\Gamma(H \rightarrow Z\gamma)$



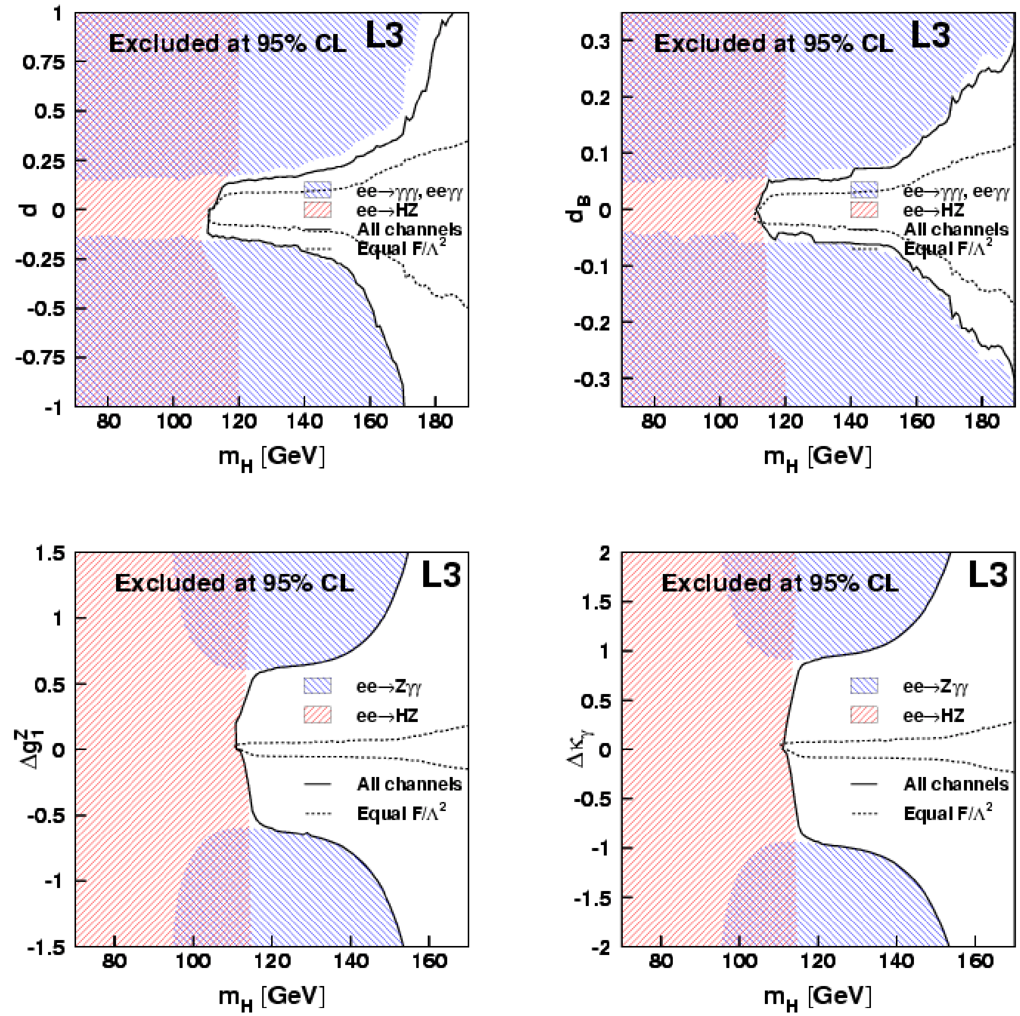
$$\mathcal{L}_{eff} = g_{H\gamma\gamma} HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma} A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma} HA_{\mu\nu}Z^{\mu\nu}$$
$$+ \; g^{(1)}_{HZZ} Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ} HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ} HZ_{\mu}Z^{\mu}$$

These six CP-conserving couplings reduce to five:

$$\begin{aligned}
g_{H\gamma\gamma} &= \frac{g}{2m_W}\left(d \sin^2\theta_W + d_B \cos^2\theta_W\right)\\
g^{(1)}_{HZ\gamma} &= \frac{g}{m_W}\left(\Delta g_1^Z \sin 2\theta_W - \Delta\kappa_\gamma \tan\theta_W\right)\\
g^{(2)}_{HZ\gamma} &= \frac{g}{2m_W} \sin 2\theta_W (d - d_B)\\
g^{(1)}_{HZZ} &= \frac{g}{m_W}\left(\Delta g_1^Z \cos 2\theta_W + \Delta\kappa_\gamma \tan^2\theta_W\right)\\
g^{(2)}_{HZZ} &= \frac{g}{2m_W}\left(d \cos^2\theta_W + d_B \sin^2\theta_W\right)\\
g^{(3)}_{HZZ} &= \frac{g m_W}{2\cos^2\theta_W}\delta_Z
\end{aligned}$$

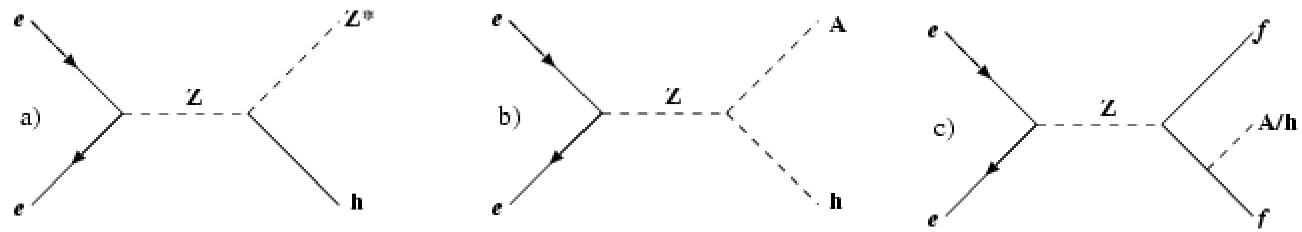
δ_Z, d and d_B are new, Δg_1^Z and $\Delta\kappa_\gamma$ are the WWV couplings!

K. Hagiwara *et al.*, Nucl. Phys. **B 282** (1987) 253
B. Grzadkowski and J. Wudka, Phys. Lett. **B 364** (1995) 49
G. Gounaris *et. al*, Nucl. Phys. **B 459** (1996) 51
O. Eboli *et. al*, Phys. Lett. **B 434** (1998) 340



Search for light Higgs Yukawa Production

CERN-EP/2001-077(OPAL)



if $\sin^2(\beta-\alpha)$ very small a) suppressed

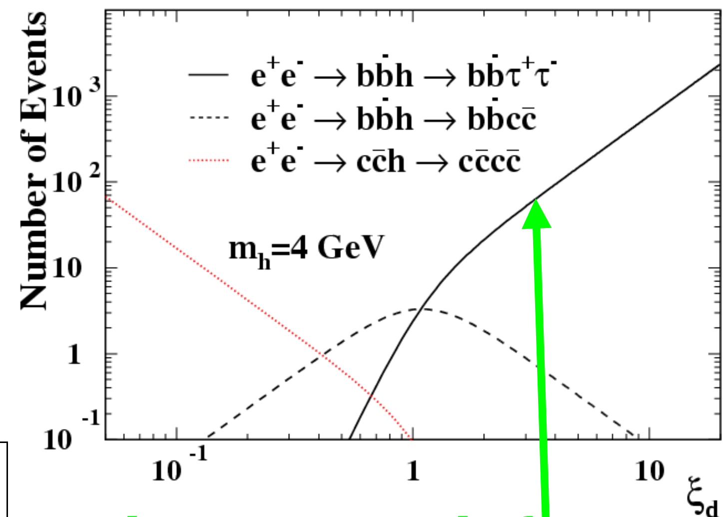
if $m_A + m_h > \sqrt{s}$ b) suppressed

...then ... c) might be dominant process

(possible in 2HDM type II)

$$\boxed{\sigma_{\mathrm{Yukawa}} \propto m_{\mathrm{f}}^2 \, N_{\mathrm{c}} \, \xi_{\mathrm{f}}^2}$$

Higgs Type	Down Type Fermions	Up Type Fermions
A	$\xi_d^{\mathrm{A}} = \tan\beta$	$\xi_u^{\mathrm{A}} = 1/\tan\beta$
h	$\xi_d^{\mathrm{h}} = -\sin\alpha/\cos\beta$	$\xi_u^{\mathrm{h}} = \cos\alpha/\sin\beta$



...here search for $bb\tau\tau$

...in LEP1 data...

Yukawa Production of a light Higgs

- assume 2HDM with SM particle content
- calculate Br(H $\rightarrow \tau\tau$) including mixing of h/A with $b\bar{b}$ states

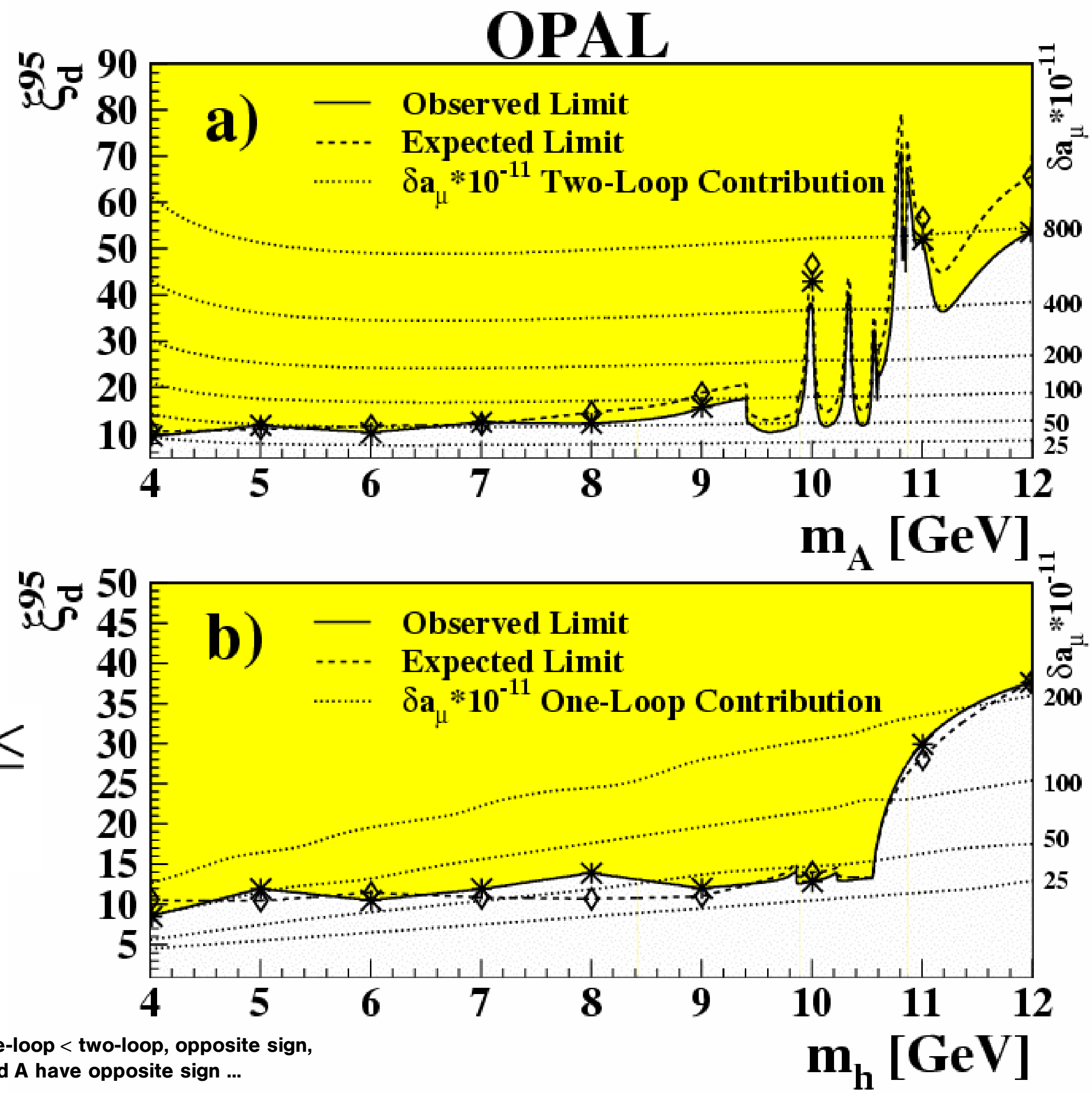
light Higgs h/A could change anomalous magnetic moment
$a_\mu = \frac{1}{2}(g-2)_\mu$
via loop diagrams

at times 2.6 σ excess was interpreted as indication for new physics with

$$(112-215)\times 10^{-11} \leq \delta a_\mu(NP) \leq$$
$$(573-690)\times 10^{-11}$$

excluded for m_h = 4.0-10.7 GeV
m_A = 4.0-9.9 GeV

... but one-/two-loop dependence ...



...one-loop < two-loop, opposite sign,
h and A have opposite sign ...

Search for Doubly Charged Higgs

$e^+e^- \rightarrow H^{++}\, H^{--}$ with

$H^{++} \rightarrow l^+l^+$, $l = e, \mu, \tau$

... predicted by LR sym. models with B/L violation ...

assume short lifetime, i.e. Yukawa coupling $h_{\tau\tau} > 10^{-7}$

(other cases covered by GMSB searches - kinks, impact parameter)

indir.coupling constraints from:

$H^{++} \rightarrow e^+e^-$ from Bhabhas

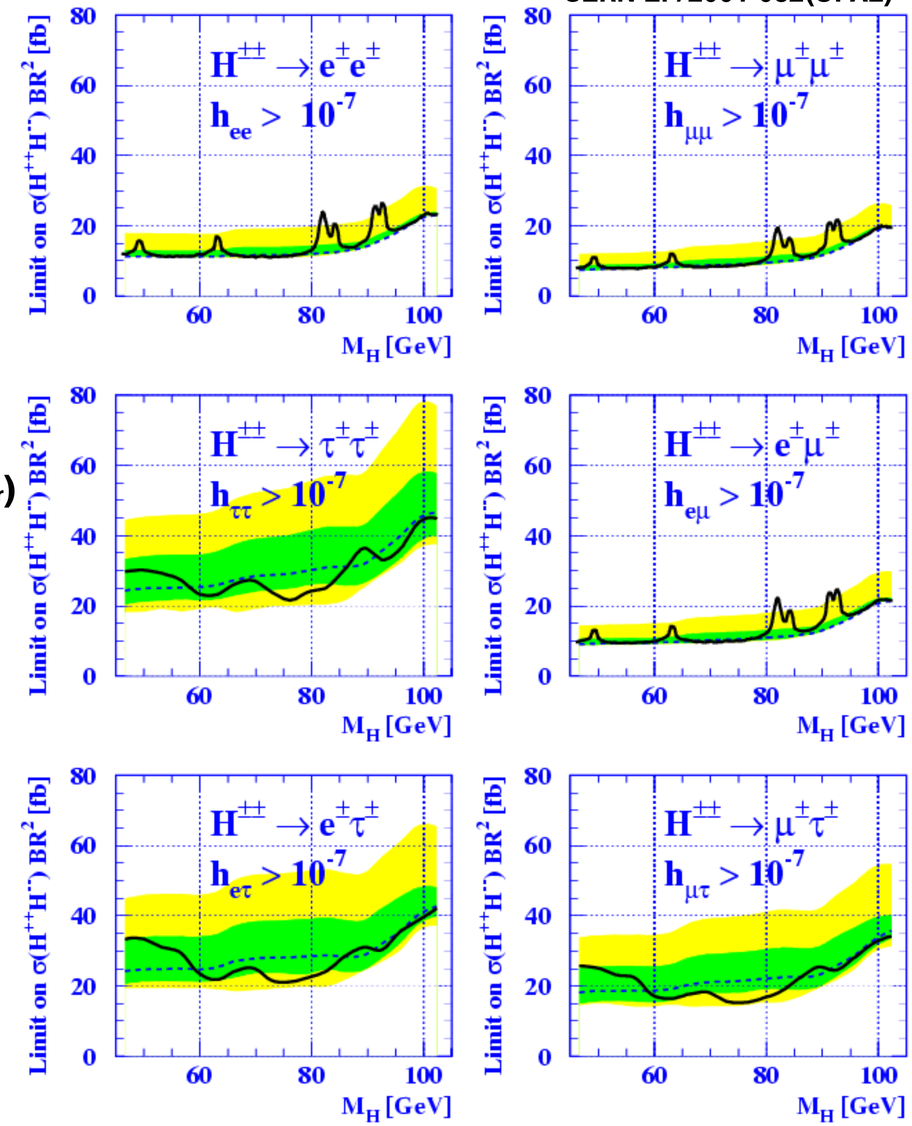
$H^{++} \rightarrow \mu^+\mu^+$ from muonium ($\mu^+e^- \leftrightarrow \mu^-e^+$)

$H^{++} \rightarrow e^+\mu^+$ from decays $\mu^+ \rightarrow e^+e^-e^+$

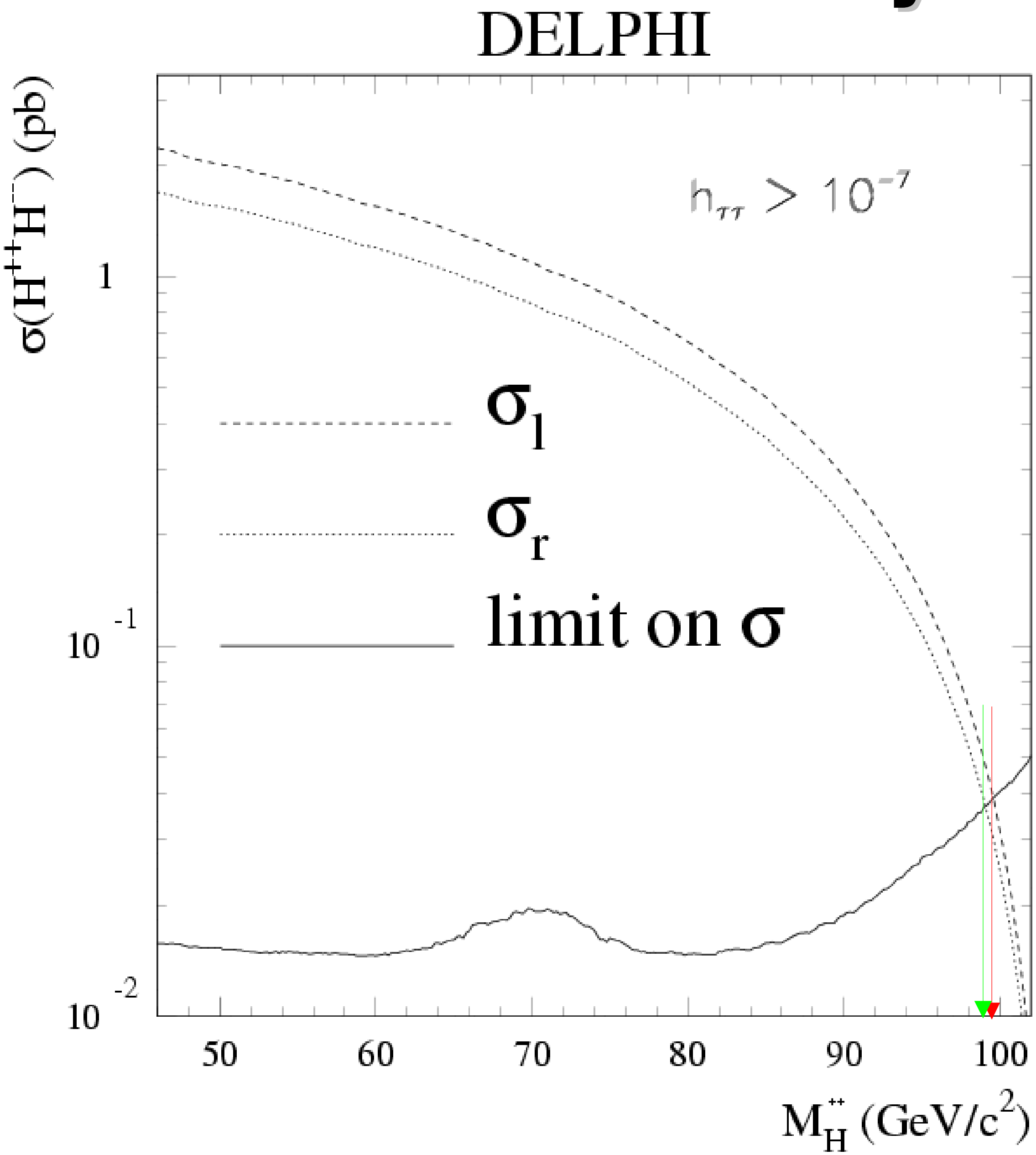
614 pb^{-1} of LEP2 data @ $\sqrt{s}$ =189 GeV and 209 GeV

OPAL

DELPHI-Moriond'02 note
CERN-EP/2001-082(OPAL)



Search for Doubly Charged Higgs



assume Br($H^{++} \to \tau^+ \tau^+$) = 100%

⇒ limit on $\sigma(H^{++}H^{--})$

compare with model

⇒ limit on masses:

	OPAL / DELPHI
$m(H_L^{++}) >$	99.0 / 99.6 GeV
$m(H_R^{++}) >$	98.5 / 99.1 GeV

Conclusion

- LEP experiments still very active on Higgs searches

- several new analyses presented (mode-independent, 2HDM, Yukawa, W*A, H^{++}, ...)

- final publications are rolling in

- final SM and MSSM results, also for LHWG combination, expected for summer conferences