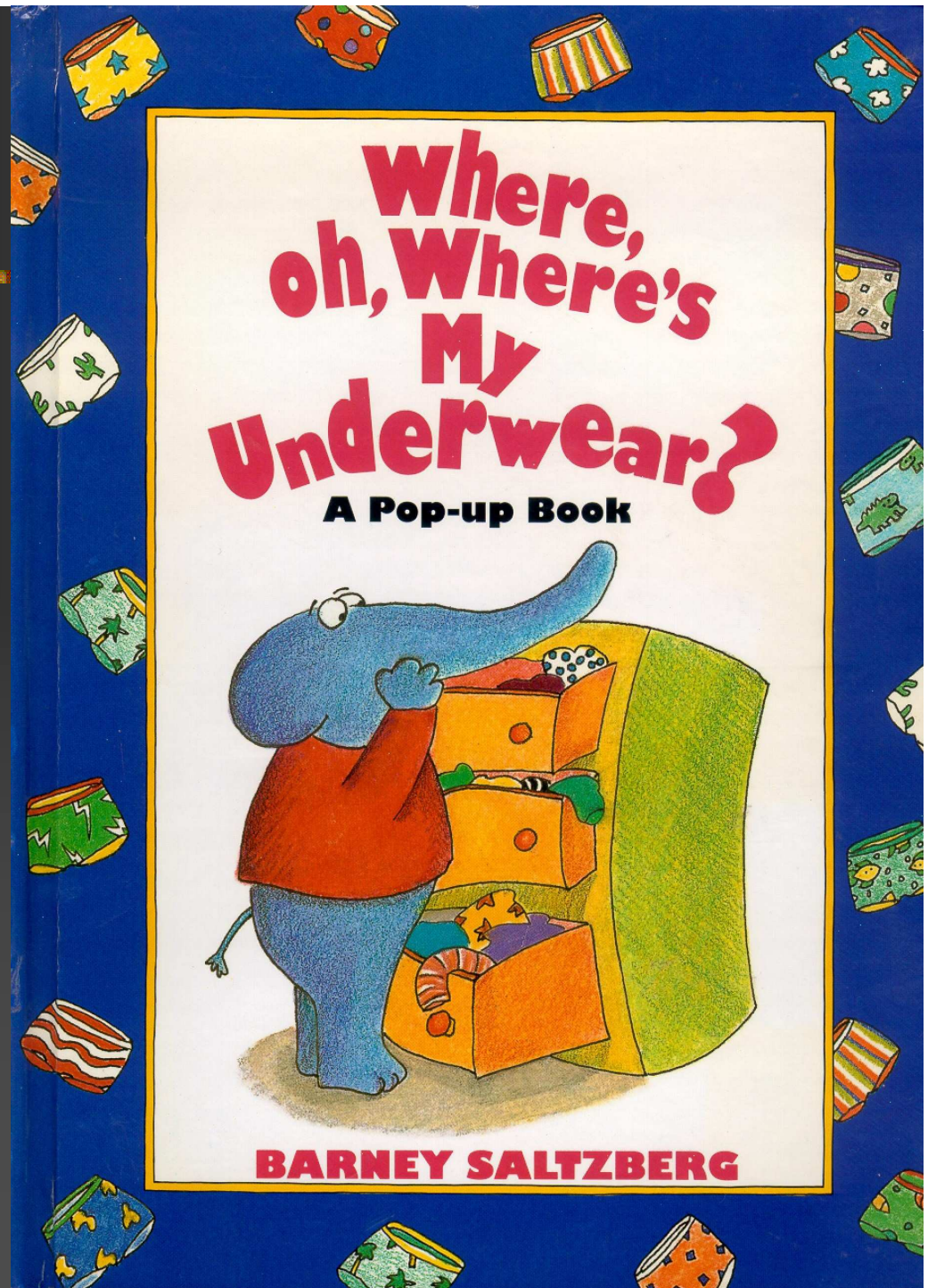
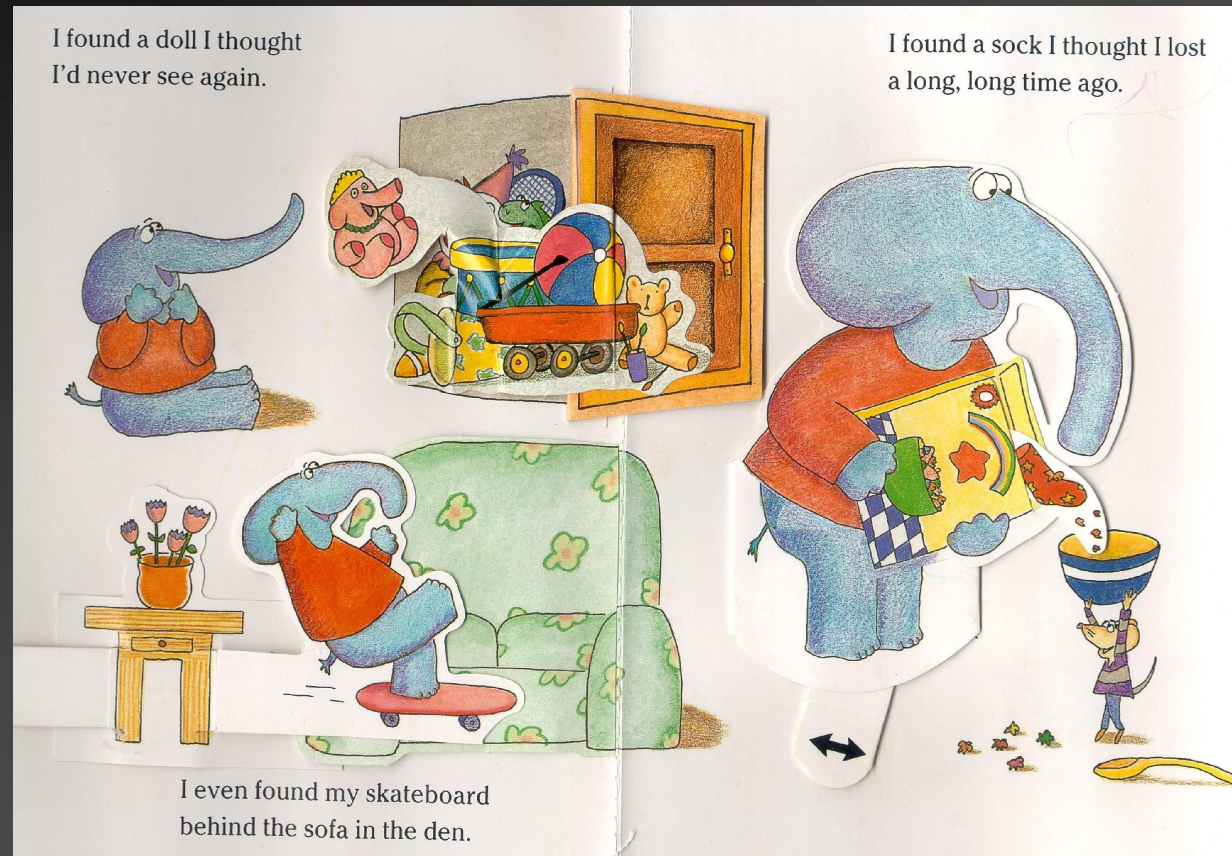


**Higgs searches
at LEP:
Beyond the SM
and MSSM
models**

**Pauline Gagnon
Indiana University**

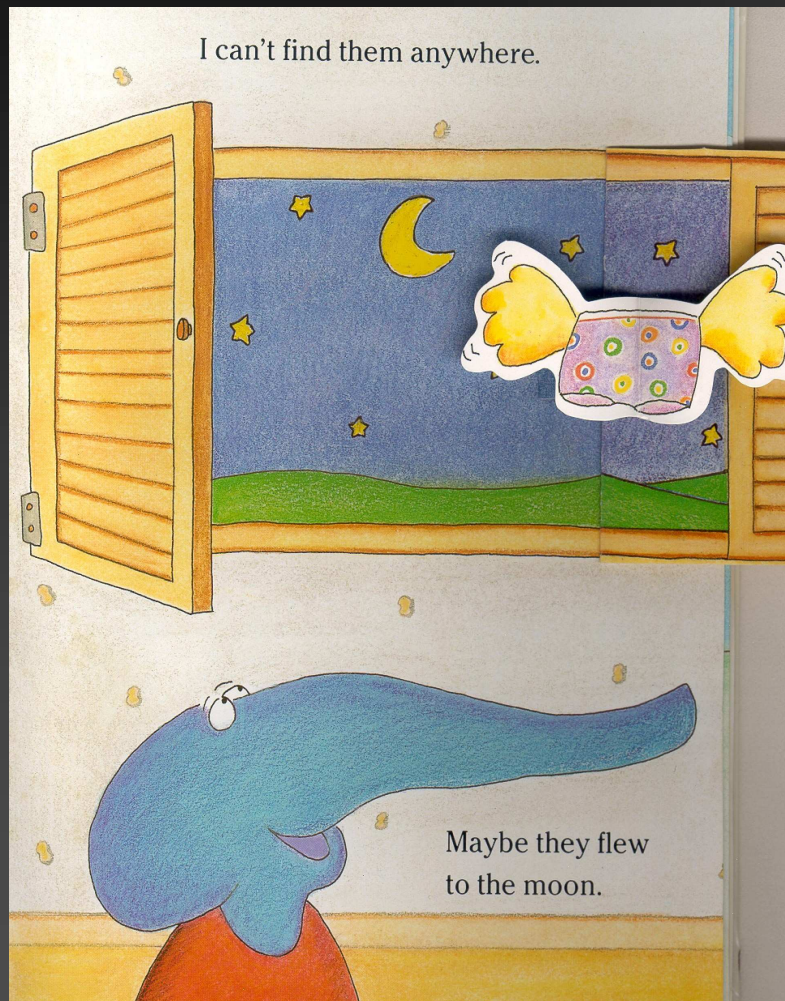


Where oh where's my underwear?
Where oh where can they be? I can't find them anywhere.



They must be hiding from me...

Have we looked everywhere?



Done so far:

- Fermiophobic and invisible decays
- Yukawa couplings
- Charged and doubly-charged Higgs searches
- Flavour and decay-mode independent searches
- Low m_A search
- Anomalous Higgs couplings
- 2HDM interpretations

Extensions to SM and MSSM

- Standard Model predicts one Higgs doublet:

⇒ one physical state: H^0

- Simplest extension: 2HDM with 5 physical states:

2 CP-odd: h^0, H^0 1 CP-even: A^0 2 charged : H^\pm

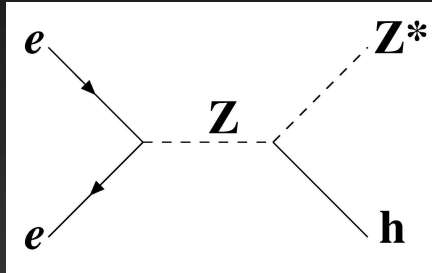
H^0 the heaviest: not expected at LEP

- 2HDM Type I: one doublet couples to fermion; one to bosons
- 2HDM Type II: one doublet couples to up-type (ν, u, c, t)
one doublet couples to down-type (l^\pm, d, s, b)
(MSSM is a special case of 2HDM Type II)

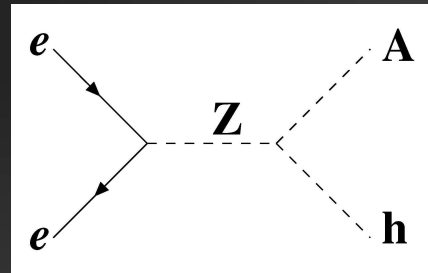
- Another possibility: one couples to leptons, one to quarks
- Higgs triplets models ⇒ H^{++}

Higgs production and decay at LEP

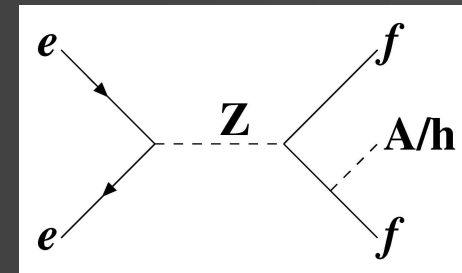
3 Higgs production modes at LEP:



Higgsstrahlung



pair production



Yukawa production

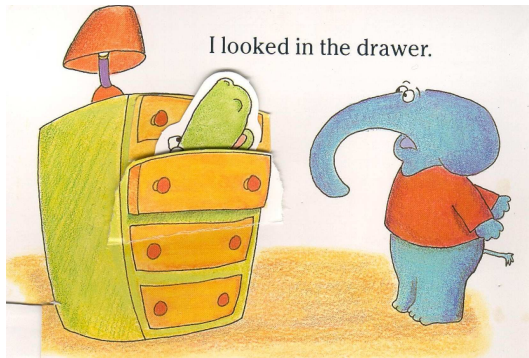
2HDM:

$$e^+e^- \rightarrow h^0 Z^0 : \quad \sigma_{hZ} = \sin^2(\beta - \alpha) \sigma_{HZ}^{\text{SM}}$$

$$e^+e^- \rightarrow h^0 A^0 : \quad \sigma_{hA} = \cos^2(\beta - \alpha) \bar{\lambda} \sigma_{HZ}^{\text{SM}}$$

$\bar{\lambda}$: accounts for suppression of P-wave near threshold

Couplings to fermions depend on the mixing angle α between the two doublets and $\tan\beta = v_2/v_1$

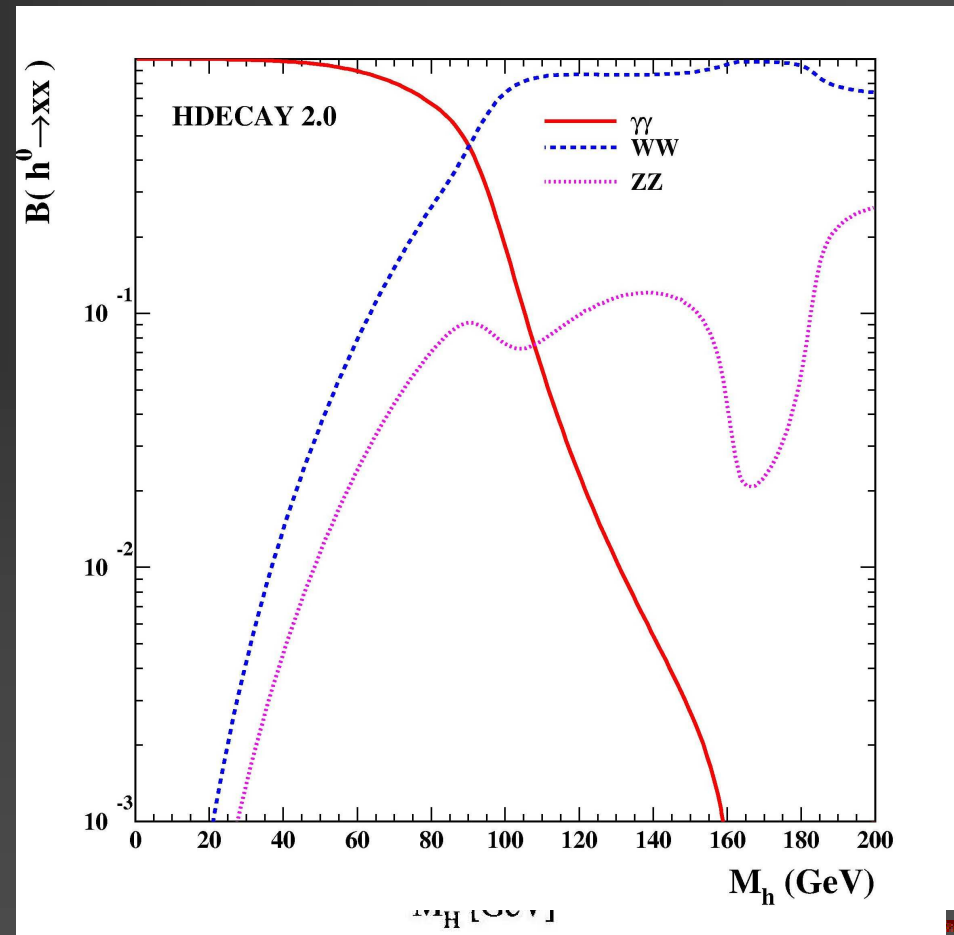


Fermiophobic Higgs decays

- SM allows $H^0 \rightarrow \gamma\gamma$ only at one-loop level ($BR \leq 10^{-3}$)
- Several models predict bosonic Higgs couplings
- In 2HDM(I), one doublet couples to bosons only

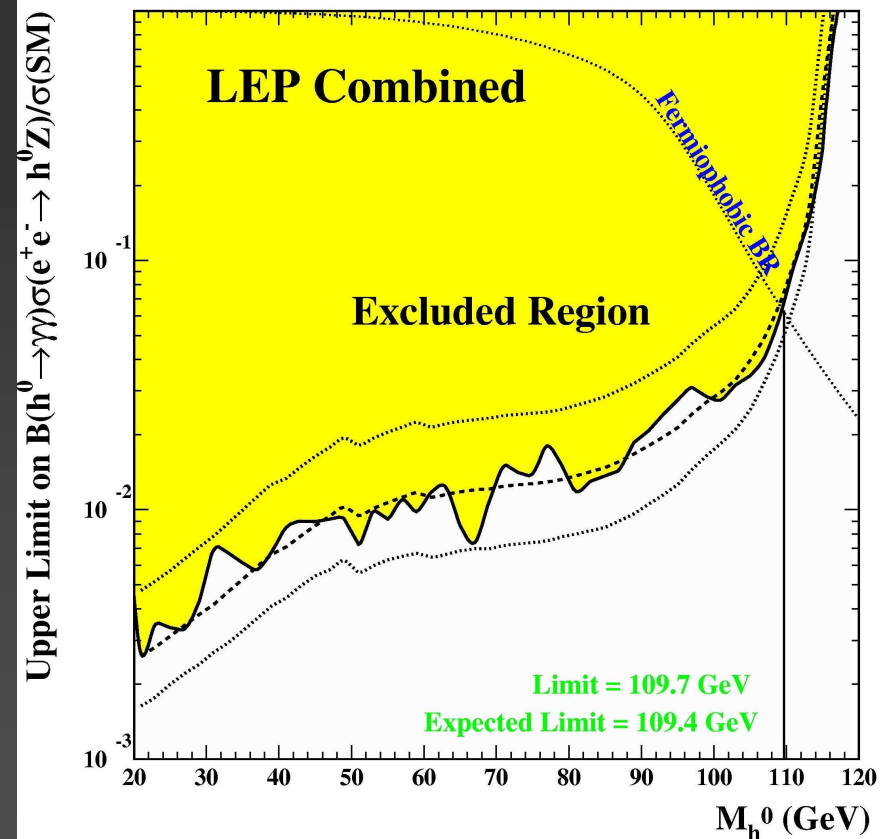
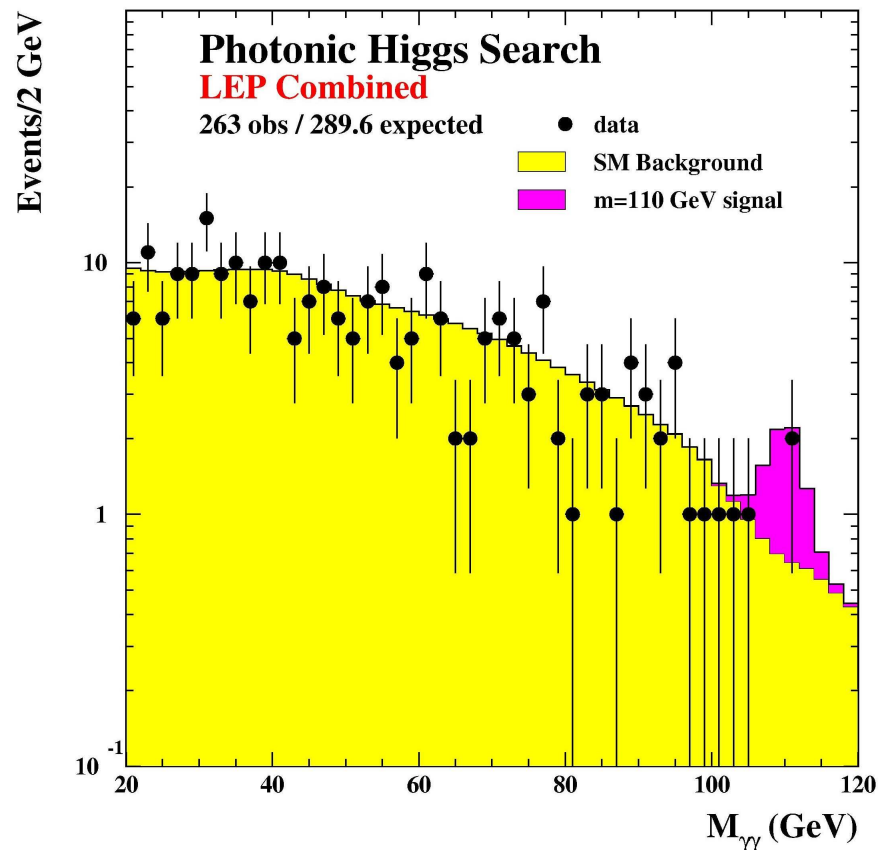
Benchmark fermiophobic Higgs boson: SM production σ with fermionic BR turned off

$\Rightarrow \sigma(h^0 Z) \cdot BR(h^0 \rightarrow \gamma\gamma)$
becomes sizeable



Combined LEP data for $BR(h^0 \rightarrow \gamma\gamma)$ in h^0Z events

Mass limit: 109.7 GeV (fermiophobic benchmark scenario)



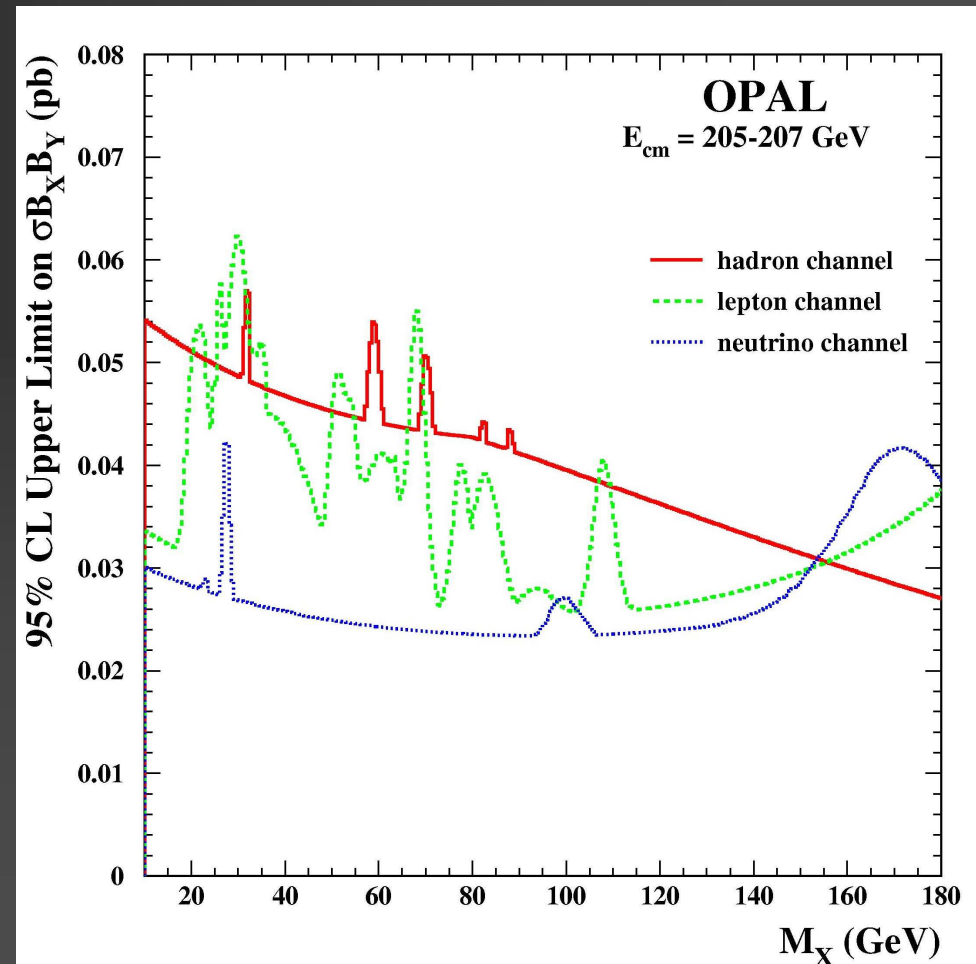
OPAL general fermiophobic search

Search for $e^+e^- \rightarrow XY$
for $\sqrt{s} = \{205-207\}$ GeV

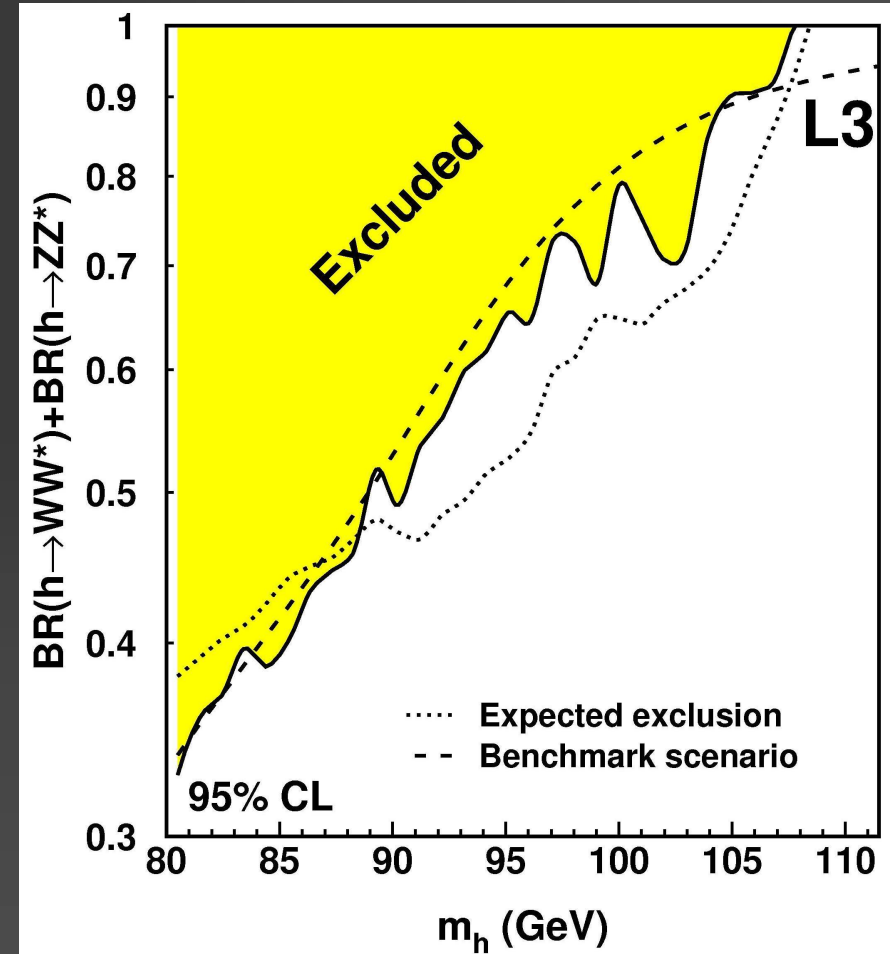
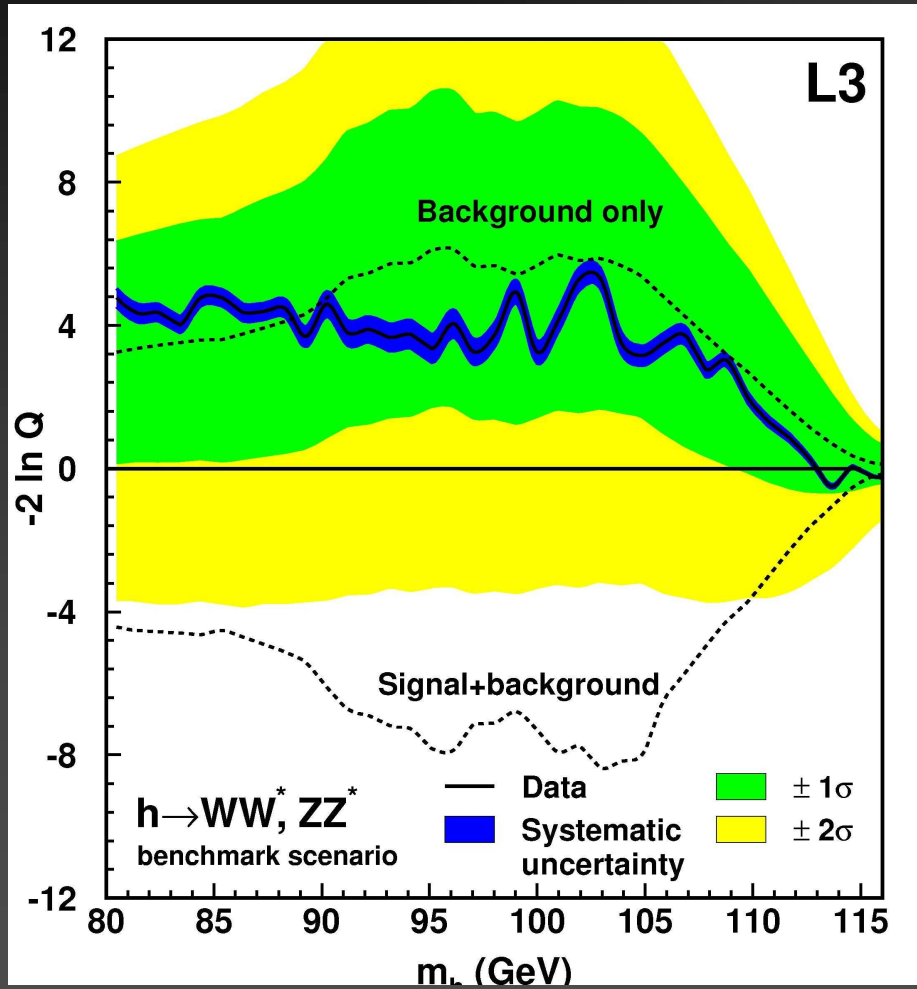
- For X: scalar $X \rightarrow \gamma\gamma$
- Y: scalar or vector
- $Y \rightarrow ff$ (qq, ll, $\nu\nu$)

Set limits on $\sigma(XY)$ *

$BR(X \rightarrow \gamma\gamma) * BR(Y \rightarrow ff)$



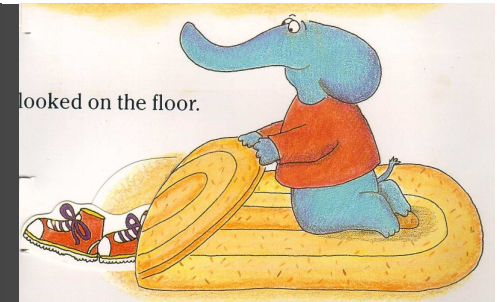
Search for h^0Z : $h^0 \rightarrow WW, ZZ$ at L3



Fermiophobic LEP searches

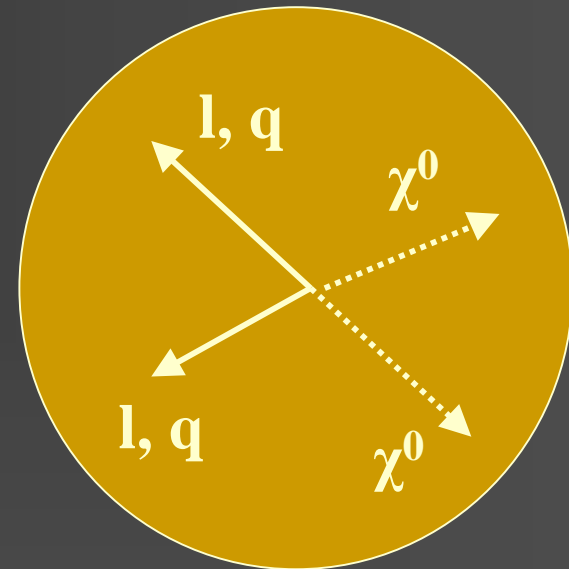
- **Delphi: search for $h^0 Z^0$ and $h^0 A^0 \rightarrow \gamma \gamma \gamma \gamma$**
Phys. Lett. B507 (2001) 89.
- **Opal: search for $e^+ e^- \rightarrow XY$, and $X \rightarrow \gamma \gamma$**
Phys. Lett. B544 (2002) 44.
- **L3: $h Z$ with $h^0 \rightarrow WW$, ZZ : CERN-EP/2002-080**
 $h^0 \rightarrow \gamma \gamma$ Phys. Lett. B534 (2002) 28.
- **Aleph: Phys. Lett. B487 (2000) 241**
- **LEP combined $h^0 Z$ with $h^0 \rightarrow \gamma \gamma$: LHWG Note/2002-02**

Invisible Higgs decay: $h^0 \rightarrow \chi^0 \chi^0$



- Dominant invisible Higgs decays possible in
 - Majoron models
 - Supersymmetric models depending on parameters choice
- h detected via associated Z : acoplanar jets or dileptons

$$\begin{aligned} Zh: & \quad h \rightarrow \chi^0 \chi^0 \\ Z & \rightarrow l^+ l^-, qq \end{aligned}$$

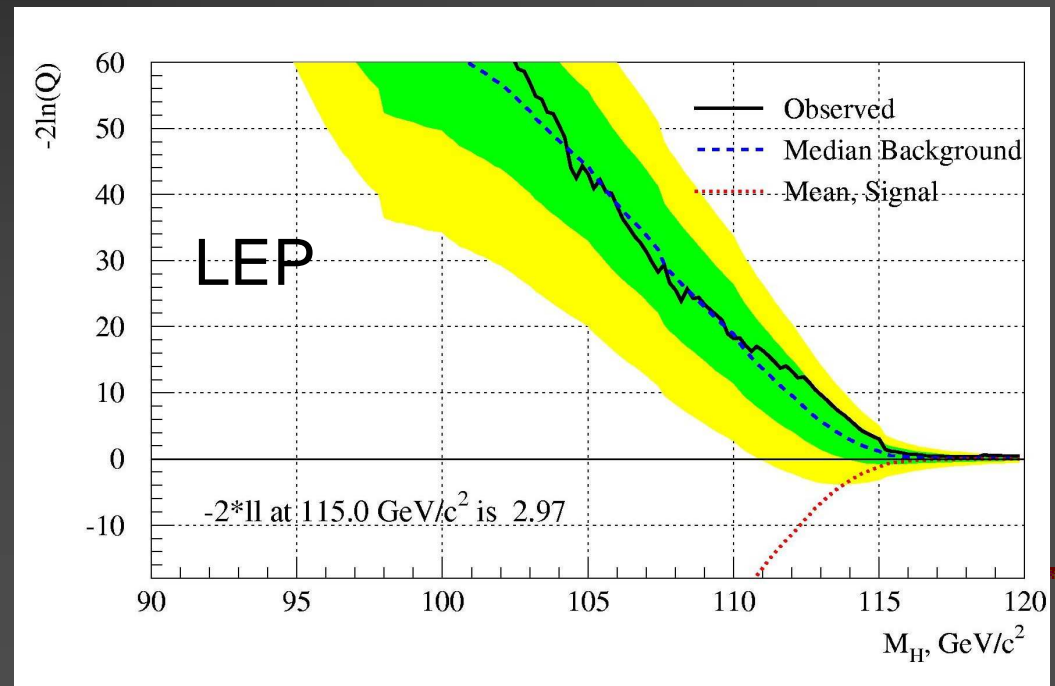


Combined LEP data for $h^0 \rightarrow \chi^0 \chi^0$

Experiment:	ALEPH	DELPHI	L3	OPAL
Integrated luminosity in 2000 (pb^{-1}):	215.6	225.1	217.3	210
Backg. predicted / Evts. observed				
Acoplanar jets:	8.17 / 8	35.9 / 30	56.2 / 50	61.8 / 47
Acoplanar leptons:	6.7 / 7	21.7 / 13	5.9 / 9	–
Events in all channels	14.9 / 15	57.6 / 43	62.1 / 59	61.8 / 47
Median 95% CL Limit (GeV/c^2) :	112.6/111.8	110.7/110.7	110.2/110.1	107.4*/108.5
Observed 95% CL Limit (GeV/c^2) :	114.1/113.1	113.0/113.0	107.6/107.5	107.0/107.4

test statistics: $-2 \ln Q$:
 a negative value
 would indicate a signal

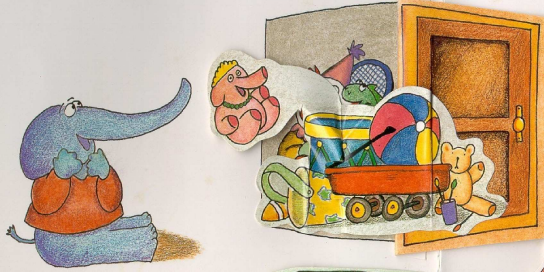
mass limit: 114.4 GeV



Latest publications on $h^0 \rightarrow \chi^0 \chi^0$

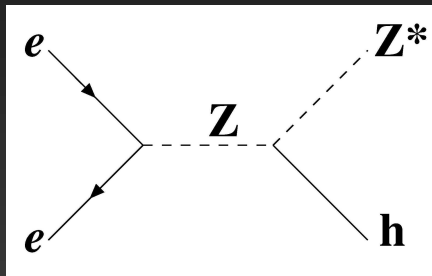
- **Aleph:** Phys Lett B526 (2002) 191
- **Delphi:** 2002-025-CONF-559 (ICHEP 2002)
- **L3:** Note #2690 (EPS 2001)
- **Opal:** Physics Note #472 (ICHEP 2002)
- **LEP combined:** hep-ex/0107032 – Summer 2001

I found a doll I thought
I'd never see again.

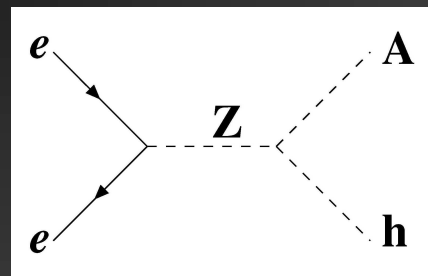


Yukawa production

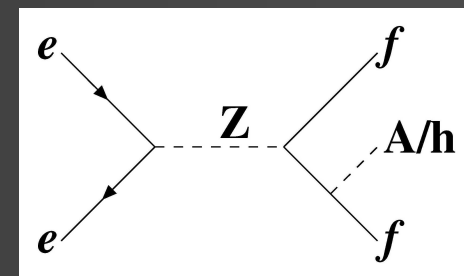
Three Higgs production modes at LEP:



Higgsstrahlung



pair production



Yukawa production

Yukawa process could dominate if:

- Higgsstrahlung is suppressed (mixing of 2 doublets in 2HDM)
- pair production impossible if $m_A + m_h > \sqrt{s}$

Scenario possible in general 2HDM model

Cross-section of Yukawa process

$$\sigma_{\text{Yukawa}} \propto m_f^2 N_c \xi_f^2$$

N_c : color factor

ξ_f : enhancement factor

	down-type	up-type
ξ_f	ξ_d	ξ_u
A	$\tan \beta$	$1/\tan \beta$
h	$-\sin \alpha / \cos \beta$	$\cos \alpha / \sin \beta$

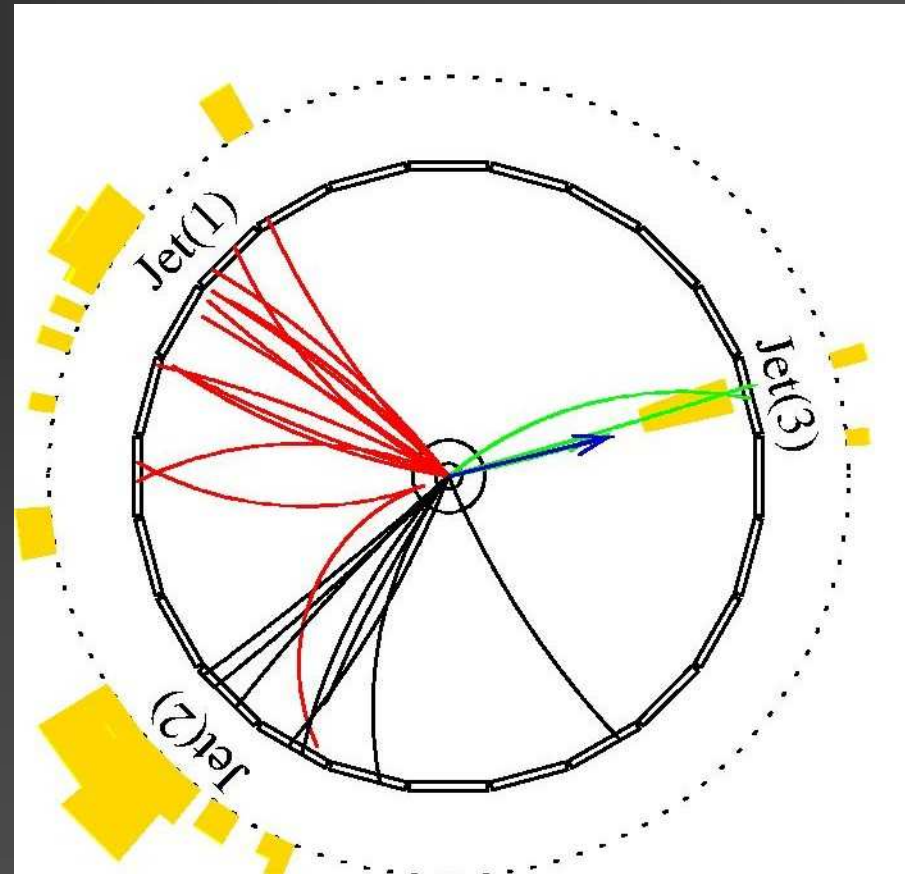
Two possible cases:

- For $\xi_d < 1$: $\xi_u > 1$
cc radiates Higgs
- For $\xi_d > 1$:
bb radiates Higgs
 $A/h \rightarrow \tau \tau$ or bb

Only LEP I data: $\sigma(bb)_{\text{LEP I}} = 100 * \sigma(bb)_{\text{LEP II}}$

Decay signature in Yukawa production

- Opal search channel:
 $e^+e^- \rightarrow b b A/h^0$
 $A/h^0 \rightarrow \tau \tau$
- Higgs emitted at high energy: decay products constrained to one single jet

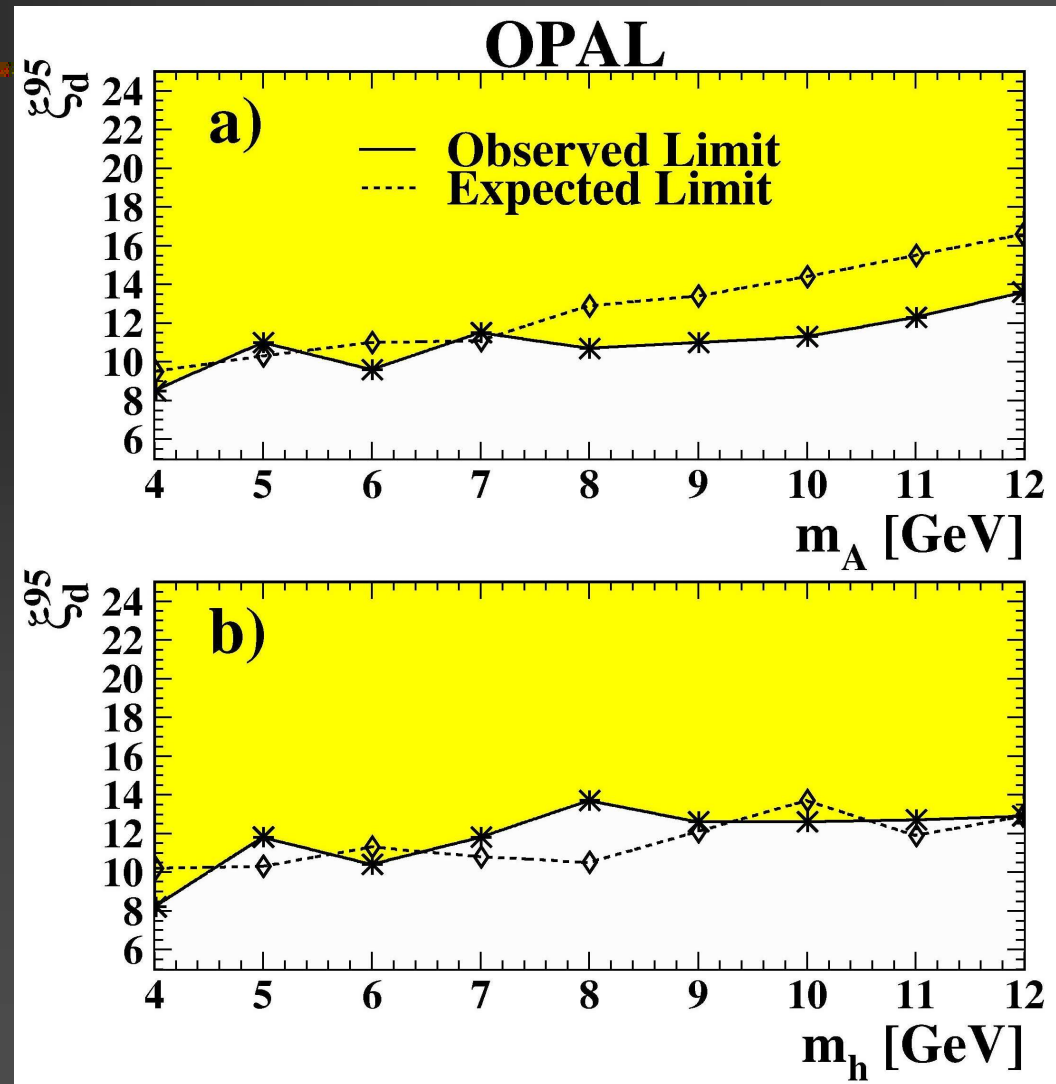


Opal results on Yukawa couplings

95% CL on ξ_d in
2HDM type II model

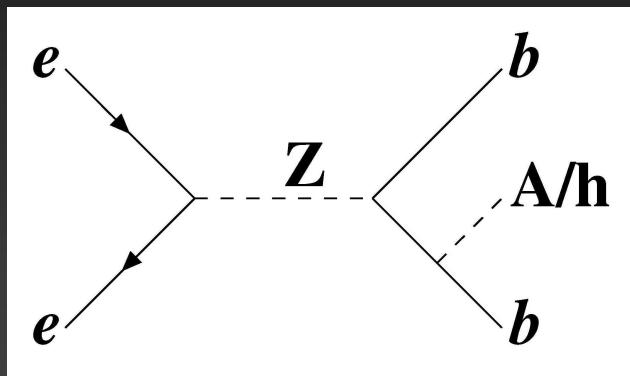
- a) for CP-odd A^0
- b) for CP-even h^0

Eur. Phys. J. C23 (2002) 397



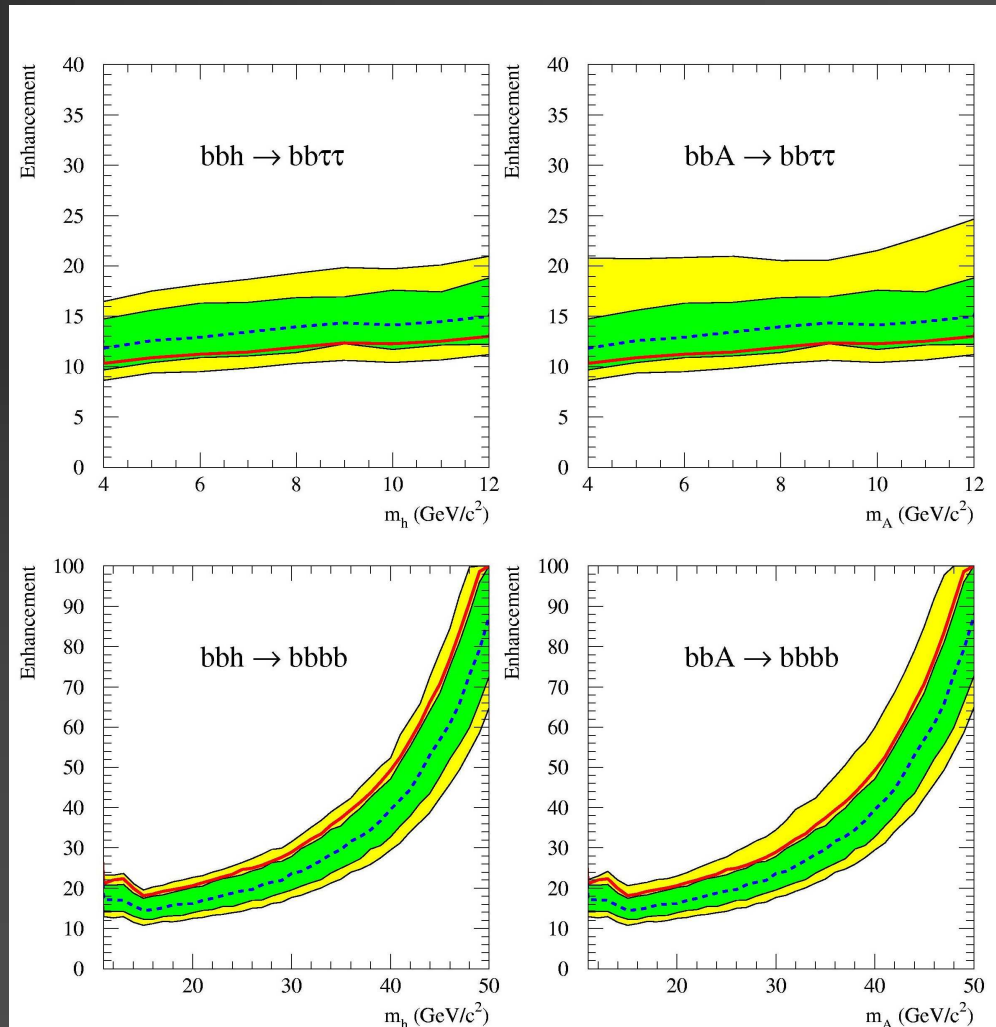
Delphi search: more general

Search modes:



$A/h^0 \rightarrow \tau\tau$ or $b\bar{b}$

$b\bar{b}\tau\tau$ and $b\bar{b}b\bar{b}$



Search for $h^0 A^0 \rightarrow \tau \tau \tau \tau$ at Delphi

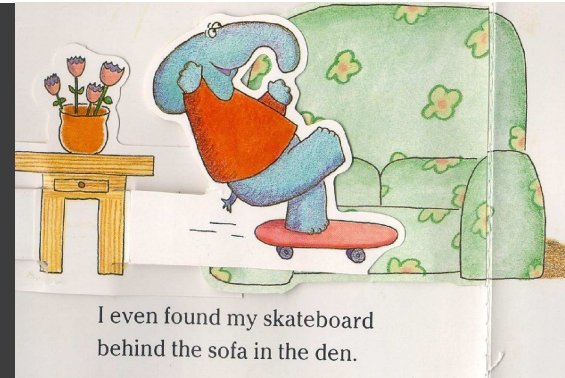
- Possible in 2HDM if one doublet couples only to leptons
- Look for 4 narrow, low-multiplicity jets
- Look in 2, 3, 4-jets events
- $m_A = [4-170]$ GeV
- $m_h = [4-90]$ GeV

- Signal efficiency:
21% - 58.6%

observed in data	expected from SM
6 events	9.5 events

see Delphi 2002-037-CONF-571 ICHEP 2002 (still preliminary)

Charged Higgs



- Predicted by 2-doublet extensions of SM
- Production mechanism:
 $e^+e^- \rightarrow H^+H^-$
- In MSSM, at tree level
 $m_{H^+} > m_{W^+}$
- $m_{H^+} < m_{W^+}$ barely allowed by MSSM but possible with R-parity violation

Assume all decays to be

$H^+ \rightarrow cs$ and $\tau^+\nu$:

$H^+H^- \rightarrow \tau^+\nu \tau\nu$

$H^+H^- \rightarrow cs \tau\nu$

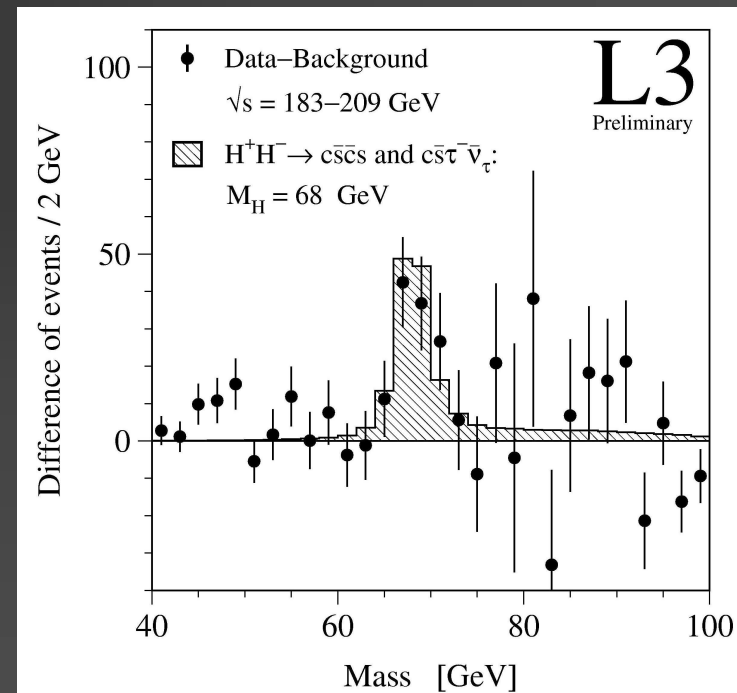
$H^+H^- \rightarrow cs cs$

**H^+H^- signal implies
beyond MSSM physics**

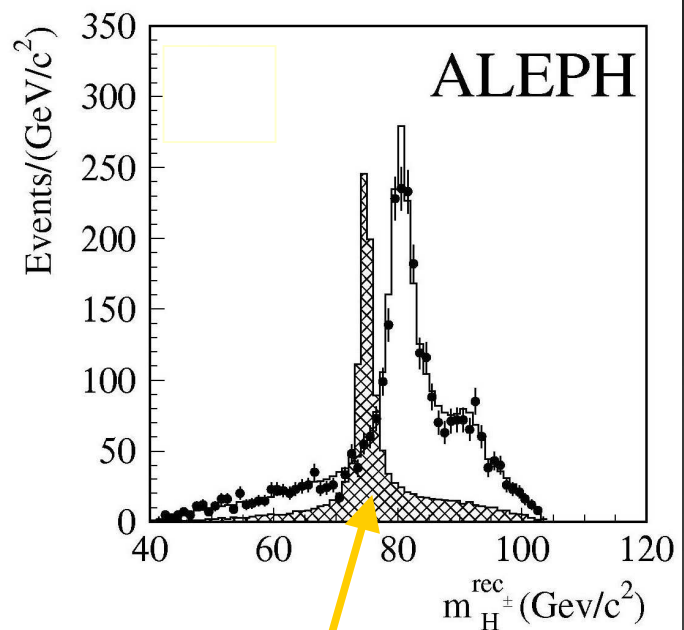
L3 excess at $m_{H^+} = 68 \text{ GeV}$

- Slight excess seen in 189-202 GeV data
 - Mass limits then were between 67.4-79.9 GeV depending on $\text{BR}(H^+ \rightarrow \tau^+\nu)$
- Excess most significant for low $\text{BR}(H^+ \rightarrow \tau^+\nu)$**

	$\tau^+\nu$ $\tau\nu$	CS $\tau\nu$	CS CS
data	44	171	961
bgnd	49.8	171.8	883.3

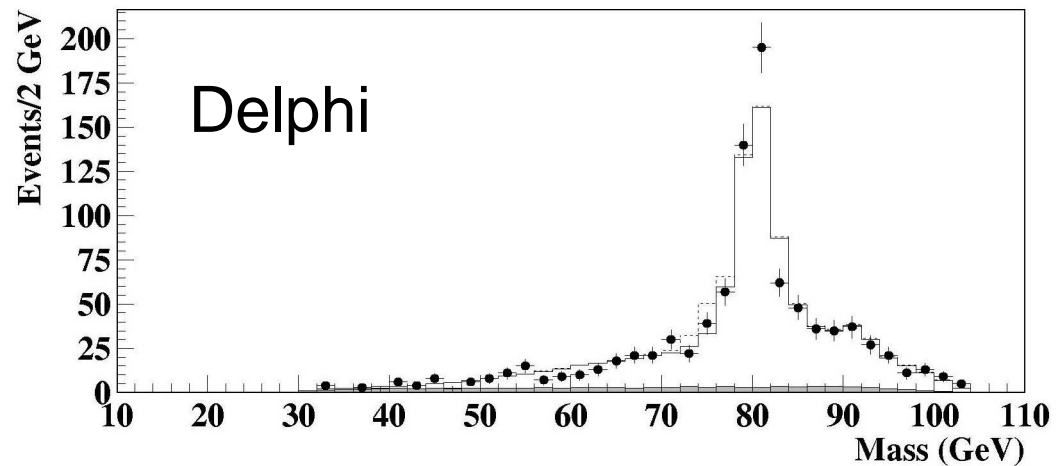
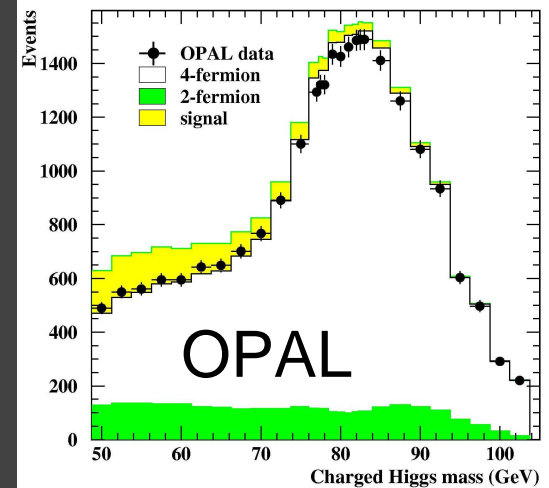


No signal elsewhere in m_{H^+}



All data taken in $H^+H^- \rightarrow cs cs$ channel, signal: $m_{H^+} \sim 70$ GeV

OPAL Preliminary: $H^+H^- \rightarrow qq\bar{q}\bar{q}$, 189-209 GeV

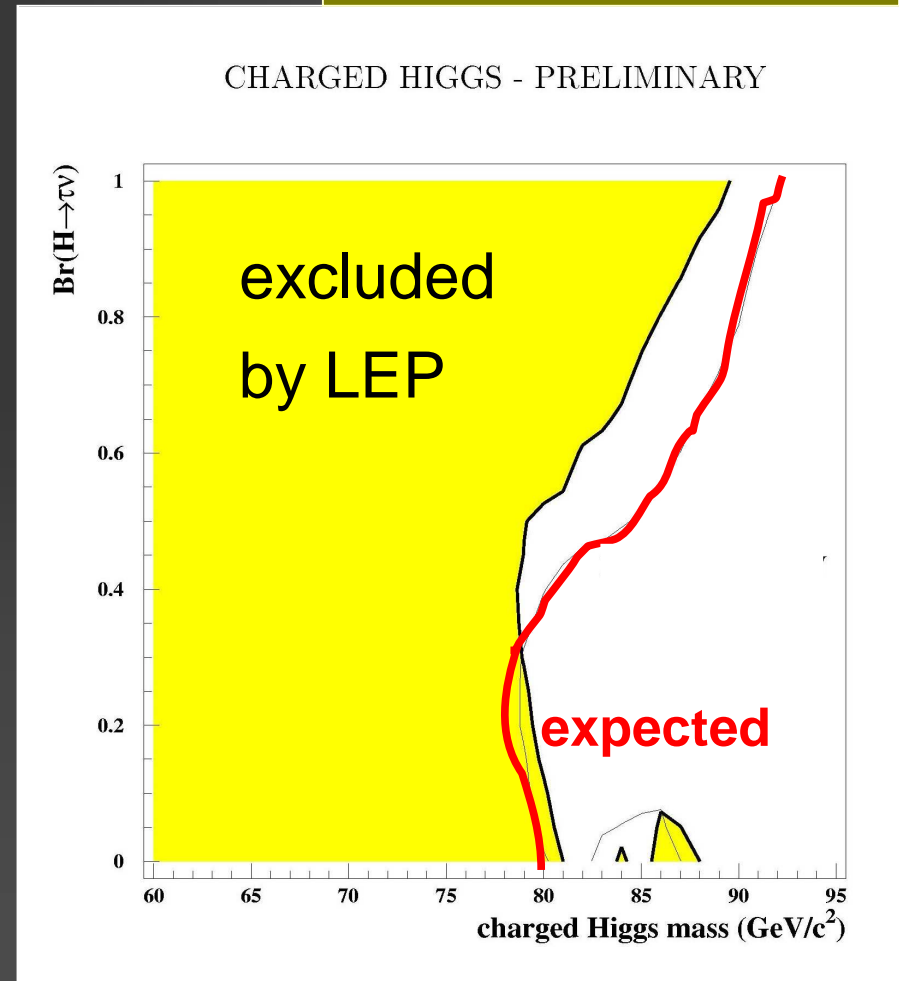


Combined LEP limits on m_{H^+}

$m_{H^+} > 78.6 \text{ GeV}$

- No signal elsewhere at 68 GeV even emulating L3 analysis
- No flaws found in L3 analysis despite great scrutiny

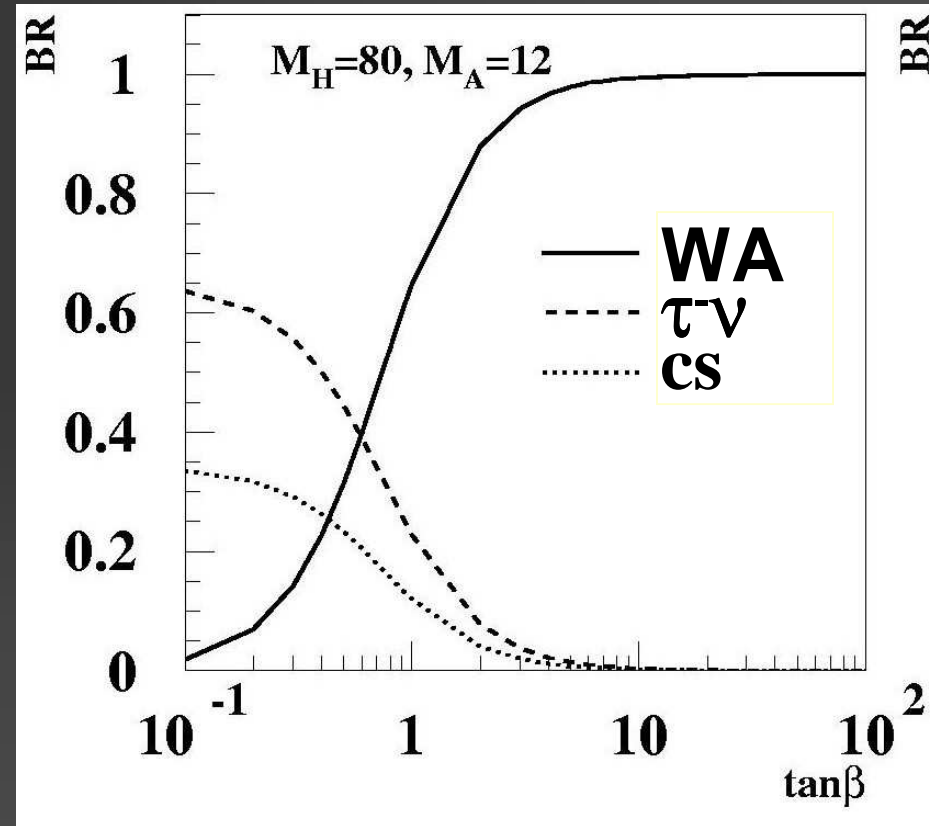
Interpreted as a 4.2σ background fluctuation



Latest publications on H^+

- **Aleph**: CERN-EP-2002-054
- **L3**: Note 2686 - (EPS 2001)
- **Opal**: PN509 - (ICHEP 2002)
- **LEP**: Summer 2001
hep-ex/0107031
- **Delphi**: 2002-038-CONF-572
(ICHEP 2002)

includes $H^+ \rightarrow W^*A \Rightarrow$



Search for doubly charged Higgs

- Exist in two Higgs triplet models
- At tree level, H^{++} only couples to charged leptons and gauge bosons
- Production mode: $e^+e^- \rightarrow H^{++} H^{--}$
- Occur naturally in left-right symmetric models
 - these allow small neutrino masses
 - $\sigma(e^+e^- \rightarrow H_R^{++} H_R^{--}) \neq \sigma(e^+e^- \rightarrow H_L^{++} H_L^{--})$
 - Do not conserve baryon and lepton number

Decay characteristics for H^{++}

- $H^{++} \rightarrow l^+ l^+$, $l = e, \mu, \tau$
- Search for events with 4 leptons + missing energy (if $l = \tau$)
- $\Gamma(H^{++} \rightarrow \tau\tau) \propto h_{\tau\tau}, m_{H^{++}}$
 $h_{\tau\tau}$: Yukawa coupling
- H^{++} lifetime \sim zero for $h_{\tau\tau} > 10^{-7}$
- Long-lived if $h_{\tau\tau} < 10^{-7}$

	Delphi	Opal
Ecm (GeV)	189-209	189-209
total int. L	570 pb ⁻¹	614 pb ⁻¹
$h_{\tau\tau} > 10^{-7}$	$m_H > 99.6$	$m_H > 98.5$
$h_{\tau\tau} < 10^{-9}$	$m_H > 99.3$	

Delphi: CERN-EP/2002-077

OPAL: Phys. Lett. B526 (2002) 221



Flavour-independent searches

- Higgs to bb coupling can be suppressed in 2HDM, MSSM and composite models

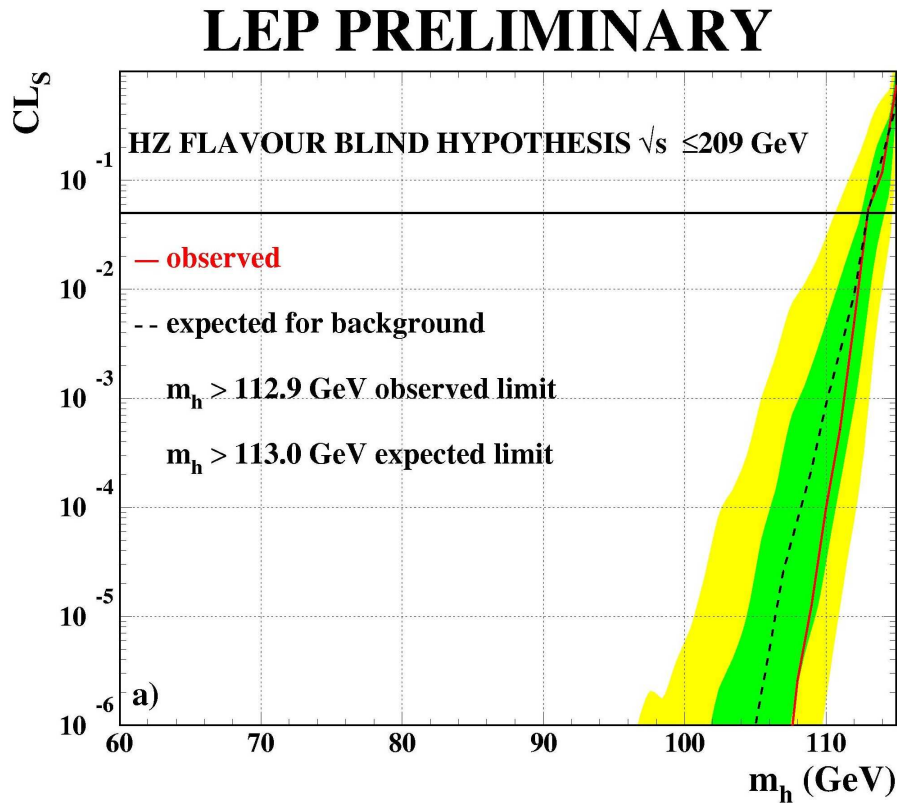
Would have been missed if h couples to any quark

Repeat SM searches without b -tag except for the 4-jet channel: add constraints to reduce background

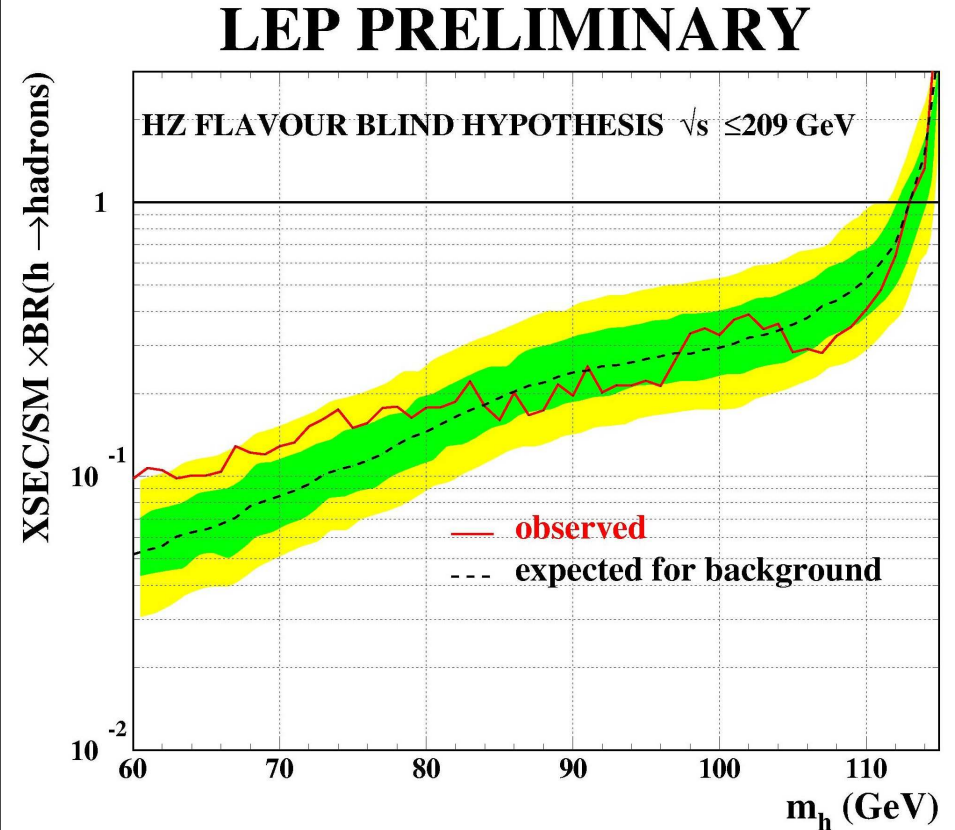
- All LEP experiments have searched for HZ in $qqqq$, $qqvv$, $qq\ell^+\ell^-$ channels where $q = \text{any flavour}$

LEP mass and cross-section limits

SM $\sigma(HZ)$ and $BR(H \rightarrow qq)=1$



PASCOS'03 – January 2003

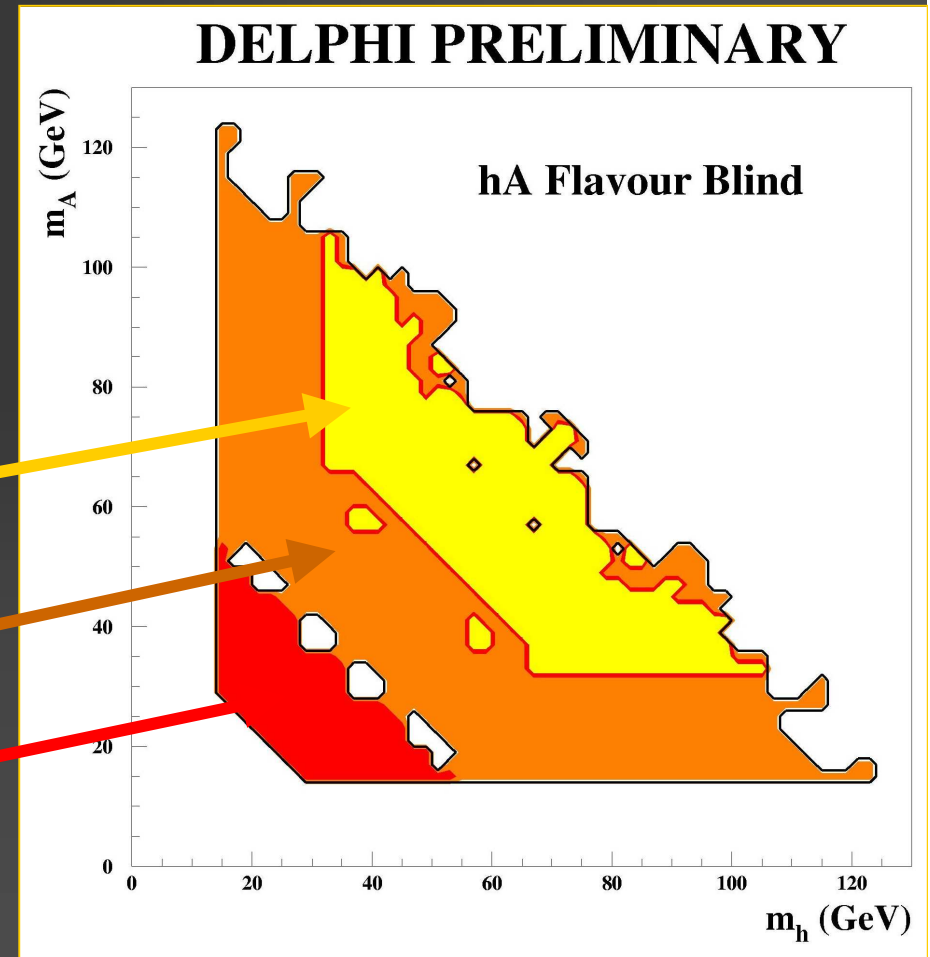


Using HZ channel only

Pauline Gagnon – Indiana University

$h^0 A^0$ channel at Delphi with $A^0 \rightarrow 4g$

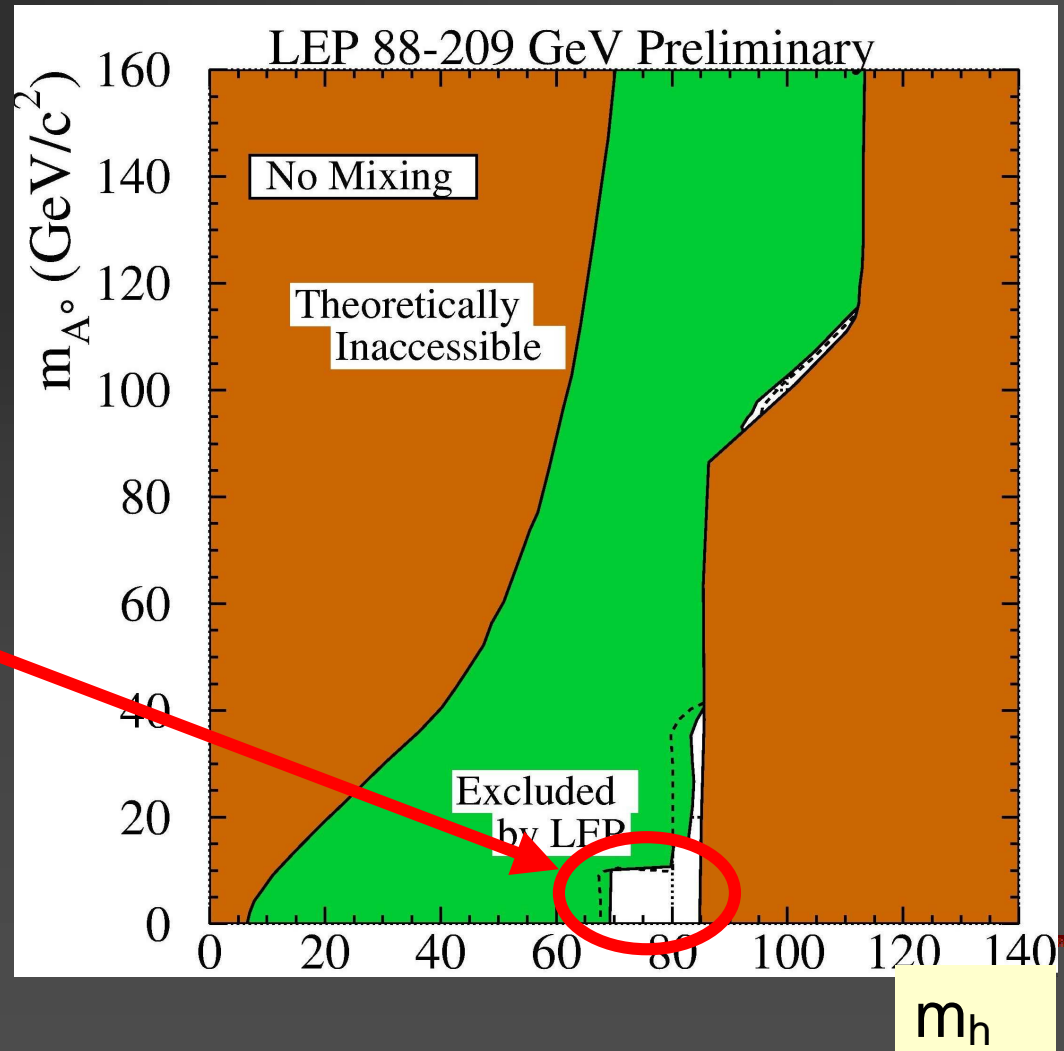
- Gluon jets have higher multiplicity than quark jets
- Search topologies:
 - 1) 4-jet: if $m_A \sim m_h$,
 - 2) 3-jet: if m_h or m_A light
 - 3) 3-jet + high thrust: if both are light



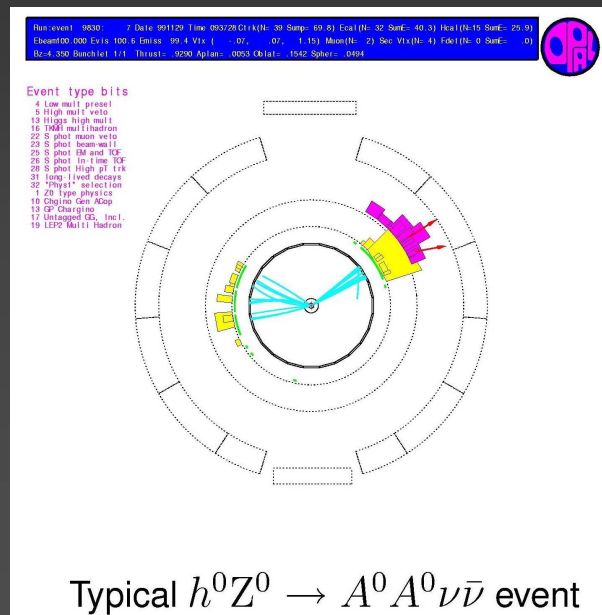
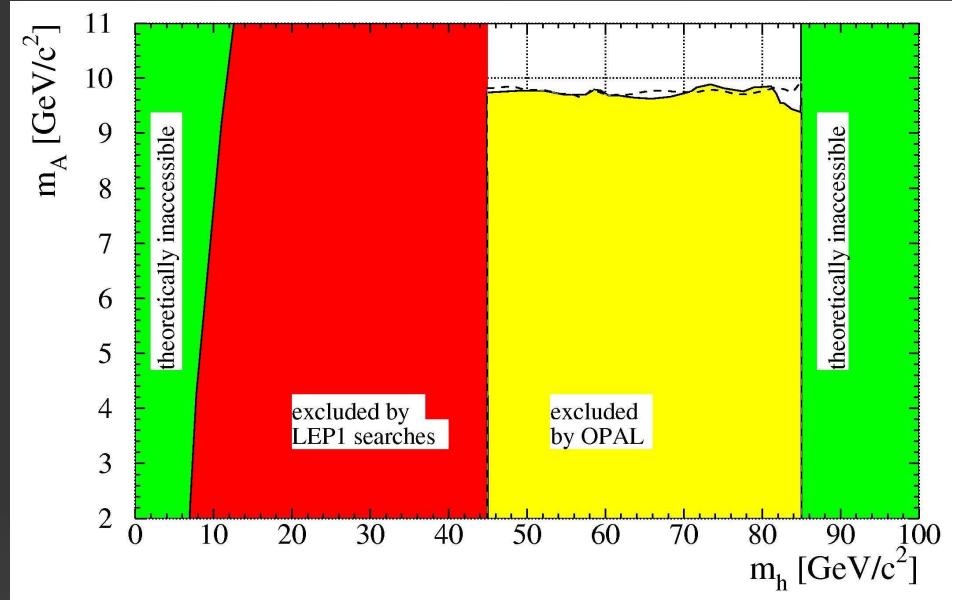
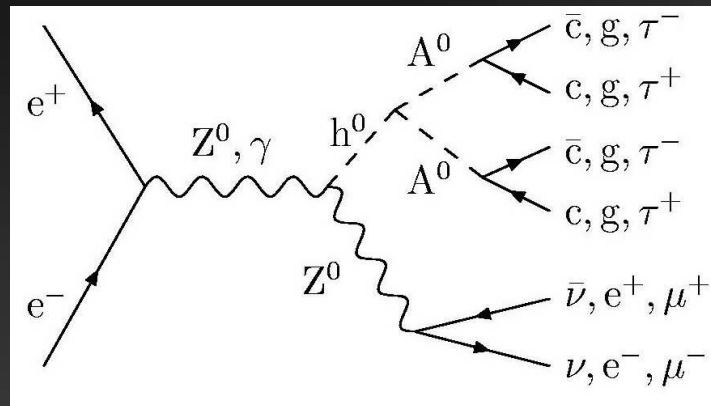
Low m_A search at OPAL

Low m_A region not explored in MSSM

This is where m_A is below the bb threshold



$h^0 Z^0$ topology with $h^0 \rightarrow A^0 A^0$



**A^0 has high boost:
see only 2 jets
 $Z^0 \rightarrow \nu\nu$ or $l^+ l^-$**

Typical $h^0 Z^0 \rightarrow A^0 A^0 \nu \bar{\nu}$ event

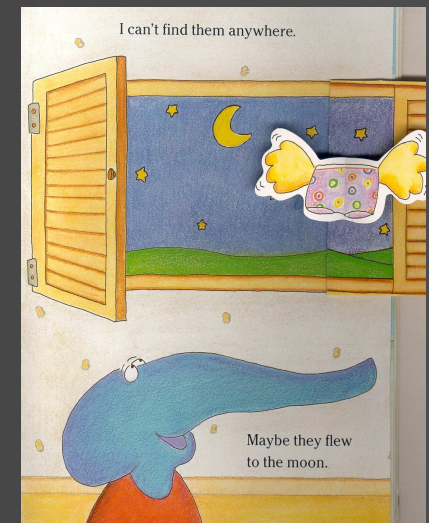
PASCOS'03 – January 2003

CERN-EP/2002-058

Pauline Gagnon – Indiana University

2HDM interpretations

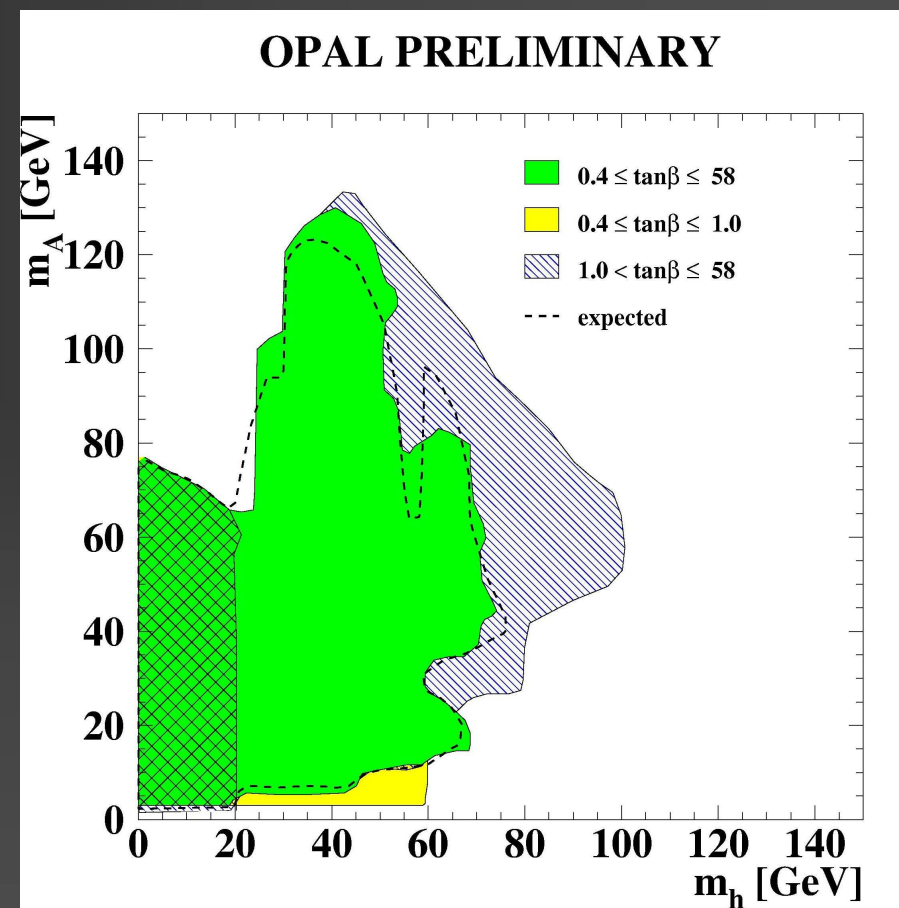
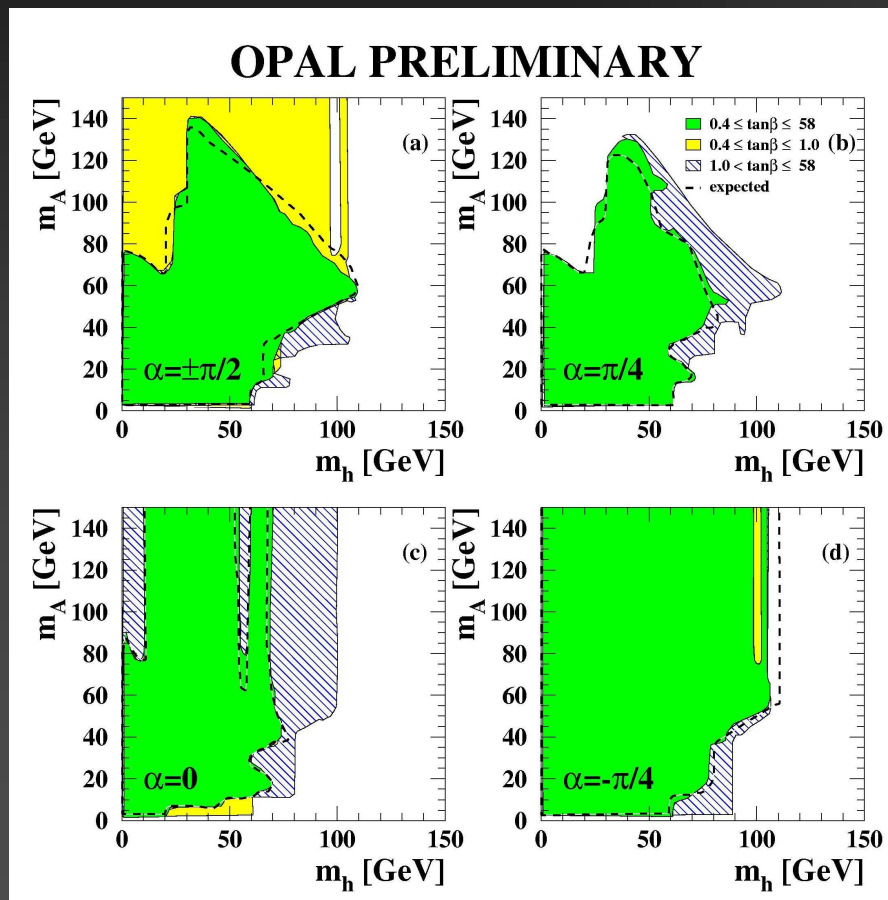
- Re-interpretation of all MSSM data in the framework of 2HDM
- Done at OPAL for 2HDM Type II
EPJC 18 (2201) 425 and OPAL PN475
- Soon to be redone with all LEP data
- Scan the parameter space for $(m_A, m_h, \tan \beta, \alpha)$



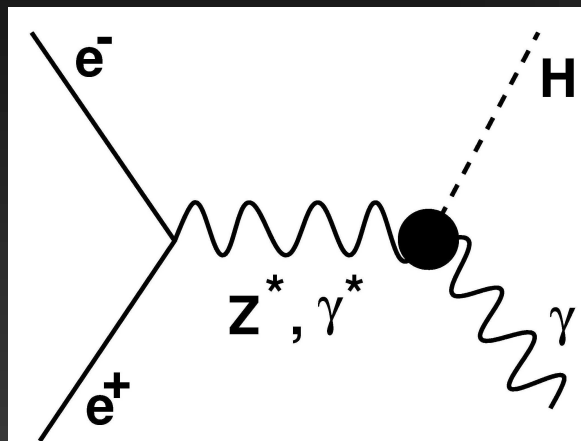
2HDM interpretation at OPAL

For any value of α

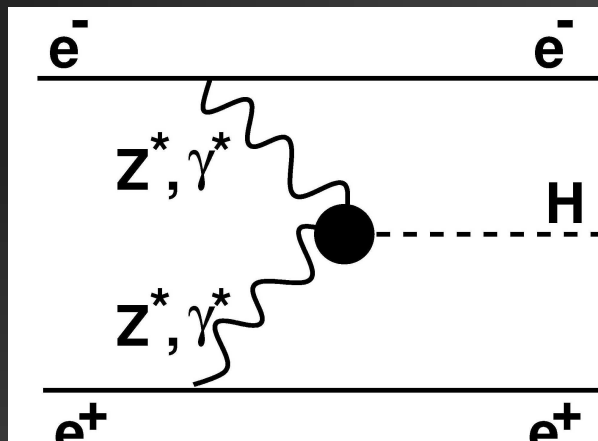
For specific values of α



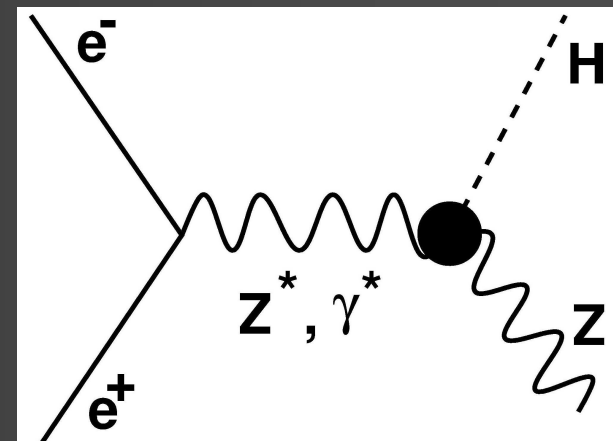
Anomalous couplings at L3



$$e^+e^- \rightarrow H \gamma$$



$$e^+e^- \rightarrow H e^+e^-$$



$$e^+e^- \rightarrow H Z$$

Depend on various couplings: d , d_B , Δg_1^Z , $\Delta \kappa_\gamma$, δ_Z

If any of these couplings is large, expect to see enhancement w.r.t. SM cross-sections

But if we find a Higgs, we'll see it everywhere

