Higgs Boson Searches at LEP

On behalf of the LEP Collaborations and
the LEP Higgs Working Group

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EPS HEP2007 Conference
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Thanks to Gavin Davies

Imperial College
London

Outline

- Overview of LEP legacy on Higgs searches
- Present only LEP-combined (ADLO) results
- No new LEPHWG publications in last year
- Results shown here are published in

  Search for the Standard Model Higgs boson at LEP, PLB565(2003)61.
  Search for neutral MSSM Higgs bosons at LEP, EPJC47(2006)547.

  ...and earlier preliminary LEPHWG notes
  (available at http://lephiggs.web.cern.ch/)
  Higgs decays to photons
  Charged Higgs
  Invisible Higgs
  Flavour-blind Higgs

LEP

LEP1 and LEP2

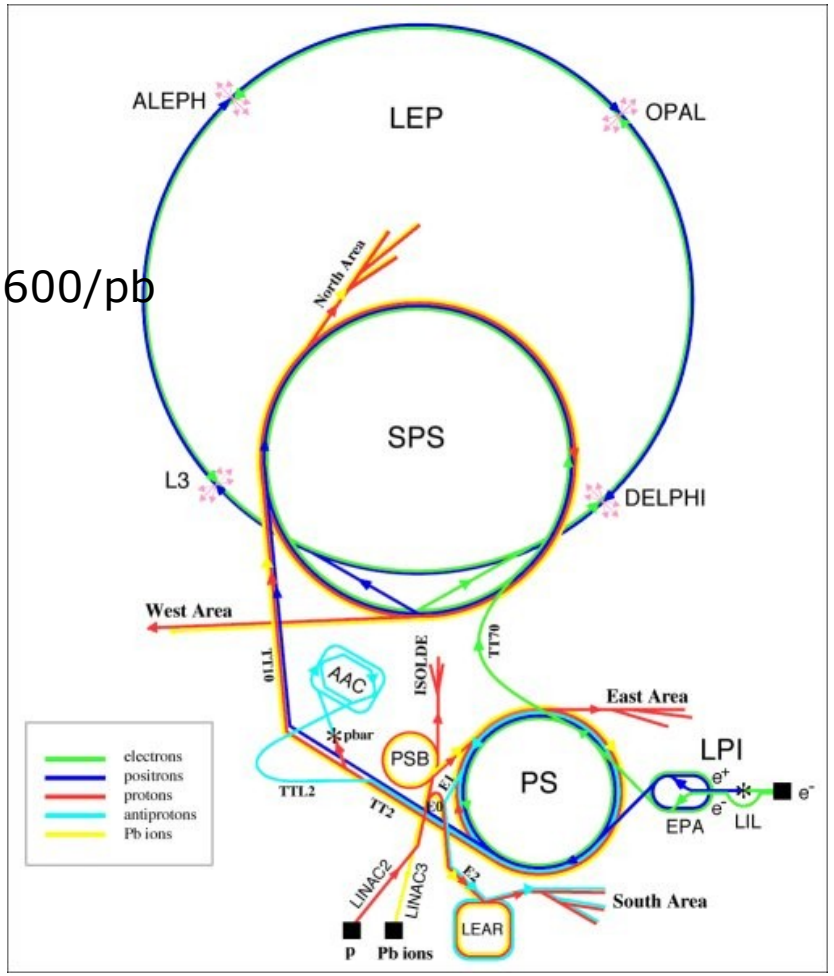
e^+e^- collisions

LEP1: $\sqrt{s}=m_Z$ (1989 – 1995), ~800/pb

LEP2: $\sqrt{s}=2m_W \rightarrow$ 209 GeV (1996 – 2000), ~2600/pb

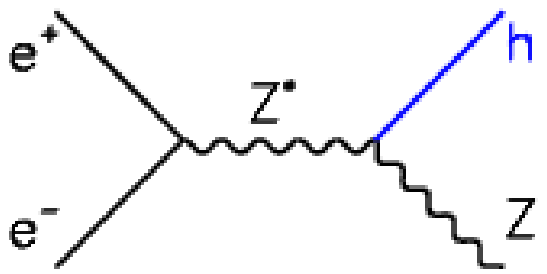
Four detectors:

ALEPH, DELPHI, L3 and OPAL

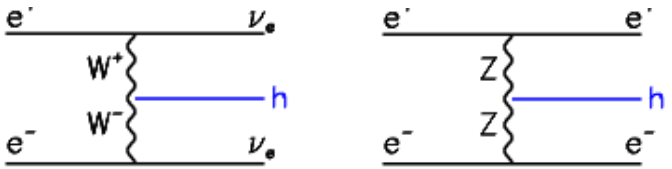


Higgs production: hZ

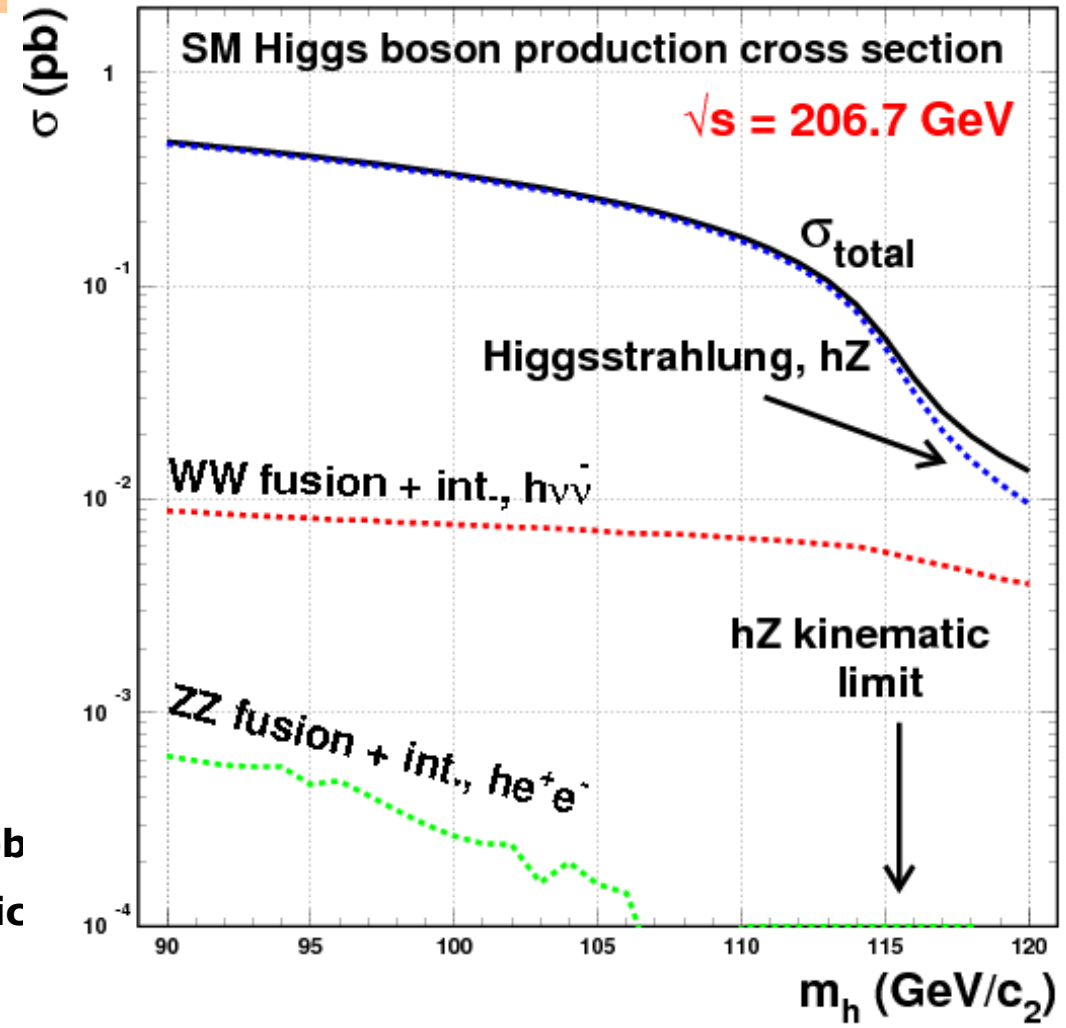
Production → Higgsstrahlung:



...+ small VB fusion contributions



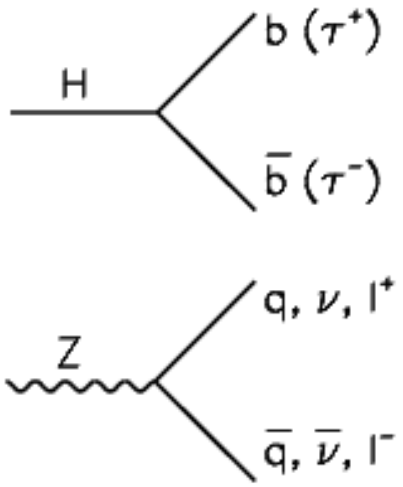
- **signal cross-section ~ 0.1 – 0.5 pb**
- **searches sensitive up to kinematic threshold ($m_H=\sqrt{s}-m_Z$)**

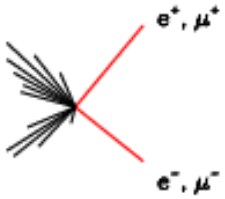
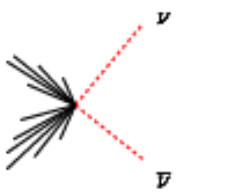
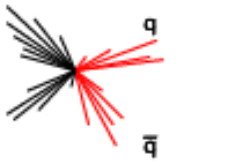


SM Higgs search topologies

Main topologies defined by combination of Higgs and Z decay modes

Decays of H and Z:



Channel	BR	Signature	
Leptonic channel $he^-e^-, h\mu^-\mu^-$	6.7 %		Two opp. charged $(e^+e^-, \mu^+\mu^-)$ isolated leptons $m_{\ell\ell} \sim m_Z$
Missing energy channel $h\nu\bar{\nu}$	20.0%		Large missing energy Acoplanar jets $\not{m} \sim m_Z$ b-tagging
Four-jet channel $hZ \rightarrow b\bar{b}q\bar{q}, b\bar{b}b\bar{b}$	52.5 %		Well isolated jets m_H, m_Z constraints b-tagging
$h\tau^-\tau^-, \tau^-\tau^-Z$	8.7%		'minijets': 1,3 tracks $m_{jets} \sim m_\tau$ Missing momentum

Main background processes / LEP2

- **ZZ irreducible bgd, for mH≈mZ**
- **WW & ZZ bgds mimic basic HZ topology (two heavy resonances, similar decay modes)**
- **several physics processes with missing energy**

Background to: $e^+e^- \to \ldots$	$H\ell^+\ell^-$	$H\nu\bar{\nu}$	$Hq\bar{q}$
$ZZ \to$ $\sigma \sim \mathcal{O}(2\ \text{pb})$	$q\bar{q}\ell^+\ell^-$	$b\bar{b}\nu\bar{\nu}$	$b\bar{b}q\bar{q}$ $b\bar{b}b\bar{b}$
$W^+W^- \to$ $\sigma \sim \mathcal{O}(15\ \text{pb})$	$q\bar{q}'\ell\nu$	$q\bar{q}'\tau\nu$	$4q$ $(u, d, s, c, \not{b})$
$q\bar{q} \to$ $\sigma \sim \mathcal{O}(100\ \text{pb})$	$+b \to c\ell\nu$	$+b \to c\ell\nu$ $+$ mism. jet	$b\bar{b}q\bar{q}$ $b\bar{b}gg$
$e^+e^-Z \to$ $\sigma \sim \mathcal{O}(5\ \text{pb})$	$e^+e^-q\bar{q}$	$e^+\not{e}^-q\bar{q}$	
$eW\nu \to$ $\sigma \sim \mathcal{O}(0.5\ \text{pb})$		$\not{e}q\bar{q}\nu$	
$e^+e^-\gamma\gamma \to e^+e^-q\bar{q} \to$ $\sigma \sim \mathcal{O}(1000\ \text{pb})$ $(W_{min} = 40\ \text{GeV}/c^2)$		$e^+\not{e}^-q\bar{q}$	

MSSM Higgs sector

Minimal Supersymmetric extension of the SM → need two complex Higgs field doublets

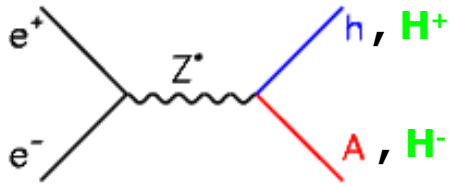
→ 5 Higgs particles (3 neutral, 2 charged):

$$h, H \text{ (CP-even; } m_h < m_H), A \text{ (CP-odd)}, H^{\pm}$$

(tan β is ratio of vevs of the Higgs fields in the two doublets)

Production

$e^+e^- \rightarrow hZ, hA, H^+H^-$



Decays

$h \rightarrow bb, \tau\tau \quad + \quad h \rightarrow AA$

$A \rightarrow bb, \tau\tau$

$H^{\pm} \rightarrow cs, \tau\nu$

In addition to hZ, searched for

$e^+e^- \rightarrow hA \rightarrow bb\ bb, bb\ \tau\tau, \tau\tau\ \tau\tau, bb\ bb\ bb, bb\ bb\ \tau\tau, \ldots$

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

SM Higgs search results

Likelihood Ratio

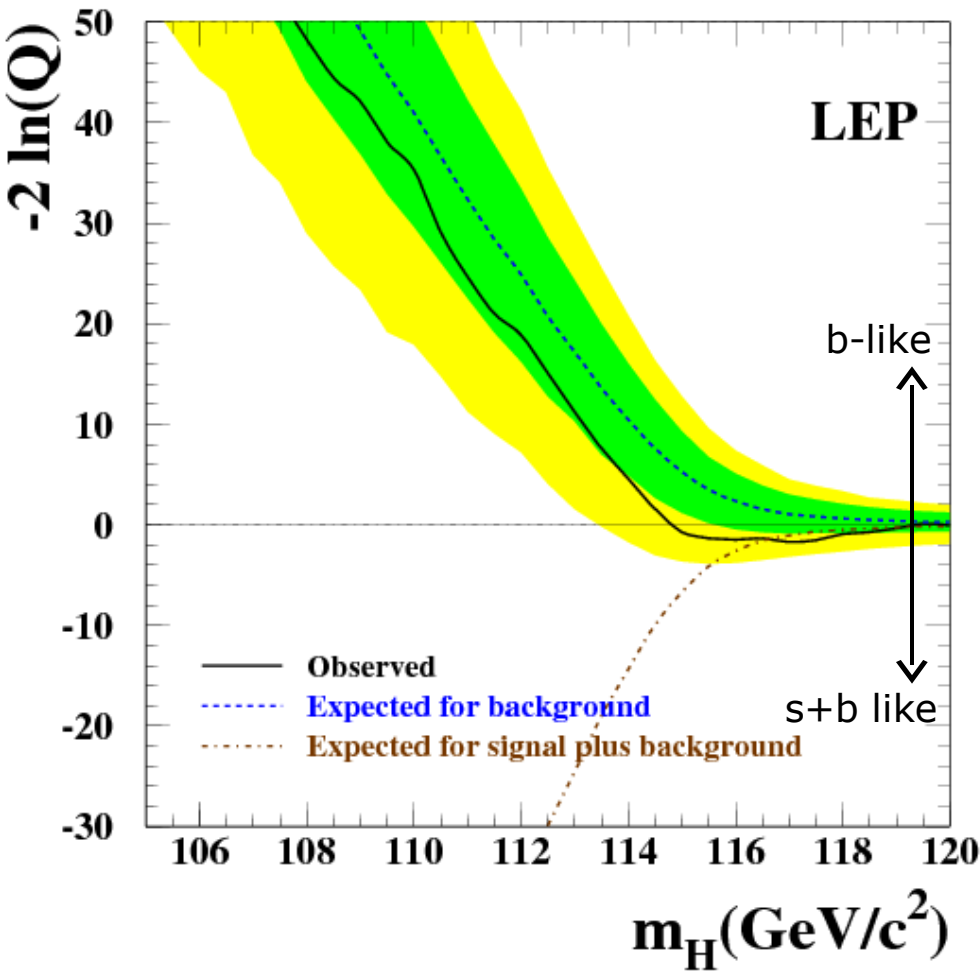
Ratio of the likelihoods for the signal+background and the background-only hypotheses:

$$Q = \frac{P(n_{obs}; s+b) \times (S(\vec{x}_i) + B(\vec{x}_i))}{P(n_{obs}; b) \times B(\vec{x}_i)}$$

Combine all channels using

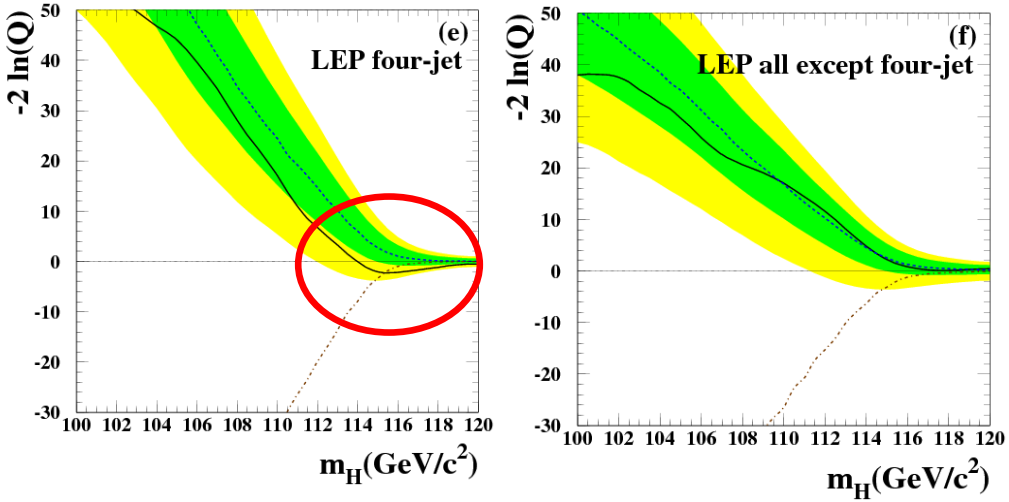
$$-2 \ln Q = 2 s_{tot} - 2 \sum_{i=1}^{n_{obs}} \ln(1 + \frac{S(\vec{x}_i)}{B(\vec{x}_i)})$$

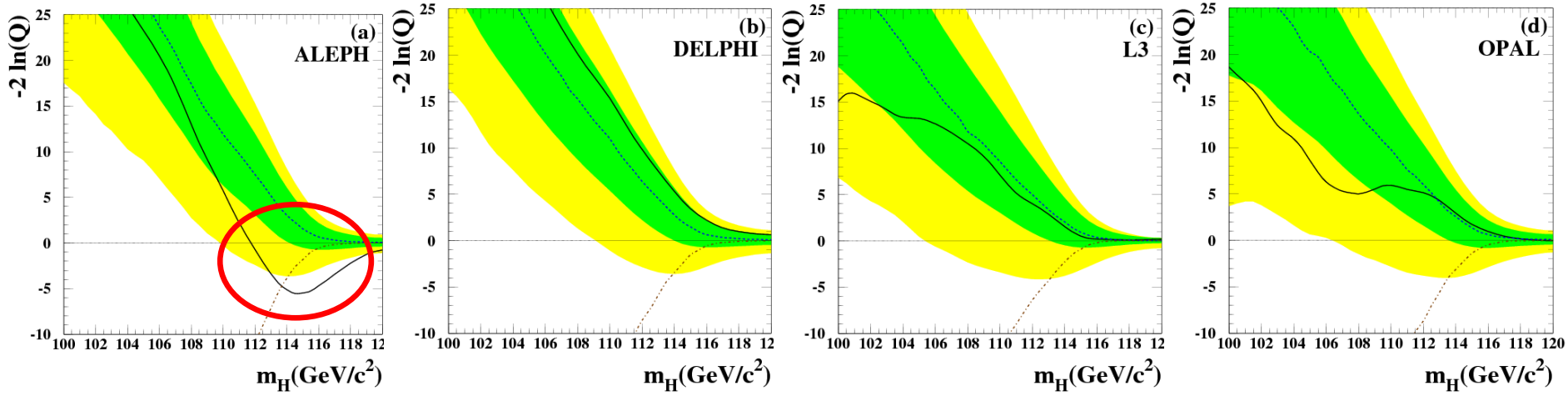
Weight of candidate i



Likelihood Ratio contributions

- Effect is predominantly in four jet channel and ALEPH experiment
- DELPHI result ~ background-like
- L3 & OPAL data slightly favour s+b hypothesis





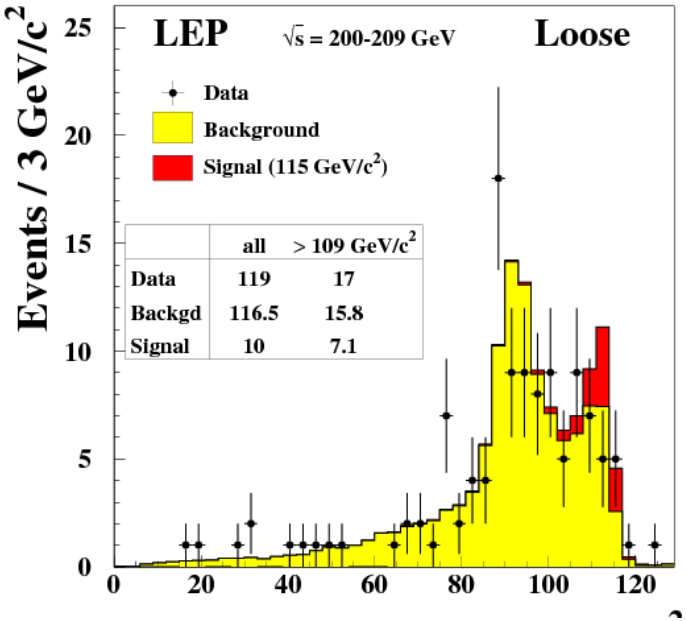
Reconstructed mass

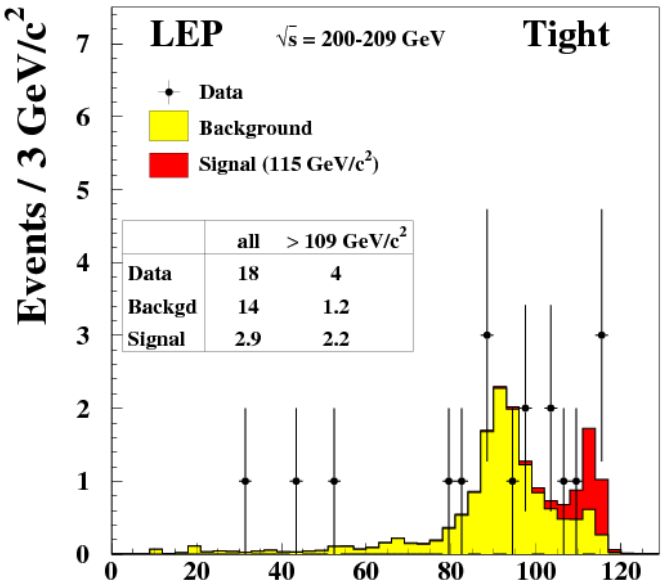
NB: these mass plots are for illustration only and are not used in calculation of signal significance!

Not taken into account here:

- weight of different channels (topologies, √s)

- additional discriminant information (e.g., b-tag) used in the calculation of the confidence levels





LOOSE event selection:
$s_{115}/b \approx 0.5$ for $m_{H,reco} > 109$ GeV

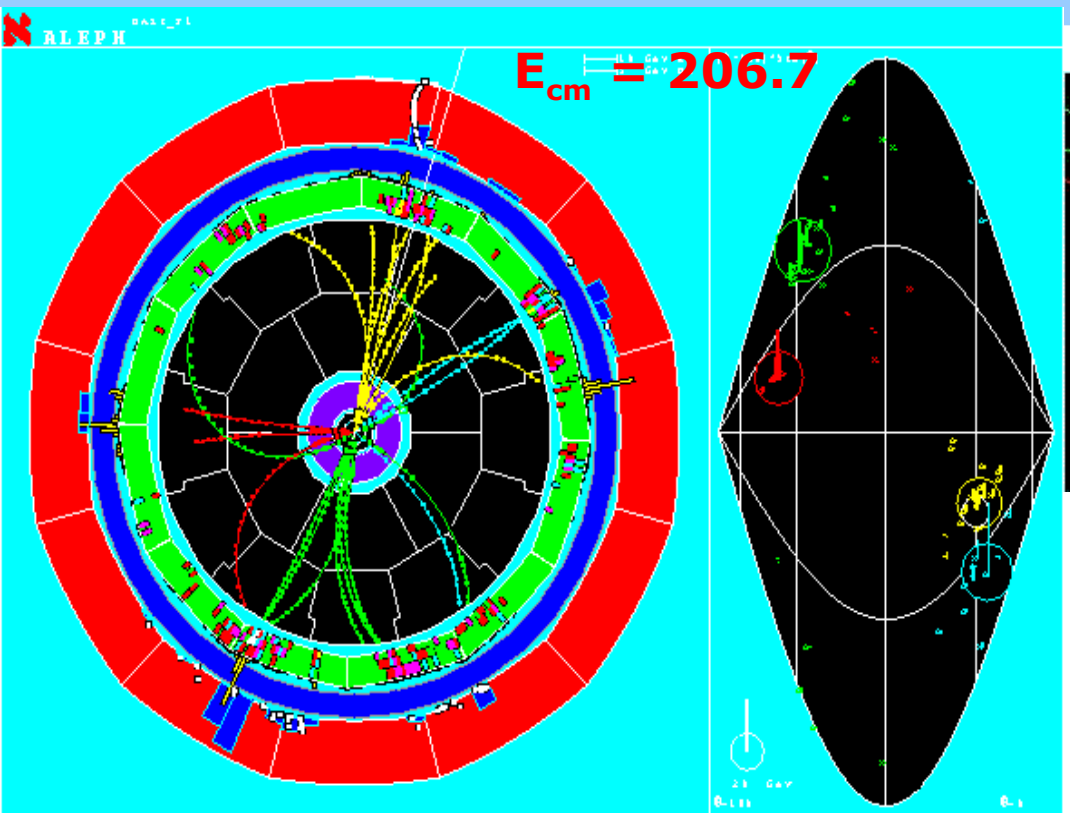
→ Good agreement between data and MC

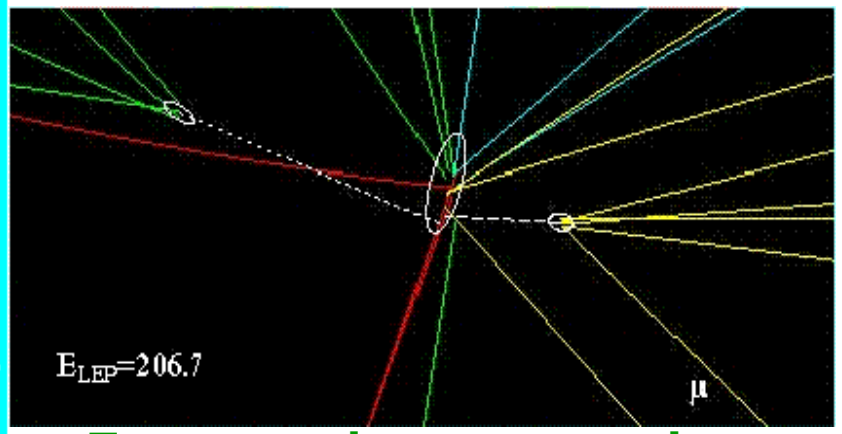
→ ZZ background peak clearly visible

TIGHT event selection:
$s_{115}/b \approx 2.0$ for $m_{H,reco} > 109$ GeV

→ Excess of candidates at high mass

An ALEPH candidate event





Two very clean sec. vertices

M_{rec}=114±3 GeV/c²

b-tag H-jets 0.99 0.99
b-tag Z-jets 0.14 0.01
NN output 0.996

Mrec (ZZ,6C) 92,102
P(ZZ)~1%

Recorded 14/06/00

- **Event well-measured**
  - jets separated (R-G~46° Y-B~37°)
  - Raw M_{qq}=92.1GeV
  - P_{mis}=14GeV, points to jet with semileptonic b-decay
  - High P_{mis} anti-correlated with soft muon
- **Consistent with threshold production**
  - planar event,balanced jet energies

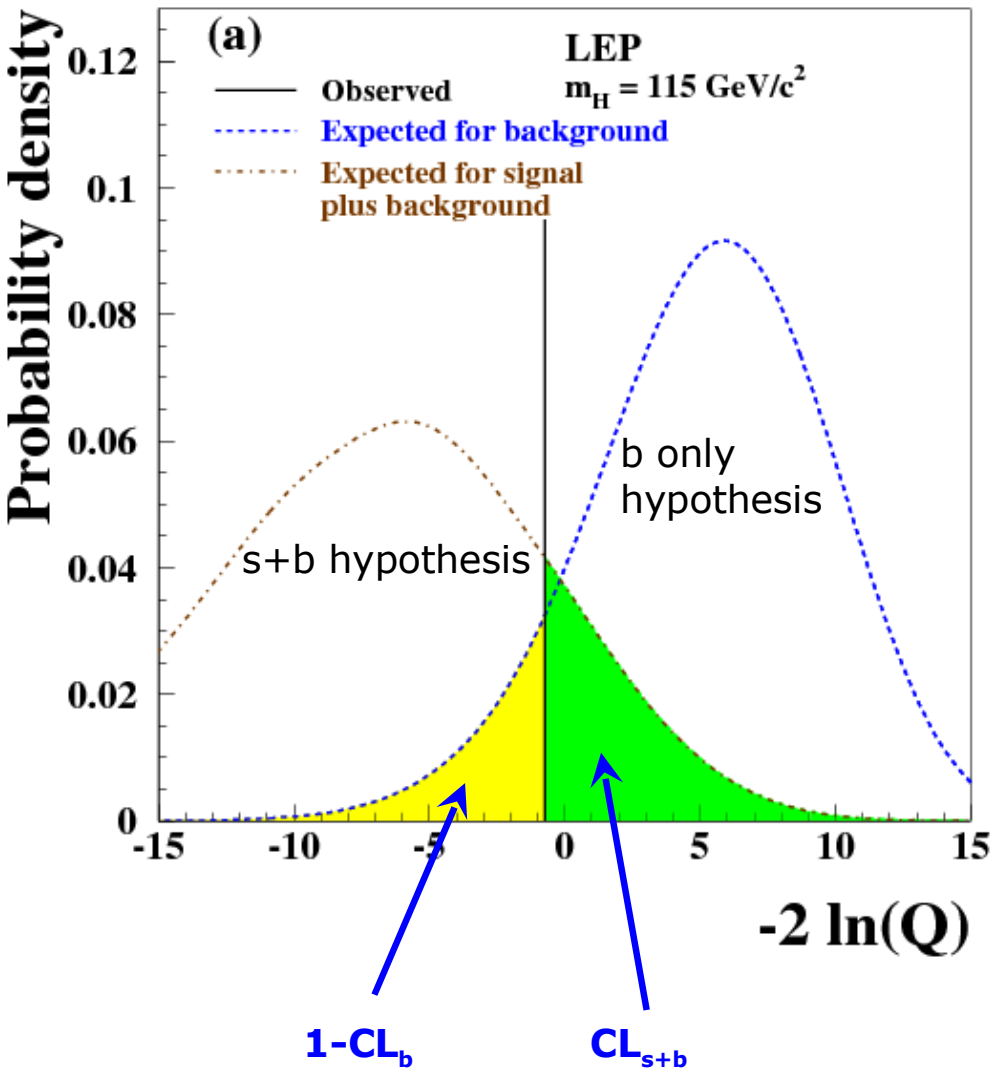
Hypothesis testing

Expected -2lnQ distributions, from toy experiments including effect of statistical and systematic errors.

Systematic errors:

Uncorrelated betw. experiments → dominated by limited MC sample size

Correlated betw. experiments → e.g., due to use of common MC event generators and cross-section calculators

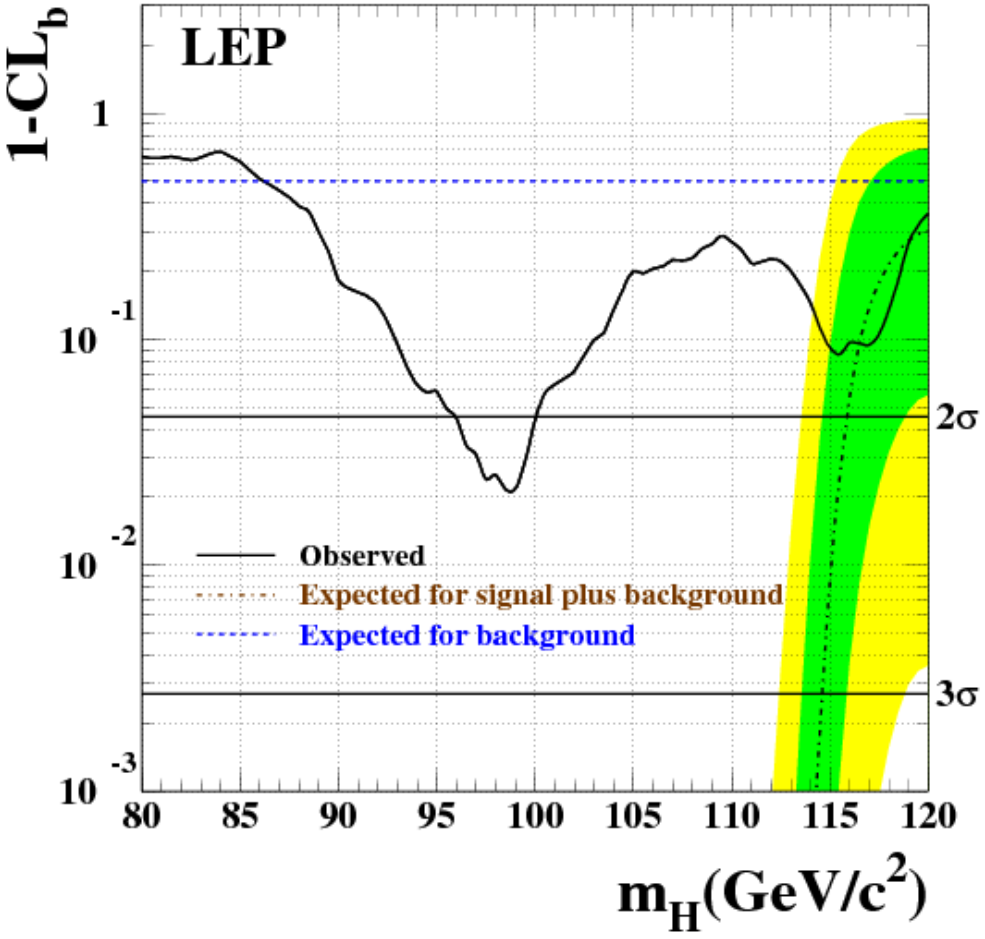


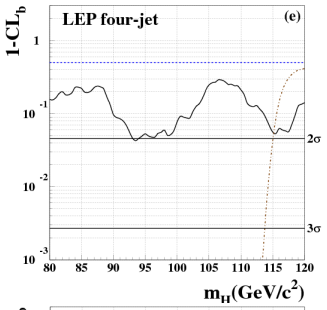
$1\text{-}CL_b$ = probability of observing a more signal-like data set than observed under the b-only hypothesis

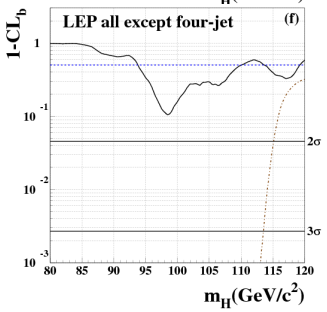
→ $\langle 1\text{-}CL_b \rangle$ = 50% (if b-only)

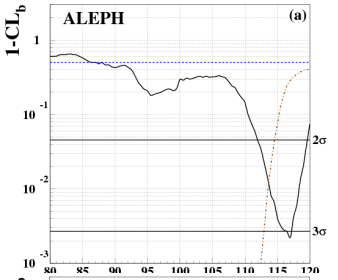
→ $1\text{-}CL_b$ tends to zero (if s+b)

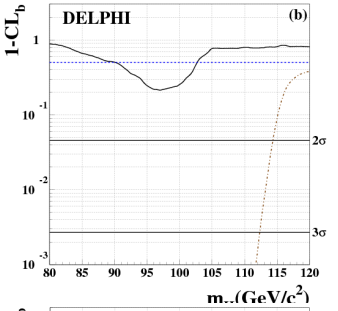
SM Higgs search: 1-CL_b

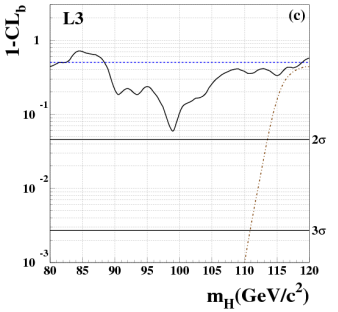


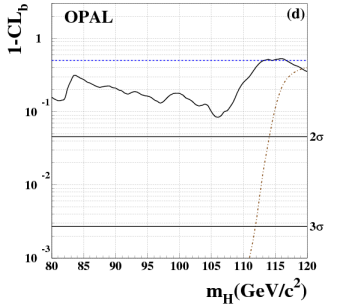












- **1.7σ significance at $m_H \approx 115$ GeV**
- **95%CL: $m_H \geq 114.4$ GeV (115.3 GeV)**

SM-like Higgs boson

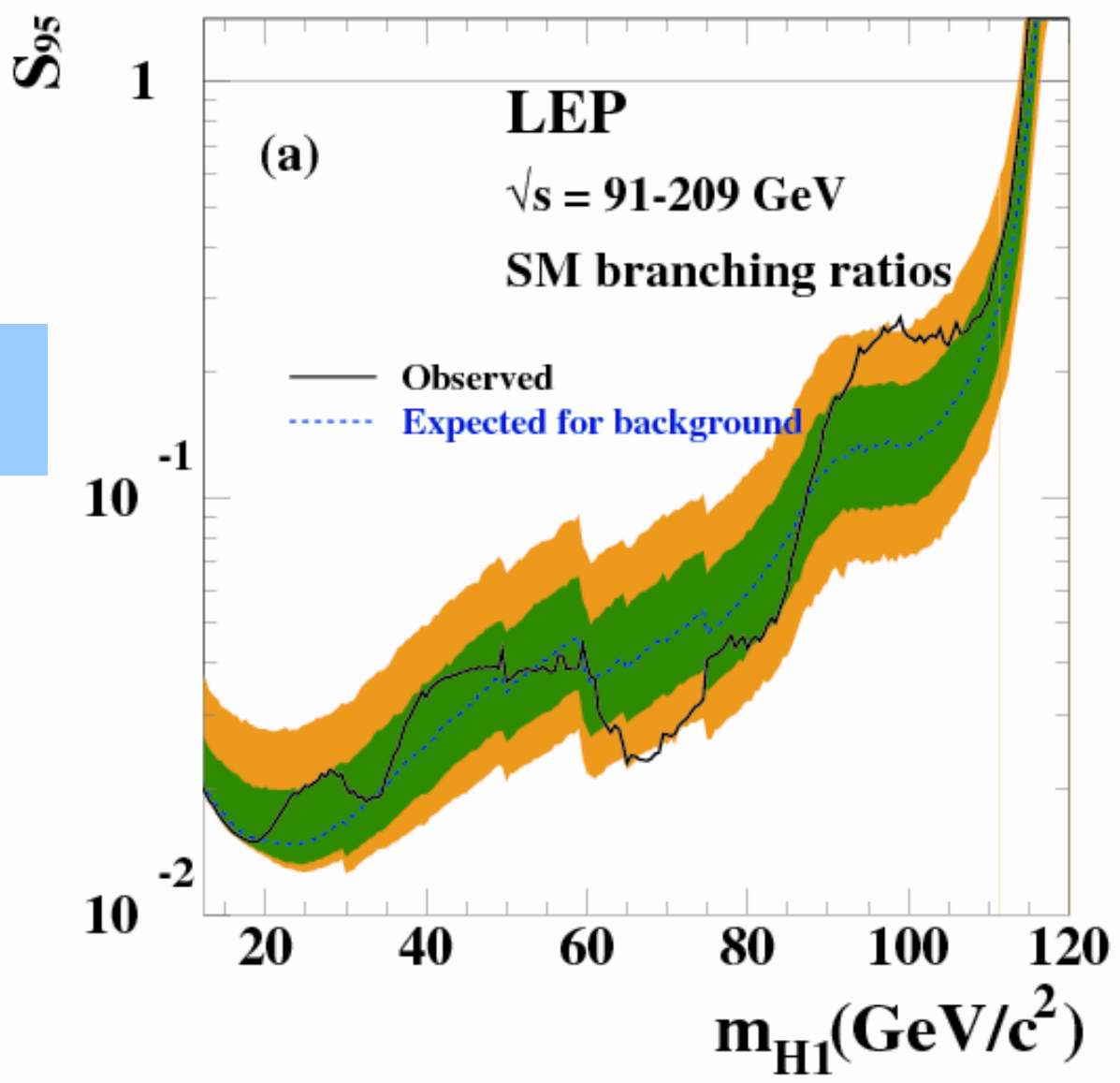
- same decay modes (BRs) as the SM Higgs
- reduced production cross-section wrt SM Higgs

$S_{95} = \sigma / \sigma_{SM}$

Exclusion at the 95% CL

Exclusion limits also derived for scenarios when Higgs decays exclusively as

H→bb OR H→ττ



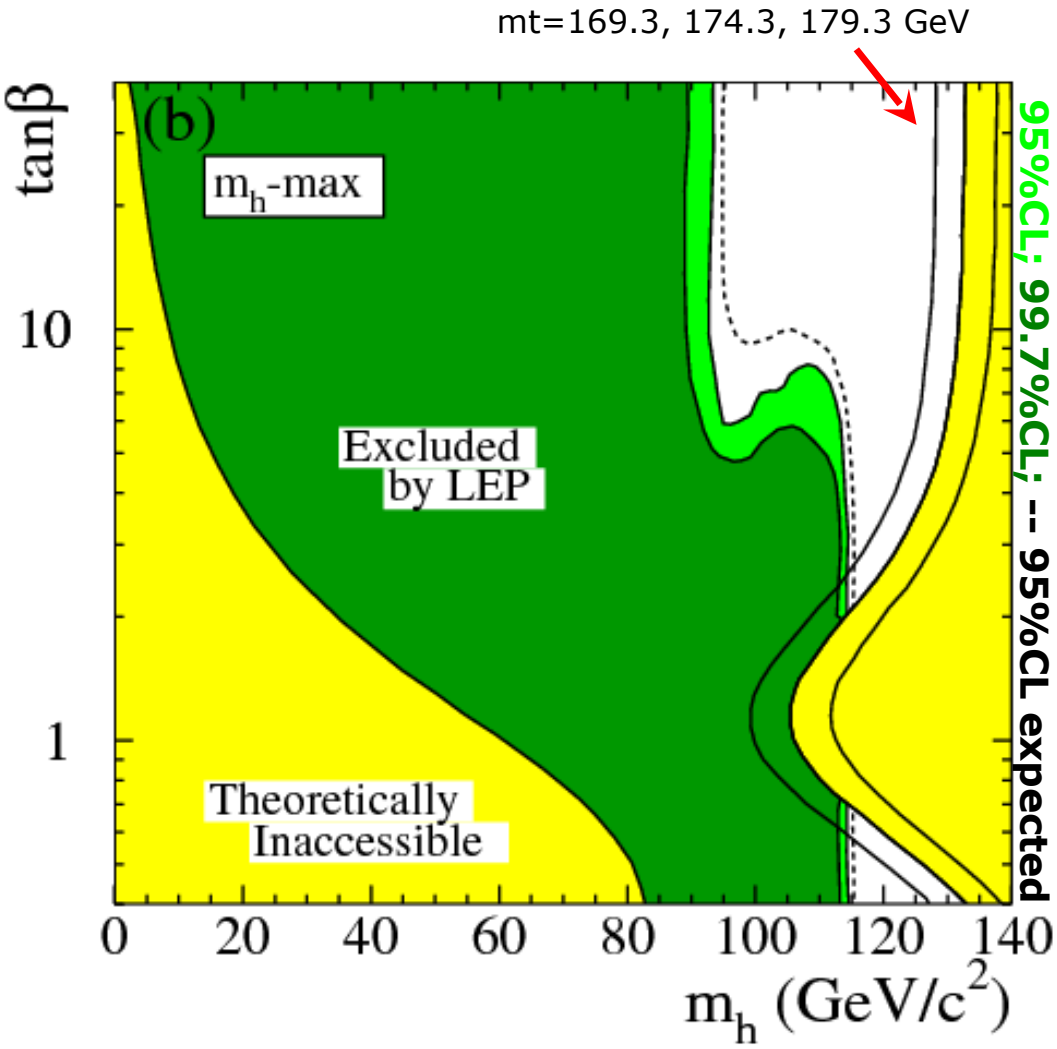
Neutral MSSM Higgs results

- CP-conserving scenarios (CPC)
- CP-violating scenarios (CPV)

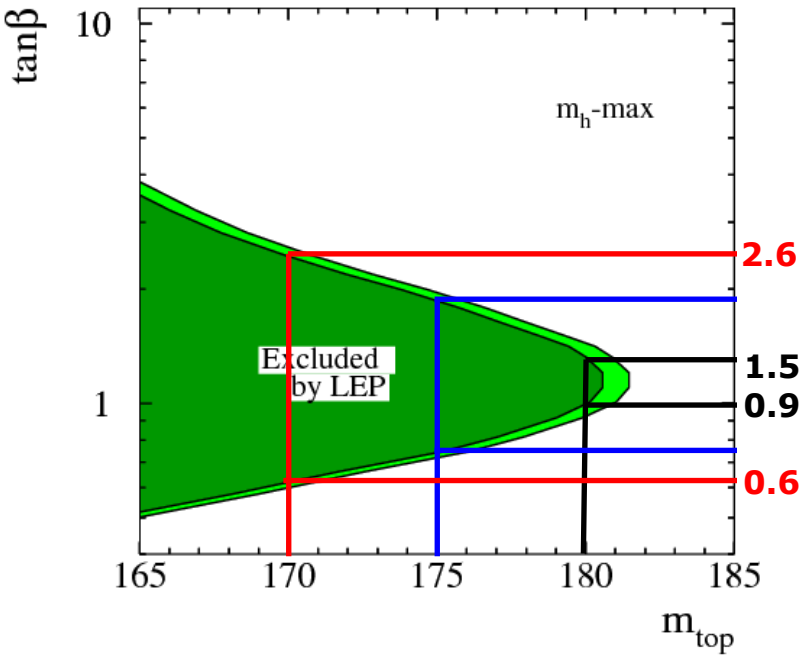
CP-conserving Higgs sector

Many benchmarks investigated
(mh-max, no-mixing, large-μ, gluophobic, small-α_{eff}, and variants…)

95%CL	mh	mA
mh-max	92.9 GeV	93.4 GeV



95% CL tan β exclusion:
strong dependency on mt



CP-violating Higgs benchmark (CPX)

- H_1, H_2, H_3 mass eigenstates without definite CP-parity (cf. h, A, H)

- Can be produced via

→ Higgsstrahlung ($e^+e^- \rightarrow H_iZ$) and

→ pair production ($e^+e^- \rightarrow H_iH_j$)

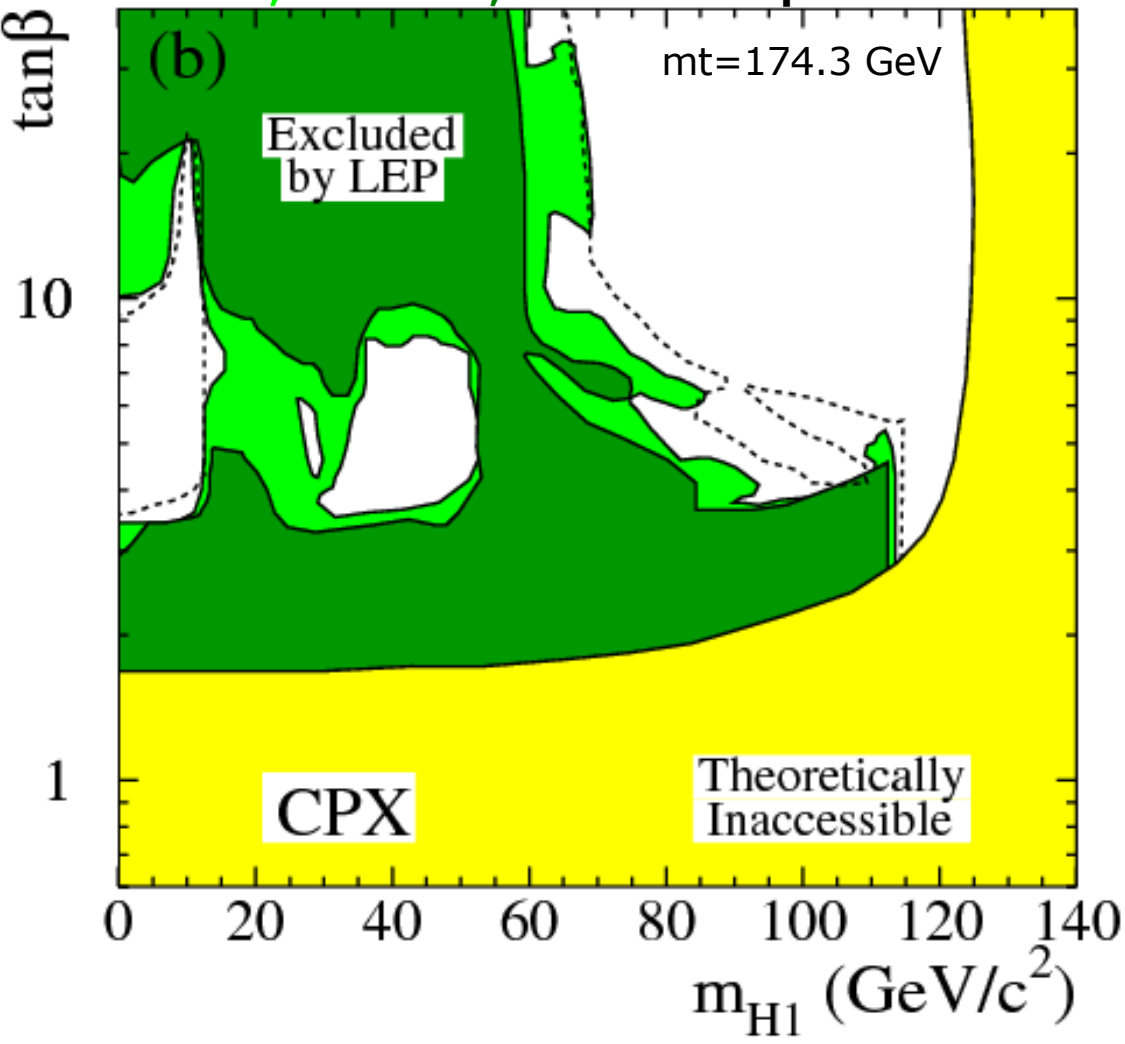
- H_i decay to fermions, or may cascade: eg $H_2 \rightarrow H_1H_1$

- CP-violating effects are proportional to $\frac{m_t^4 \,\mathrm{Im}(\mu A)}{v^2 M_{SUSY}^2}$

- CPX benchmark designed to maximize CP violating effects: low M_{SUSY} (500 GeV) and arg(A) = 90°

CPX benchmark results

95%CL; 99.7%CL; -- 95%CL expected

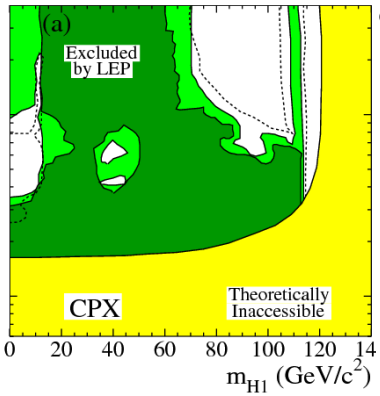


weak exclusion,
esp. for 3.5 < tan β < 10

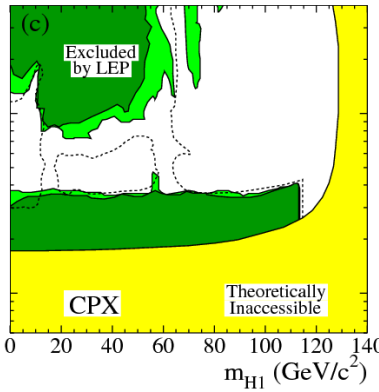
due to low detection efficiency and ~2σ excess in one of the experiments.

mt-dependence:

mt=169.3 GeV



mt=179.3 GeV



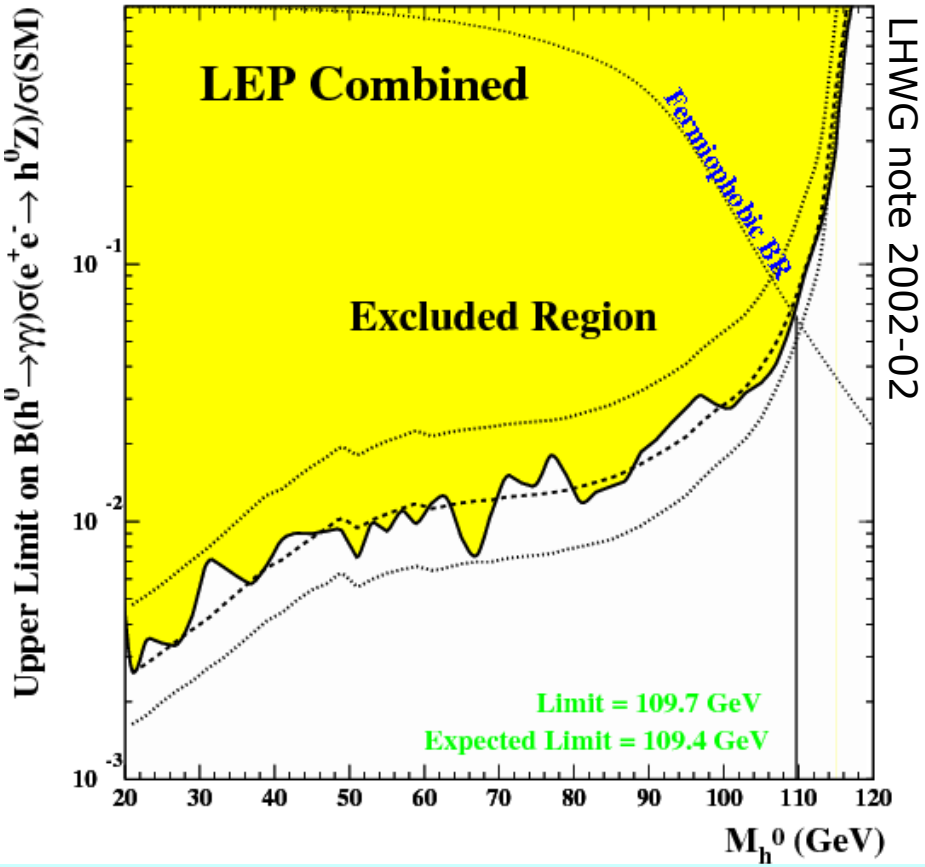
More searches...

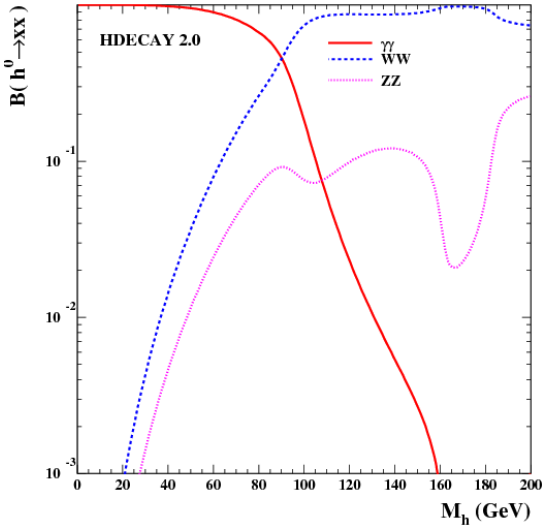
- Fermiophobic Higgs boson
- Charged Higgs bosons
- Invisibly-decaying Higgs boson
- Flavour-blind Higgs boson

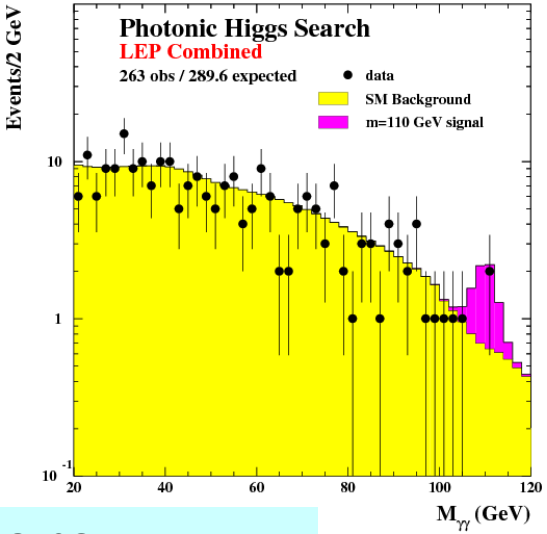
Fermiophobic Higgs boson

Decays mostly to γγ and WW

LEPHWG combination (2002): ONLY h → γγ

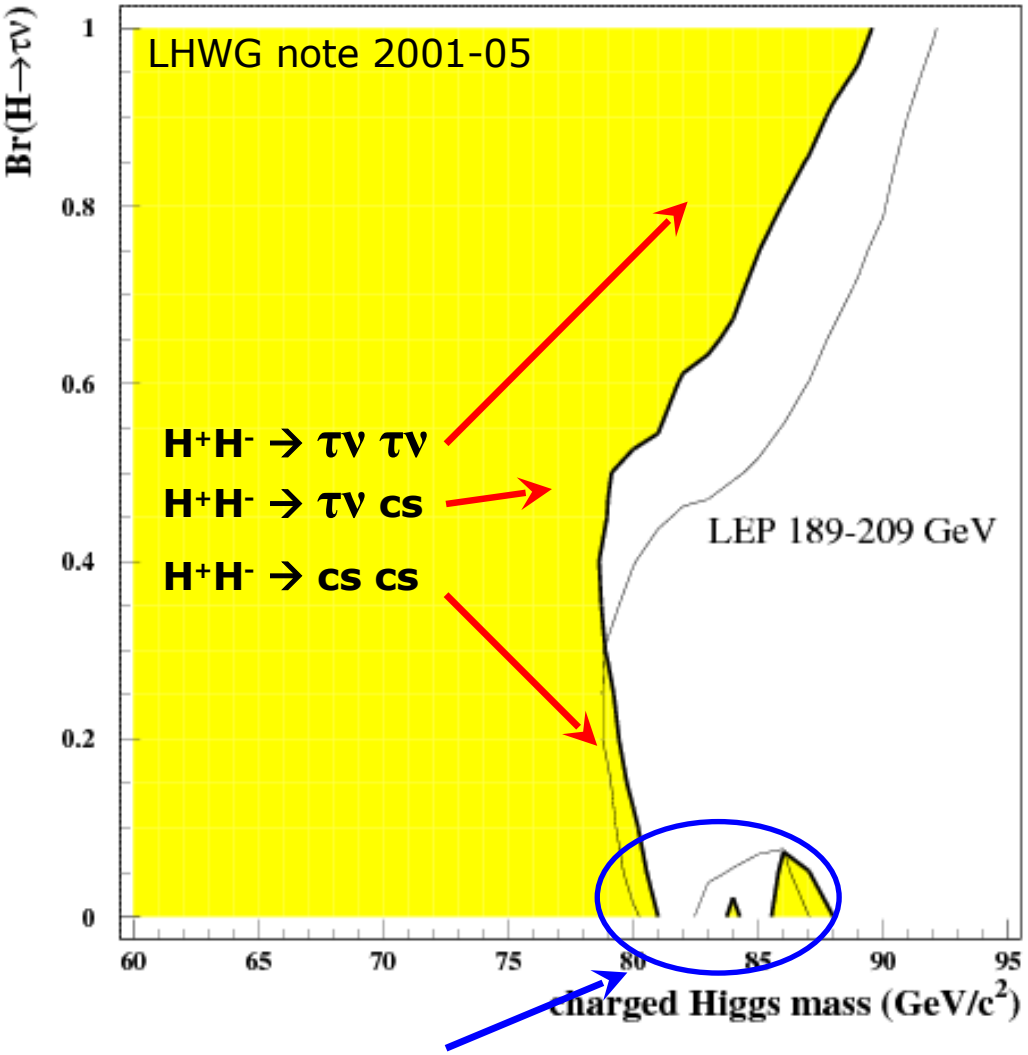






L3 [PLB568(2003)191] and ALEPH [EPJC49(2007)439] have now searched for h→WW and published combined h→γγ+WW limits

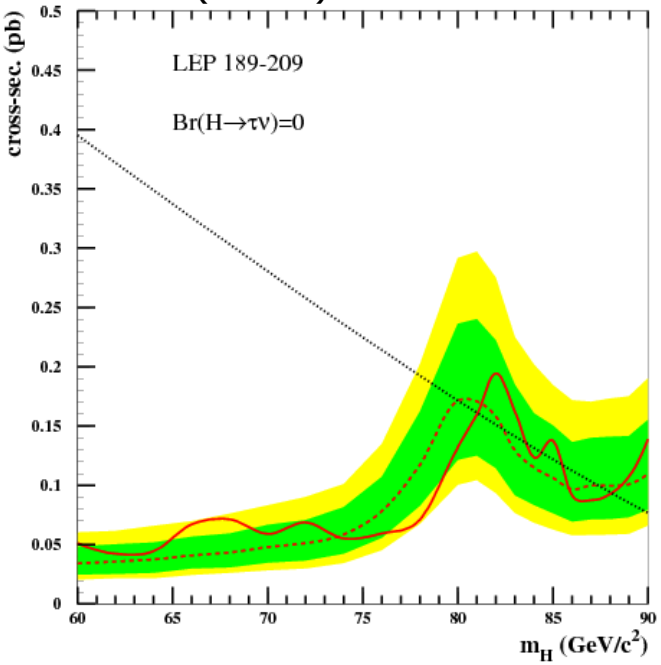
Charged Higgs bosons



95% CL:

$mH^{\pm} > 78.6$ (78.8) GeV

95%CL: σ(H+H-) → cs cs



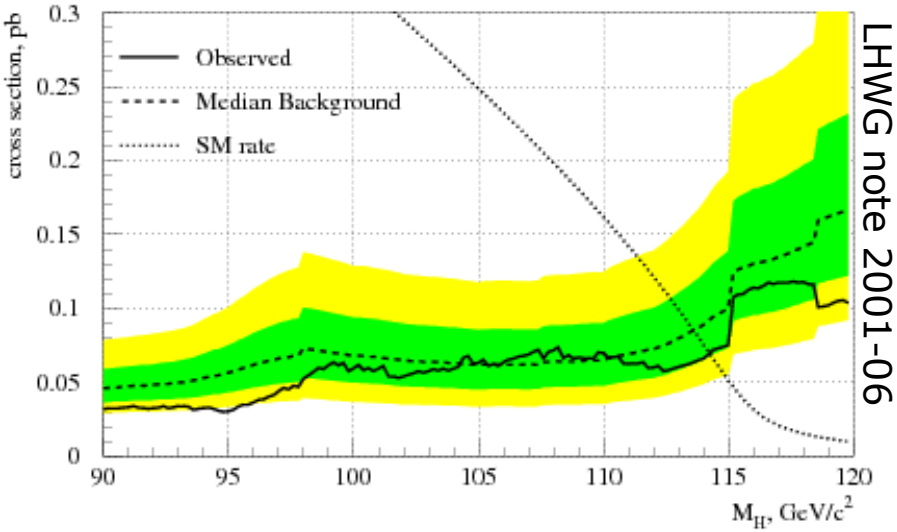
Loss of sensitivity due to multihadronic background from WW → qq qq

Invisible Higgs & Flavour-blind Higgs

Invisible Higgs decays (eg, H → χχ)

- **search for acoplanar jets or leptons from Z → qq, ℓℓ**

95% CL upper bound on $\sigma \times B(\text{inv.})/\sigma_{SM}$:

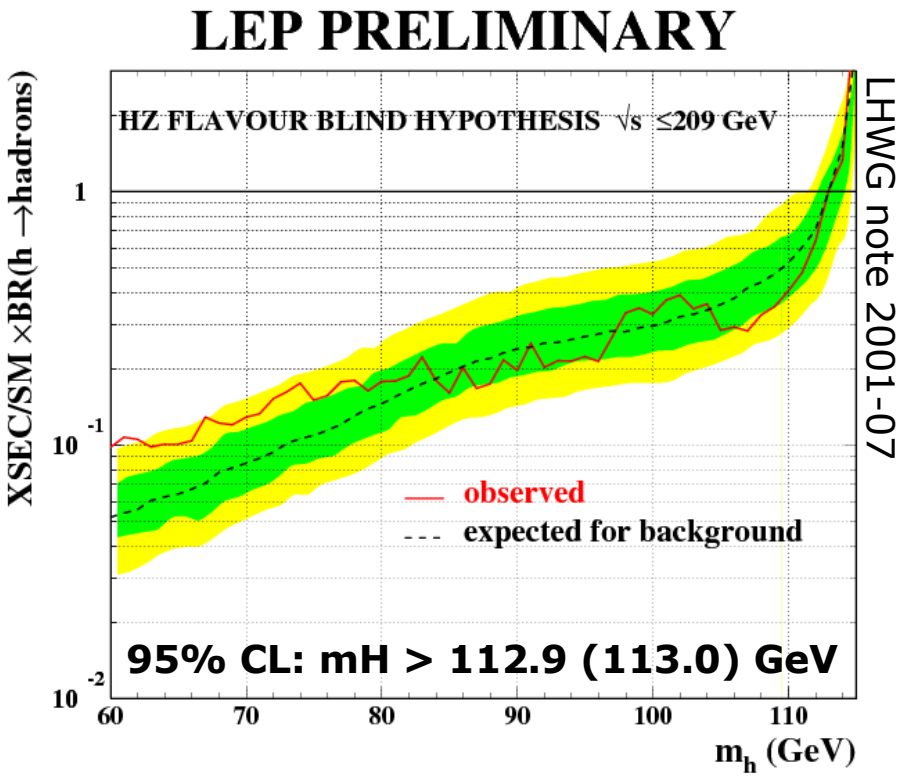


95% CL: mH > 114.4 (113.5) GeV

➔ See talk by **Koichi NAGAI** on OPAL inv. Higgs search (BSM session, Sat. am)

Flavour-independent hadronic Higgs decays

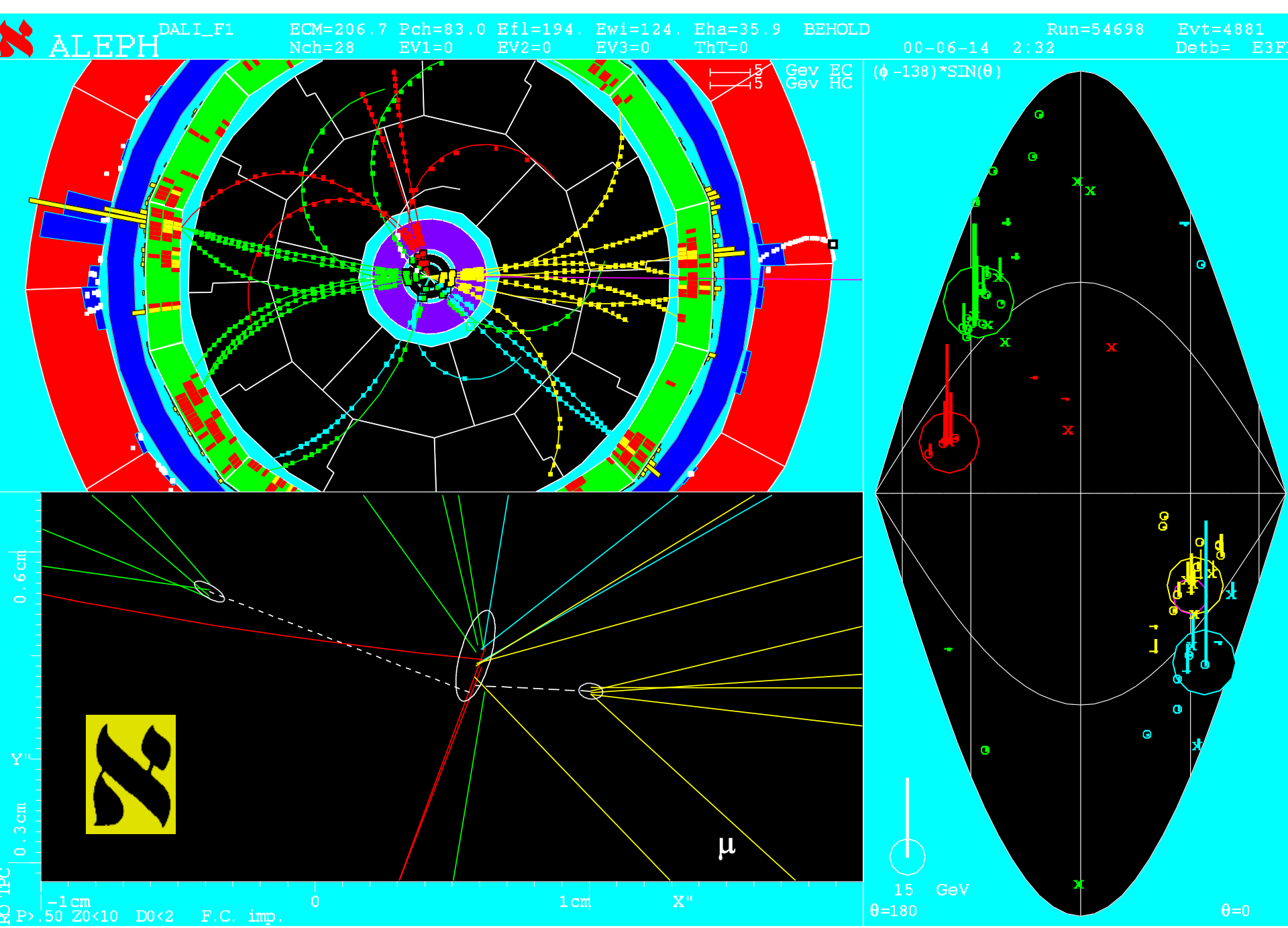
- do not assume h → bb; no b-tagging
- reduced model-dependence
- search for hZ → 4 jets, jj VV, jj ℓℓ



Conclusions

- **Major Higgs search legacy:**
  huge improvement in knowledge before → after LEP
- **Developed advanced analysis techniques and limit setting**
- **Best limit on SM Higgs so far**
  possible hint ? (+light H favoured by EW fits)
- **MSSM benchmarks: strong limits on h/A**
  independent of tan β
- **Wealth of other scenarios tested**
  nothing seen, but significant gaps in CPX benchmark
- **Baton now passed to TeVatron & LHC**
  using similar techniques

Backup slides


ALEPH
DALI_F1
ECM=206.7 Pch=83.0 Efl=194. Ewi=124. Eha=35.9 BEHOLD
Nch=28 EV1=0 EV2=0 EV3=0 ThT=0
Run=54698 Evt=4881
00-06-14 2:32
Gev EC
Gev HC
(ϕ -138)*SIN(θ)
μ
0.6cm
0.3cm
-1cm
0
1cm
X"
P>.50 Z0<10 D0<2 F.C. imp.
15 GeV
θ=180
θ=0

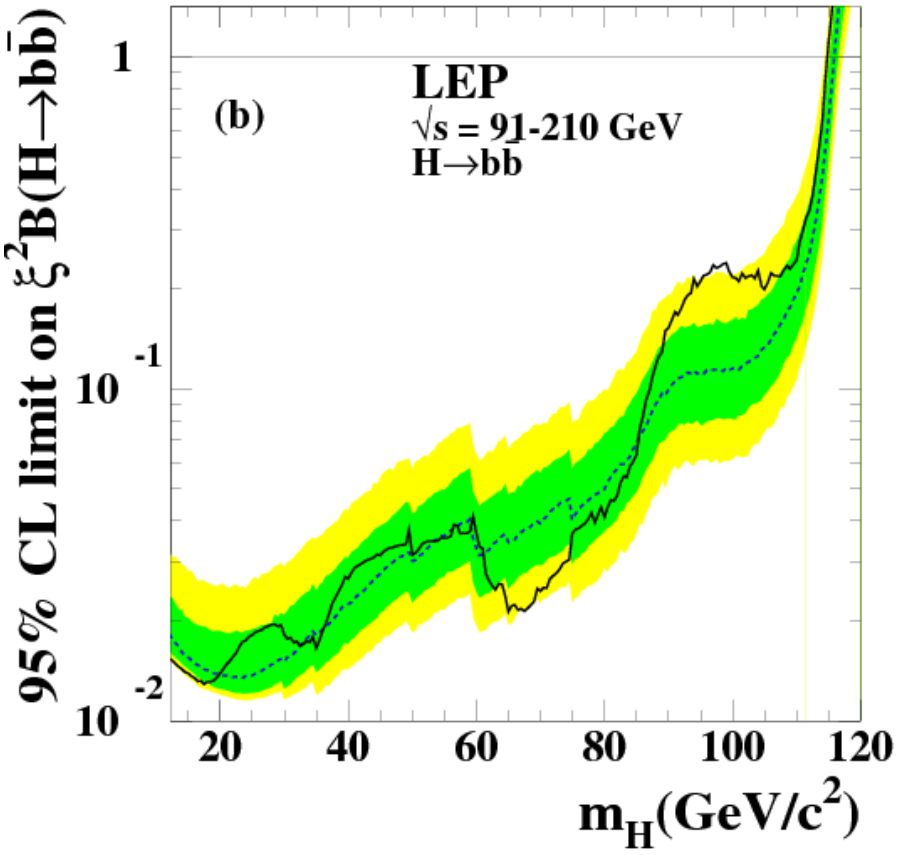
Candidate 54698/4881

(recorded on 14/06/2000)

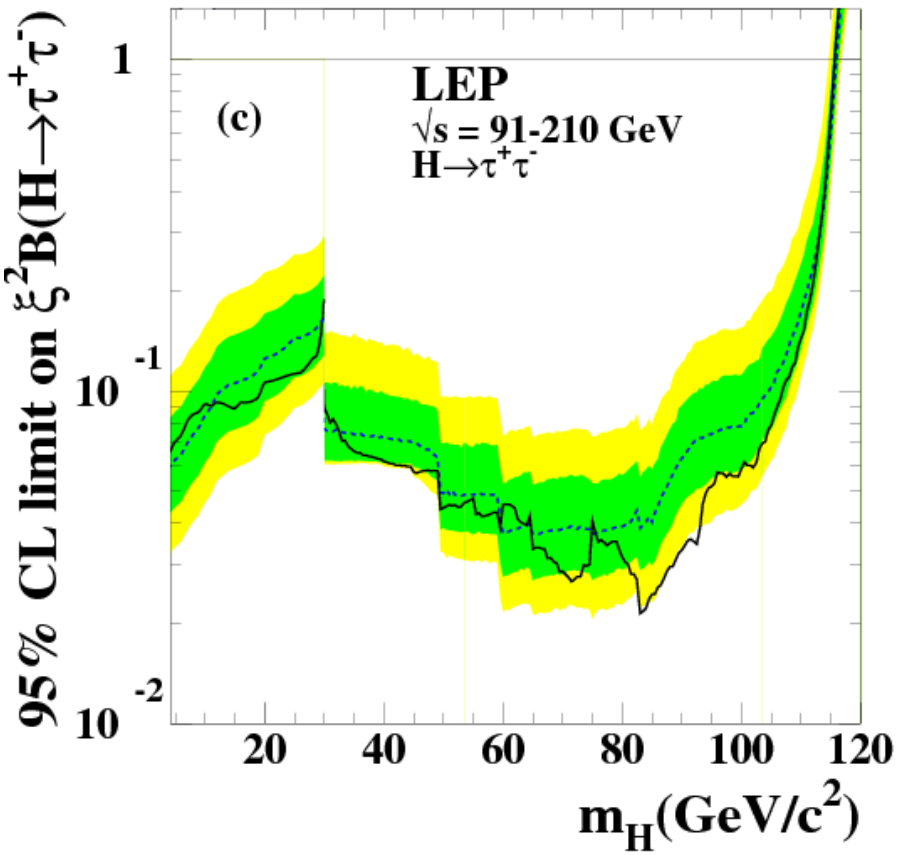
- Properties
  - Two clear b-jets (dec. length, inv. mass of tracks in vertex)
  - Event well-measured: P_{mis} in direction of jet with μ from vertex
  - Planar event, as in threshold production of two heavy particles
  - b-jets: 55GeV & 59GeV, like in a decay almost at rest
  - Non-b jets: 43GeV & 49GeV, like in a Z decay almost at rest
  - Raw invariant mass of non-b jets 92.3GeV
  - non-b jets: leading parton effect, low multiplicity (q vs. gluon)
- Impossible to be a WW, very unlikely to be bbgg, very unlikely a $ZZ^* \rightarrow qqbb$ (and if it is we were very unlucky!)
- One candidate is not a discovery, but if $m_H \sim 116$GeV, this event was the first Higgs ever observed!

Higgs decaying excl. bb or excl. ττ

Higgs decays exclusively to **bb**

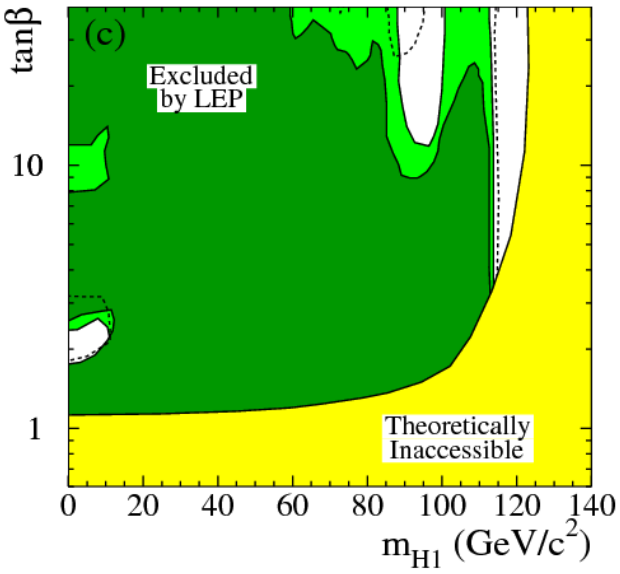


Higgs decays exclusively to **ττ**

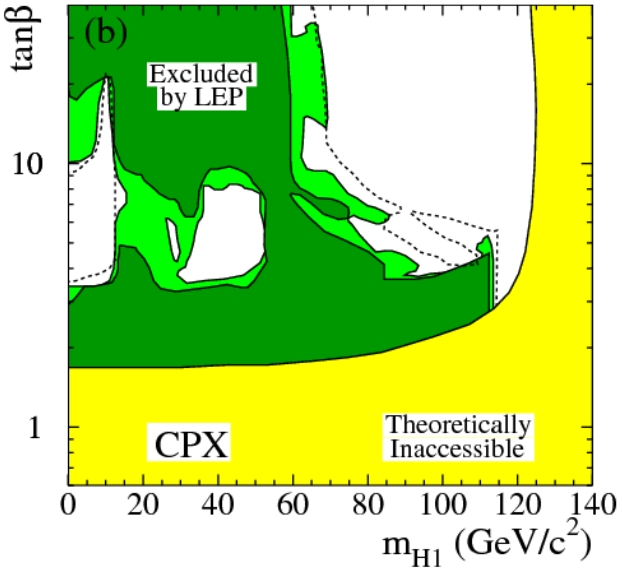


CP-violating scenarios

arg(A) = arg(m_g) = 60°



90° (CPX)



135°