Search for the SM Higgs Boson At LEP

Chiara Mariotti

The Standard Model Higgs

The experimental data test the Standard Model at
the **per mille** level

Yet the Higgs boson has not been discovered

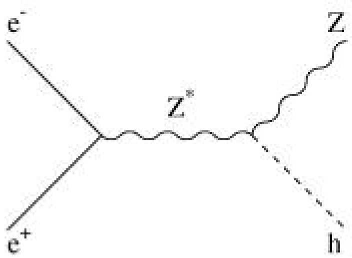
The existence of the Higgs boson is well supported by the data on radiative corrections

But what is the value of its mass?

The Theory
The Precision Measurements
THE DIRECT SEARCH

LEP: the ideal place

Higgsstrahlung

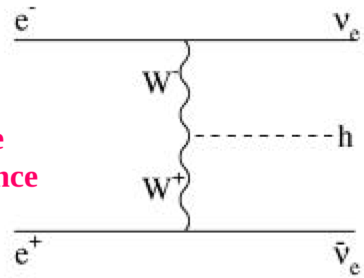


Dominant mode

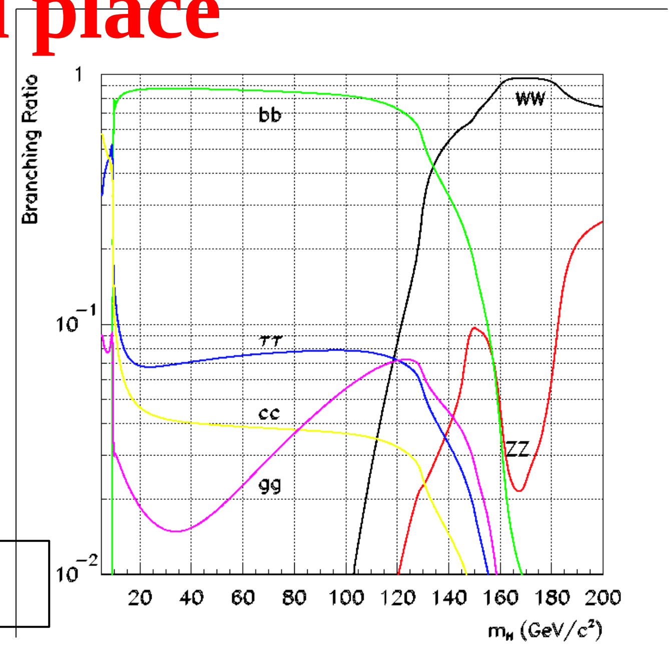
$m(H) \le \sqrt{s} - m(Z)$

WW fusion

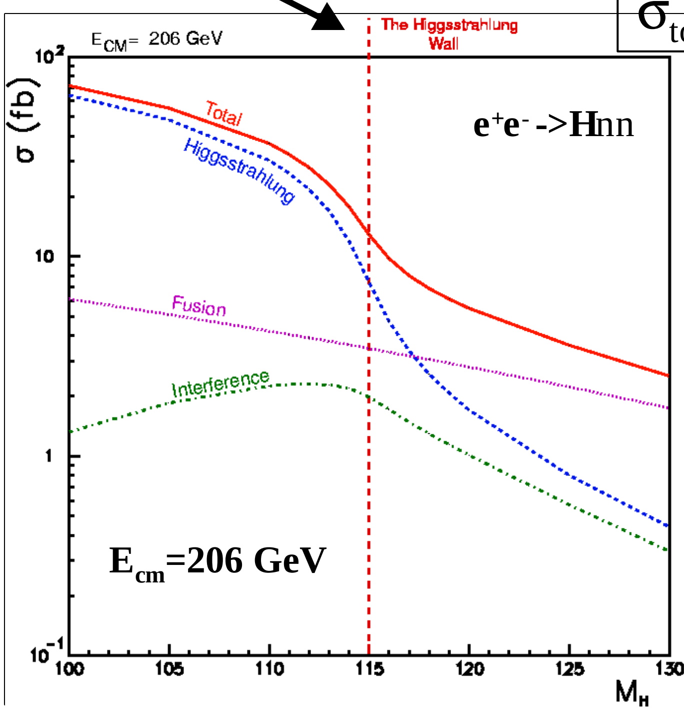
+ positive interference

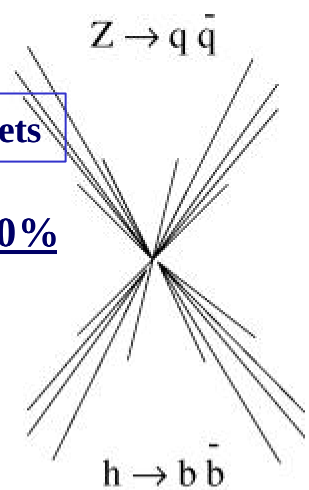


possibility to go beyond !



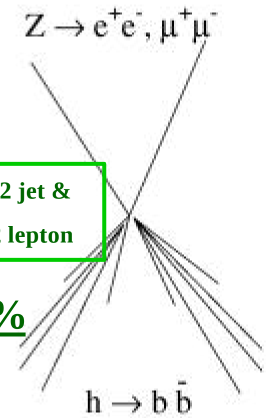
$\sigma_{tot}(m_H=115) \sim 40$ fb





4 jets

60%



2 jet & 2 lepton

6%

2 jets & missing energy

19%

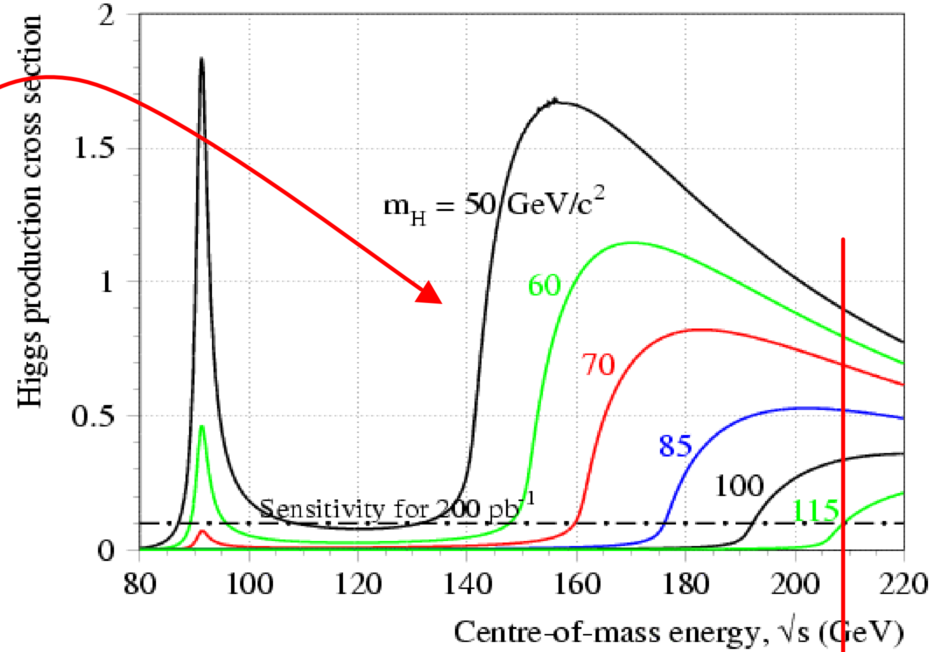
Or a t instead of the b

LEP: the ideal place (2)

Direct Searches:

LEP is the perfect machine to search for the Higgs

IF **m(Higgs) < E_{cm} – Mz**



At LEP1 : 1989-1995, E_{cm} = 91 GeV
H->ll,qq
m(Higgs) > 65 GeV /c^2 at 95%CL

At LEP2 : 1995-2000, E_{cm} = 130 – 209 GeV
***L* > 2.5 fb^{-1} @ E_{cm}> 187 GeV**

Indirect Searches:

Information from LEP precision measurements:

m(H) = 81 +53 – 30 GeV/c^2

m(H) < 193 GeV/c^2 at 95%CL

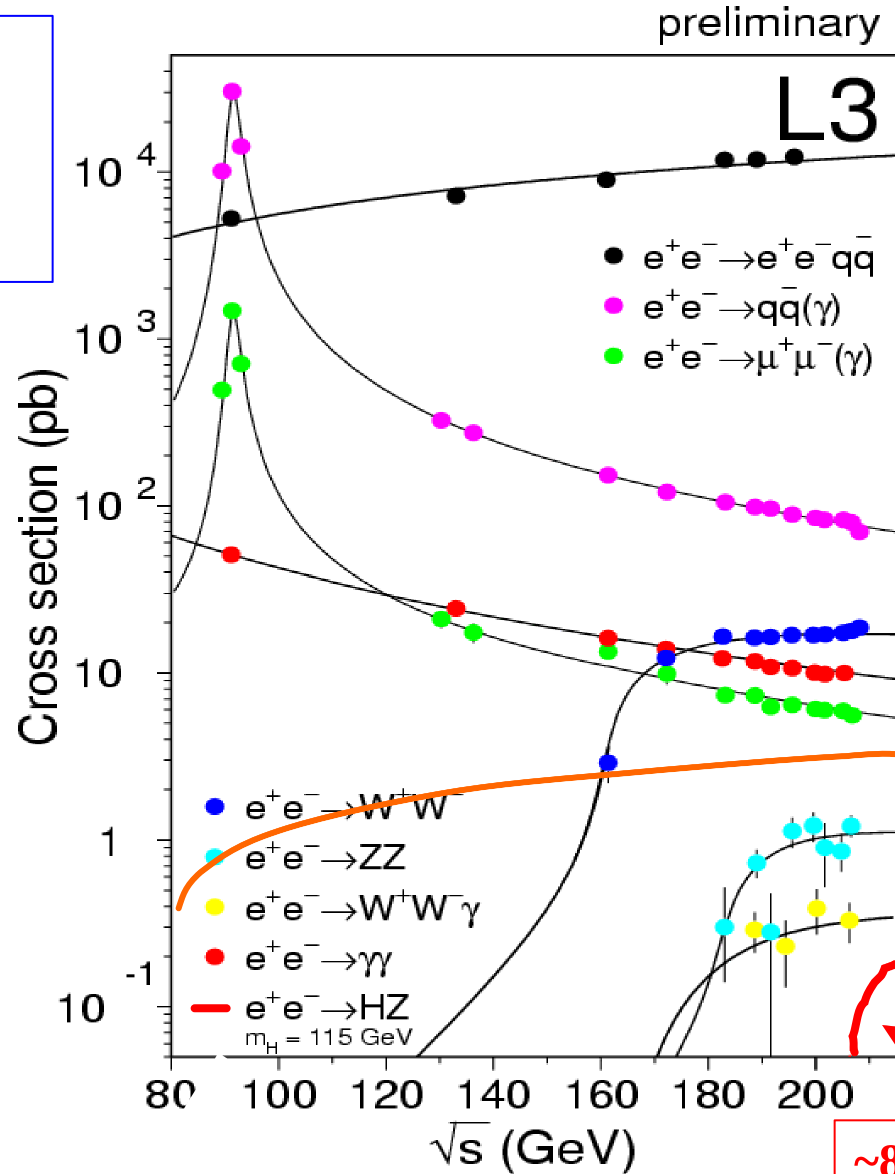
But… a very small cross section

qq(g) is
the dominant s
but easy to reduce
Except….

Hermeticity

eeZ
en W
missing
energy

Energy flow



WW is
dominant
in 4-jets

mass

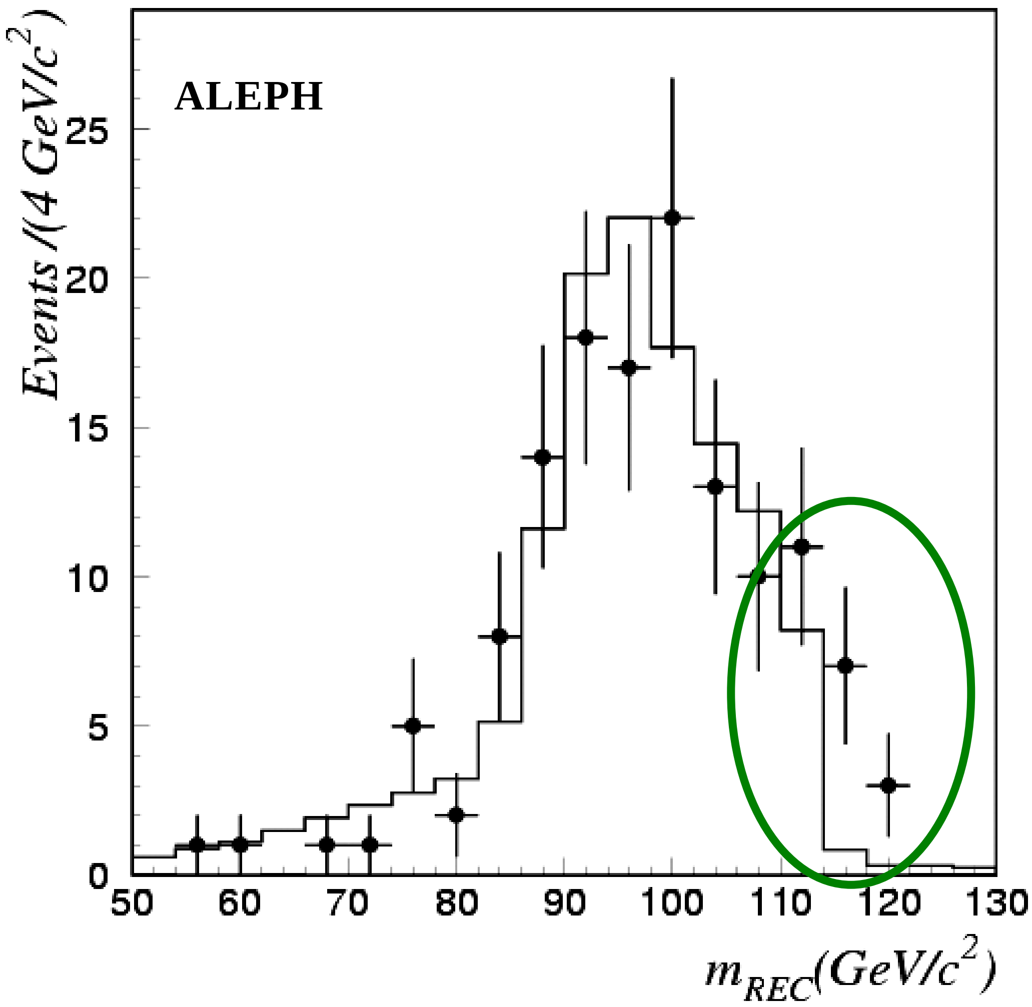
ZZ is
sometimes
irreducible

Higgs of
115 GeV/c^2

~8 events per exp

The challenge of the search: the control of the tails

Pre-selection level



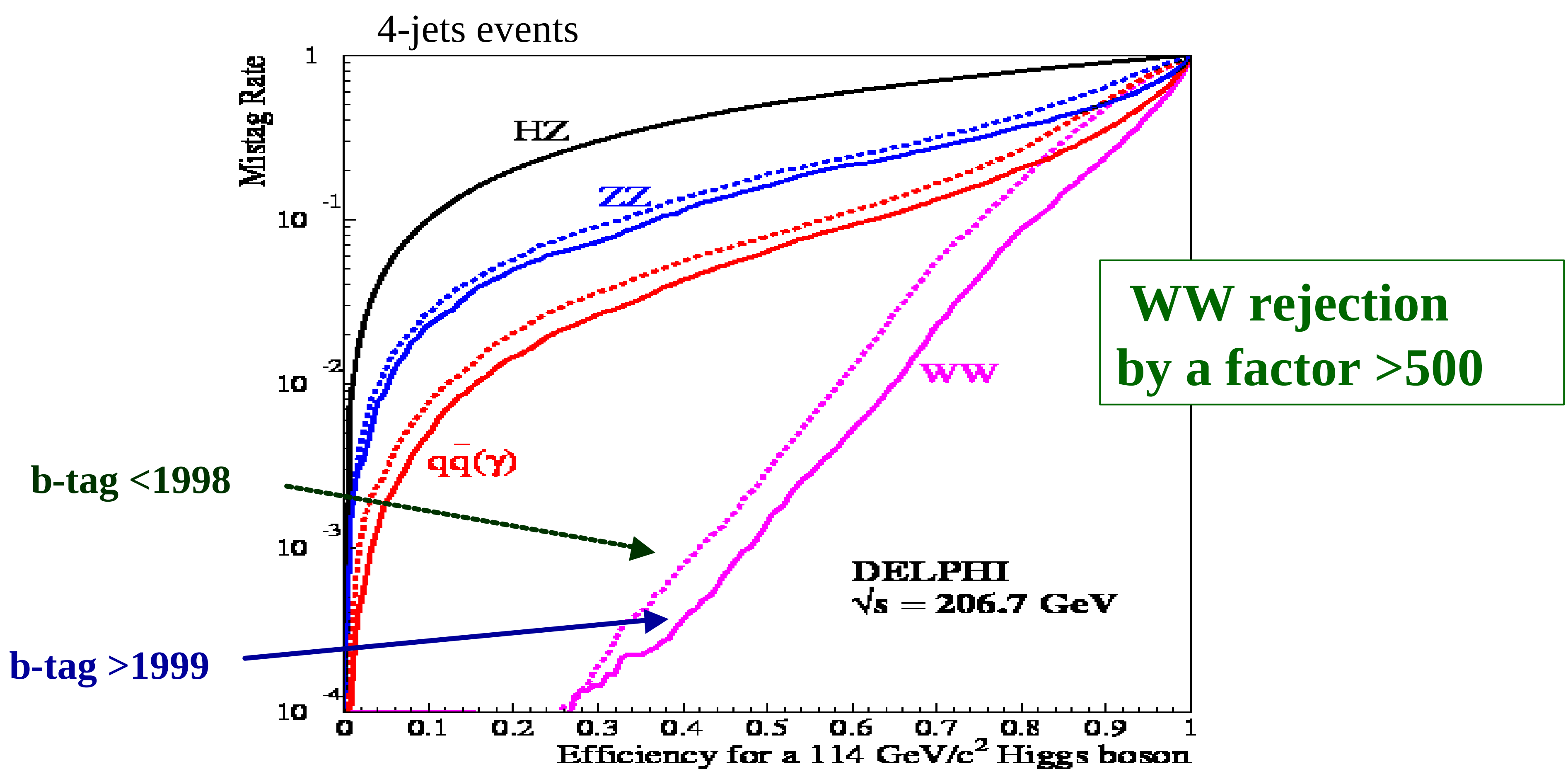
All the significant variables
Should be well understood.

The mass reconstruction depends heavily on the good calibration of the detectors (tracking, calorimetry..) and on software techniques…

… and the b-tagging

from the power of the micro-vertex to the software techniques

all we have learned in 10 years is used in the Higgs search:



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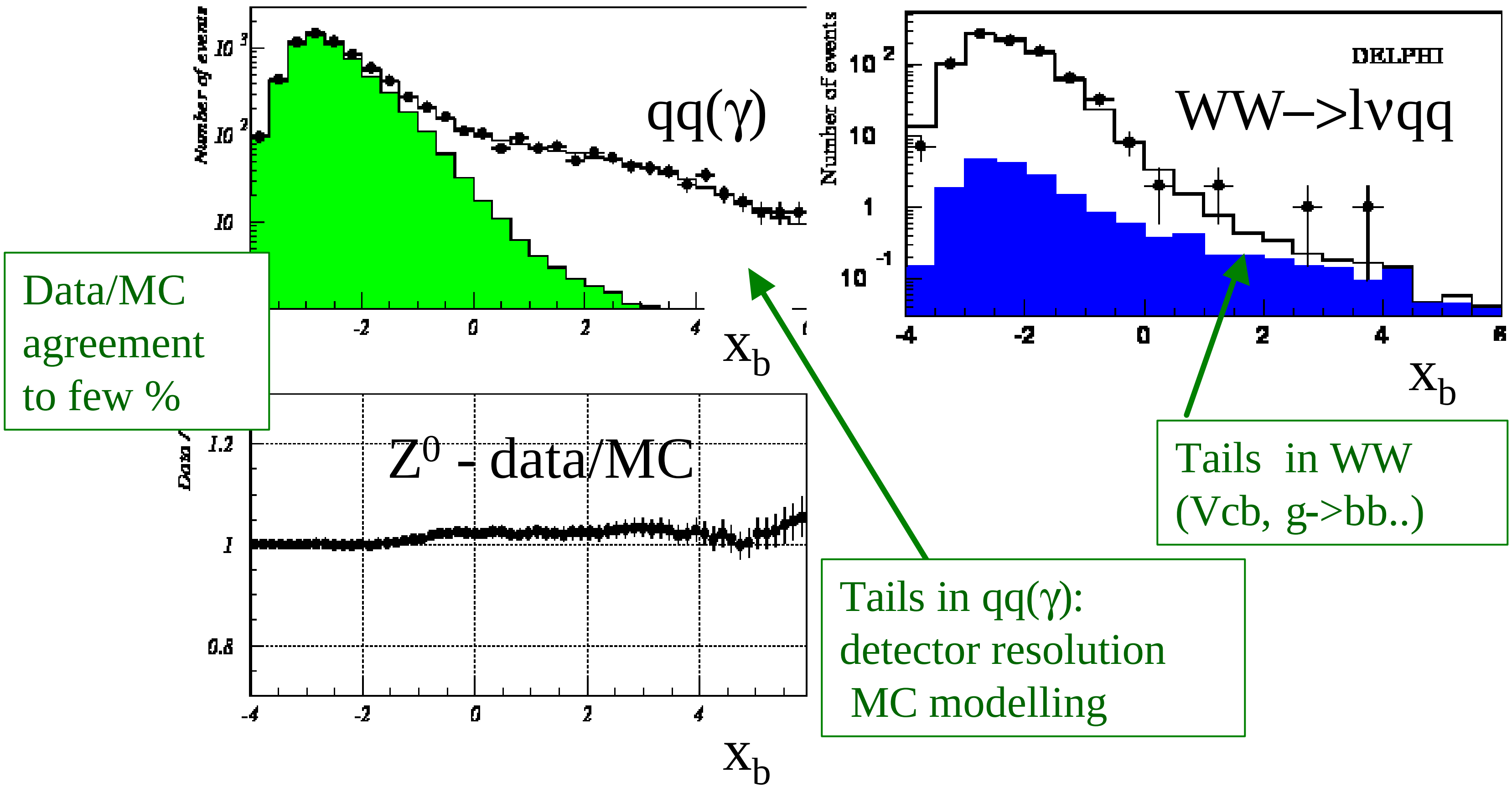
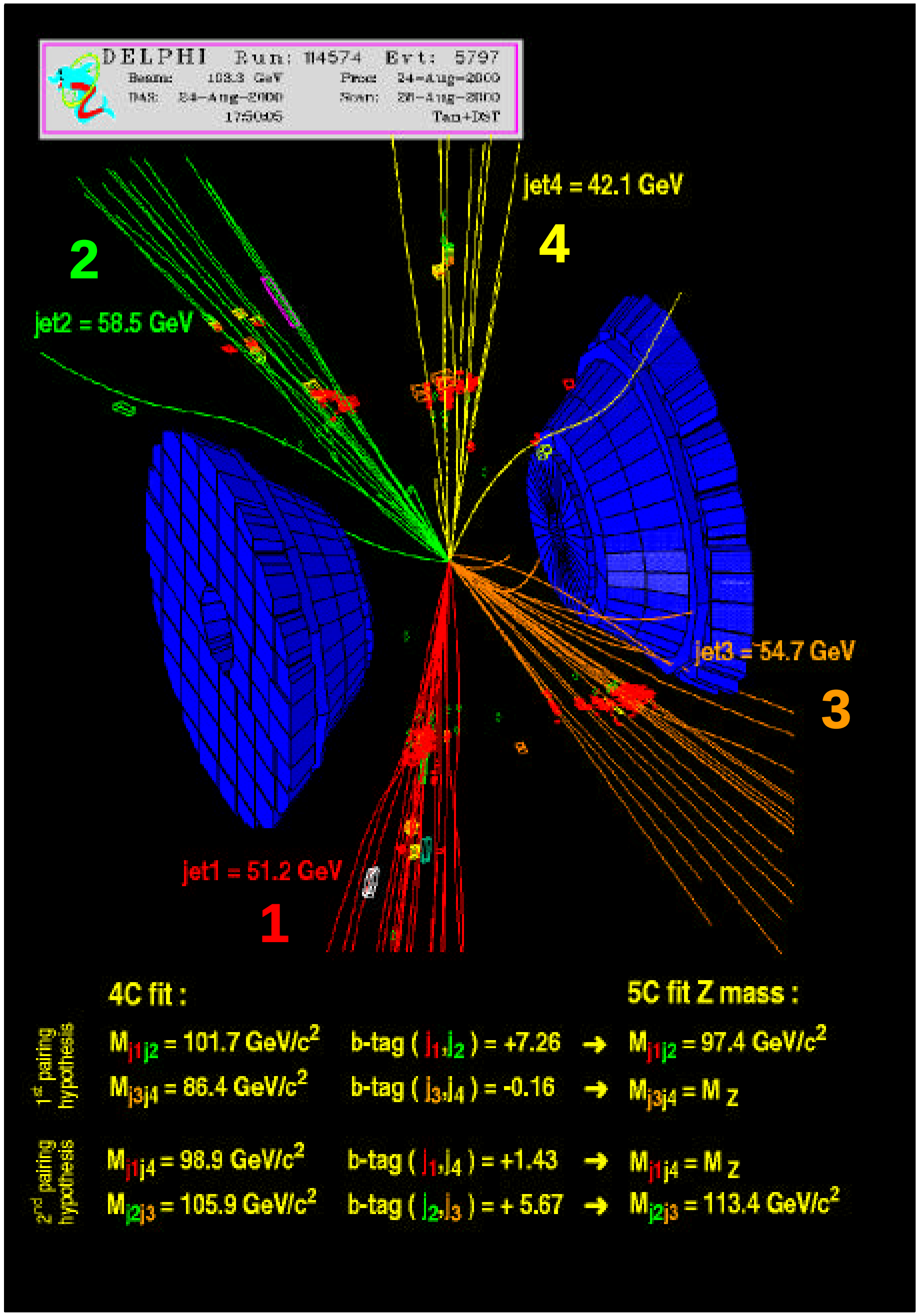


The search of the SM Higgs ⇒ a "precision measurement"



from Jesus Marco, Budapest

The 4 jets channel: pairing & mass reconstruction

six possible pairings:

H dijet	**(1,2) M=97 B=5.7**	**(1,3)**	**(1,4)**	**(2,3) M=113 B=3.4**	**(2,4)**	**(3,4)**
Z dijet	**(3,4) M=M$_Z$ B=-0.5**	**(2,4)**	**(2,3)**	**(1,4) M=M$_Z$ B=2.0**	**(1,3)**	**(1,2)**

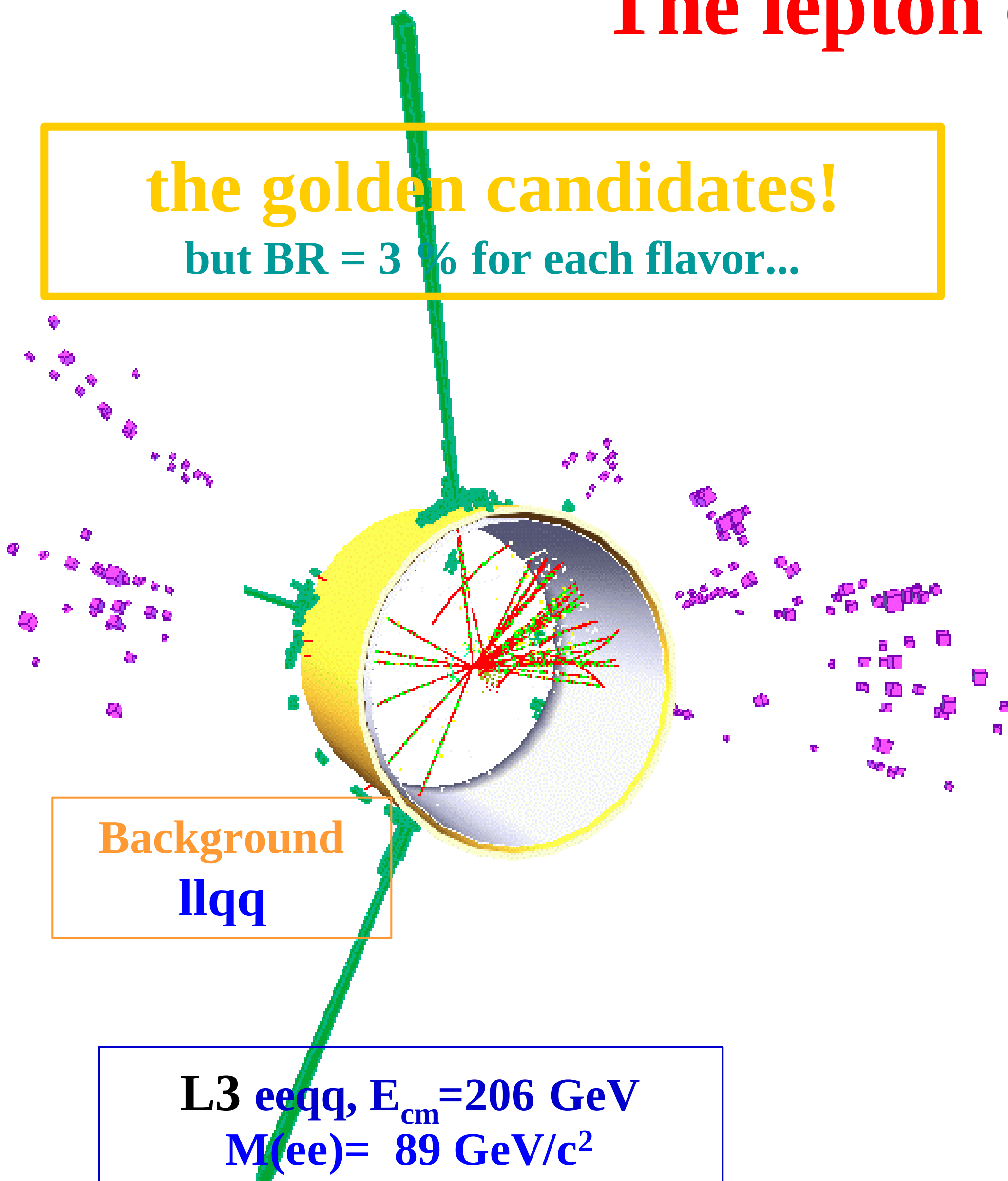
•For each pairing,
make a 5C fit with $M_{ij} = M_Z$
& build a likelihood including the probability that the two other jets are b-tagged coming from the Higgs decay.

•A unique mass value is selected from the most likely combination

The lepton channel

the golden candidates!

but BR = 3 % for each flavor...

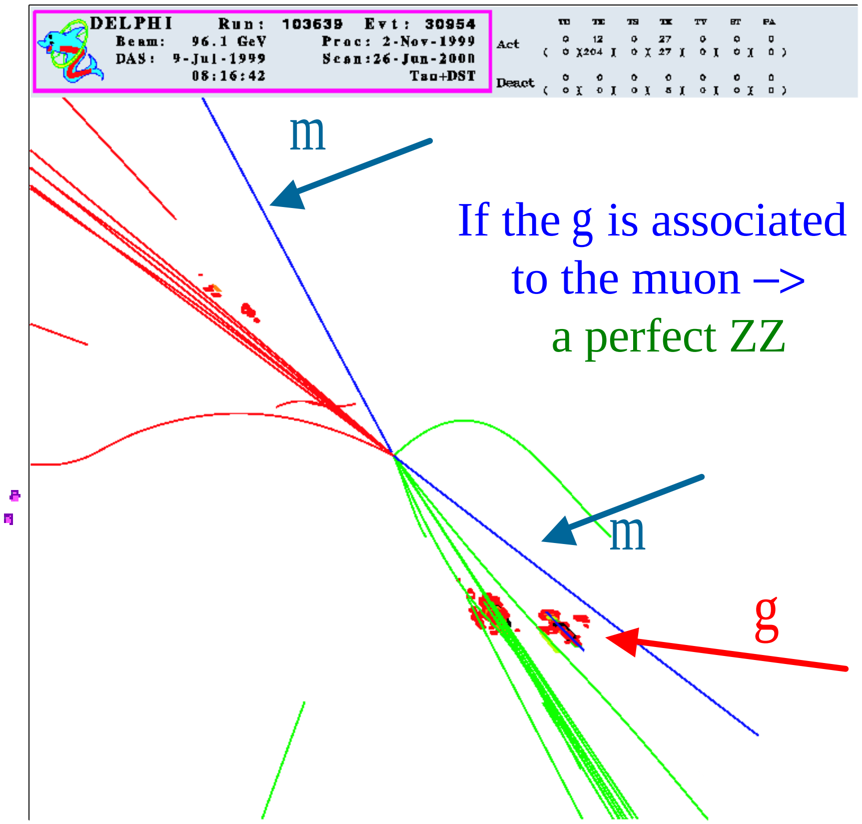


Background

llqq

L3 eeqq, E_{cm}=206 GeV
M(ee)= 89 GeV/c²
M(qq)= 108 GeV/c²

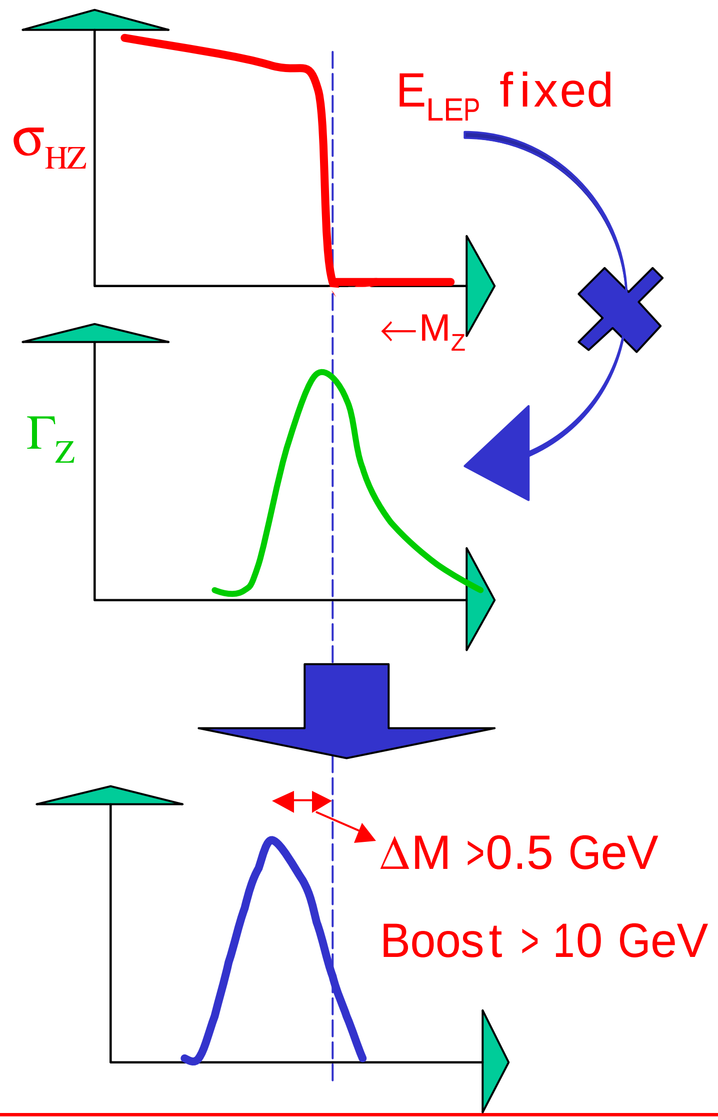
but…radiated photons



If the g is associated
to the muon –>
a perfect ZZ

If the g is included in the jet:
a very high di-jet mass –>
good high mass Higgs candidate !

Hnn: an irreducible background, ee->bb

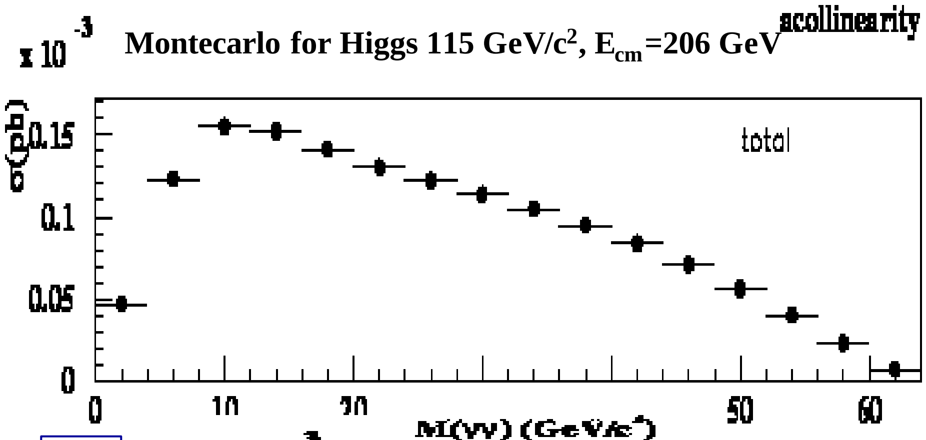


Hnn: an irreducible background, ee->bb

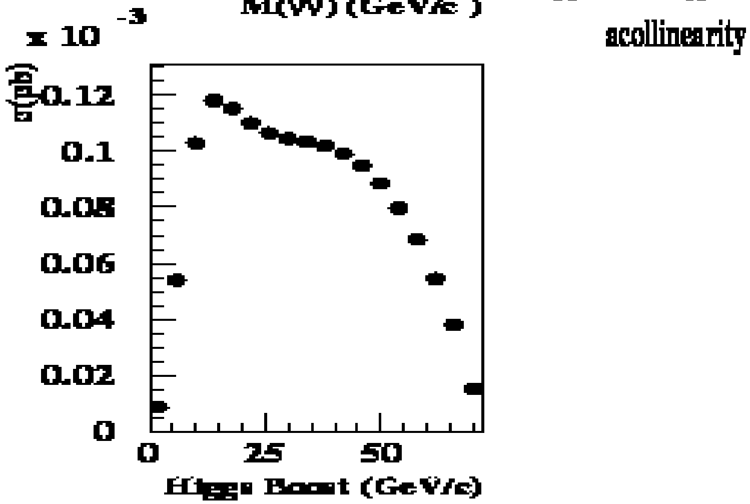
The signal is not collinear !

for acollinearity < 5°
5% of Higgs σ ~ 0.015 pb
30% of qq(g) σ ~ 80 pb

Montecarlo for Higgs 115 GeV/c², E_{cm}=206 GeV



WPHACT



The collinear events are:

- **-Zgg double radiative events to the Z with (visible mass ~M(Z))**
- **-qq where the energy is lost in n or for detector problems, (high visible mass)**

at 206 GeV 6×10^{-4} ee -> qq
5×10^{-4} ee -> bb
loose > 60 GeV in neutrinos:

In 2000 for L= 220 pb^{-1}, every exp. has ~10 events ee ->bb that loose more than 60 GeV in neutrinos

Of these 10 evts , 80% have p_T>10 GeV

The new results

All 4 experiments implemented various modifications in order to improve the sensitivity and/or better control the background

- Full data processing: final detector calibration, alignment, b-tagging…
- New MC generators (DELPHI) , more MC statistics (all)
- Precise knowledge of the LEP cm energy (all)
- Upgrades for some analyses:
  - New analyses with better sensitivity (OPAL):

    new jet pairing (4- jet), and L –> NN(miss.ener)
  - Better rejection of beam-related background (ALEPH)
  - Extension of analyses down to bb threshold (DELPHI)

L3: final result already last year :

Few candidate events compatible with the Higgs hypothesis

ALEPH: **Excess of events compared to what is expected from SM background, suggesting a Higgs boson with mass m_H~114 GeV/c^2**

DELPHI: **No evidence for any Higgs signal, limit set to m_H> 114.1 GeV/c^2**

OPAL: **No evidence for any Higgs signal, limit set to m_H> 112.7 GeV/c^2**

The statistical procedure

LEP HIGGS WG

The data from all channels (**Hqq, H**nn**, Hll, qq**t t) at all E_{cm} are combined in a 2-Dimensional space:

- reconstructed Higgs mass $\mathbf{M_H^{rec}}$
- discriminant variable **G** (b-tag, kinematical info..)

In each bin of M_H^{rec} and G:

- Background (MC) $\mathbf{b_i}$
- Signal (MC) $\mathbf{s_i}$
- Num. of candidates $\mathbf{N_i}$

For each "test mass" m(H)

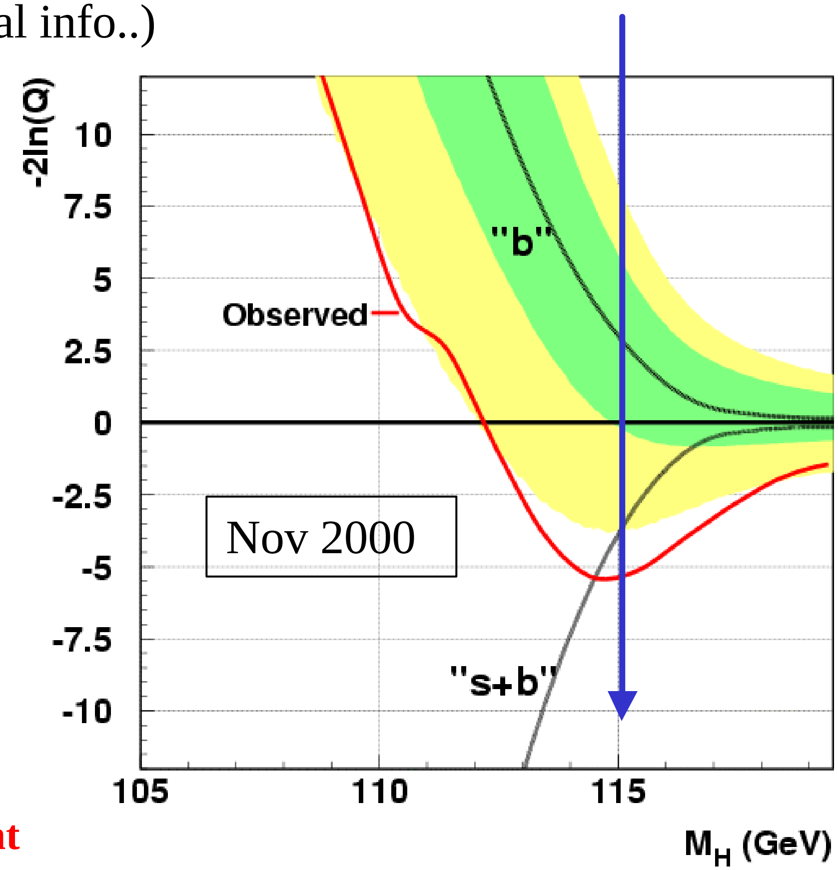
LIKELIHOOD TEST :

"sig+bkgr " Û **'bkgr"**

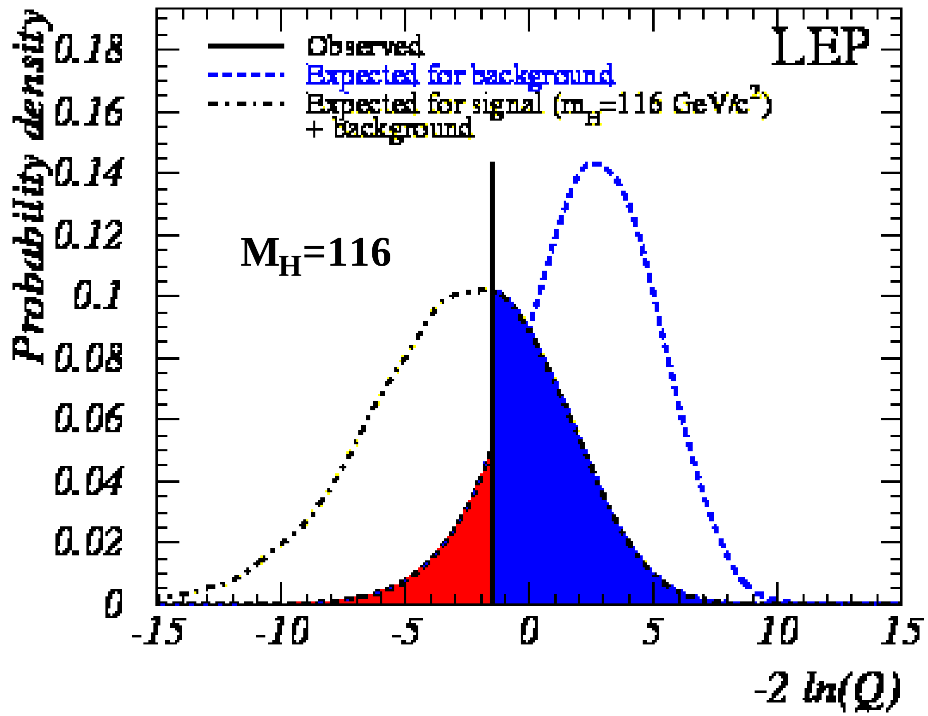
$$\ln Q(m(H)) = - S_{tot} + \text{å}\ N_i \ln[1+s_i (m(H)) / b_i]$$

W_i of the event

$$Q(m(H)) = L(s + b) / L(b)$$ **"test statistic"**



Confidence Level

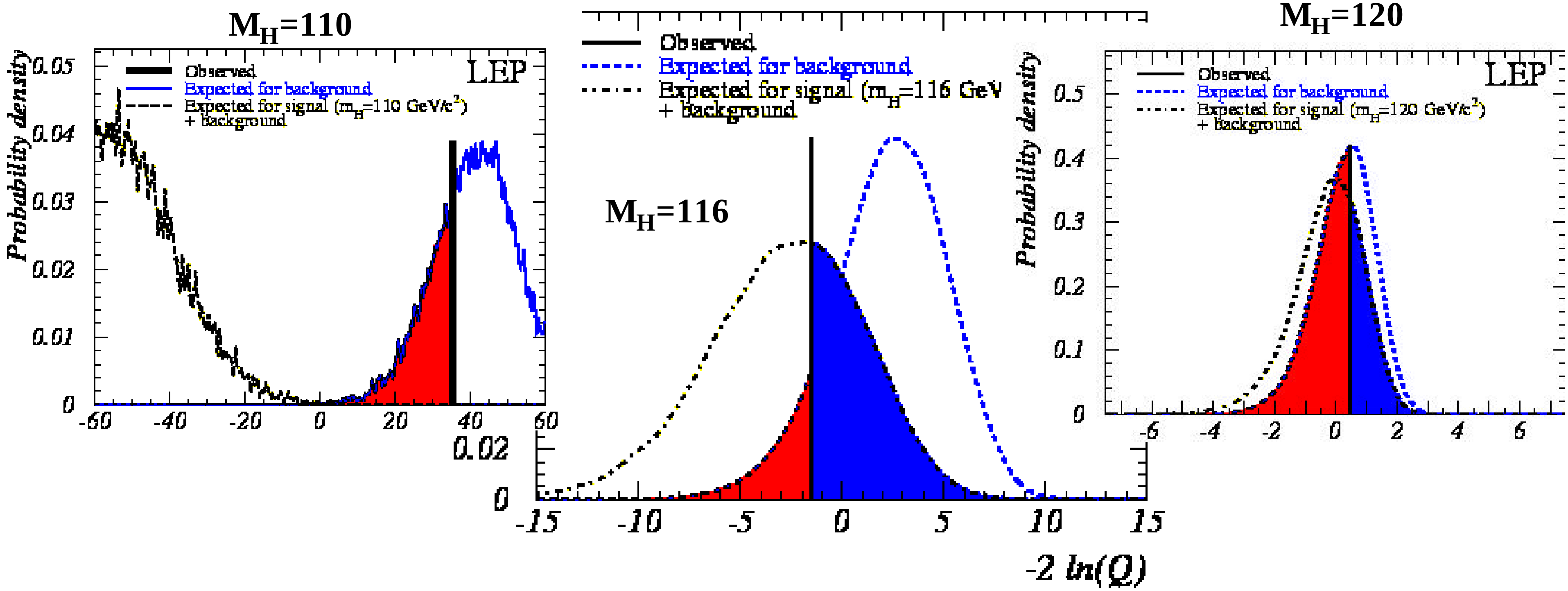


- $1 - CL_b$: a measure of incompatibility with “b”

$1 - CL_b$	0.32	0.064	2.7×10^{-3}	6.3×10^{-5}	5.7×10^{-7}
	1s	2s	3s	4s	5s

- CL_{s+b} : a measure of compatibility with “s+b”
- $CL_s = CL_{s+b} / CL_b$ gives the lower bound on Higgs mass

Confidence Level



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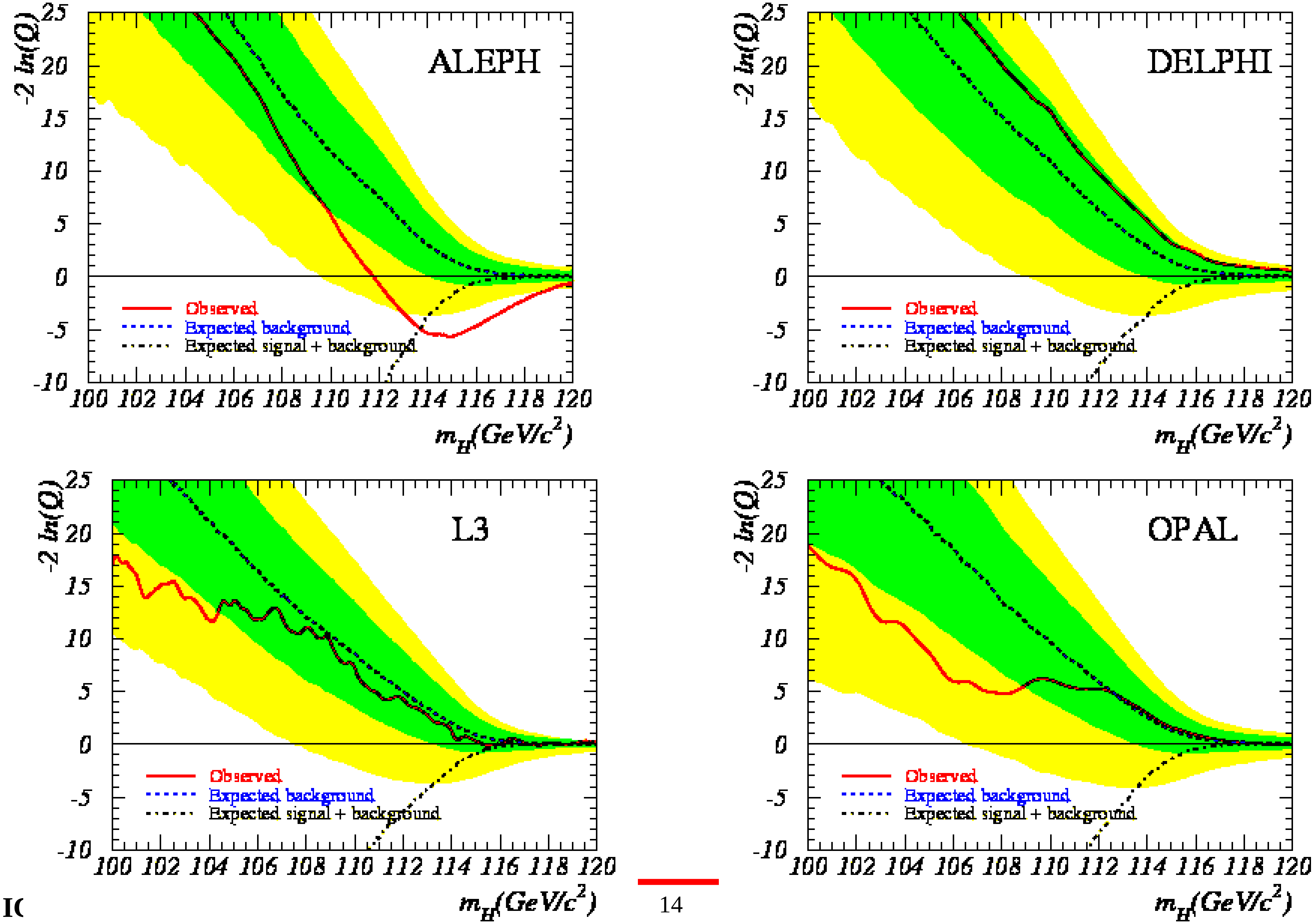
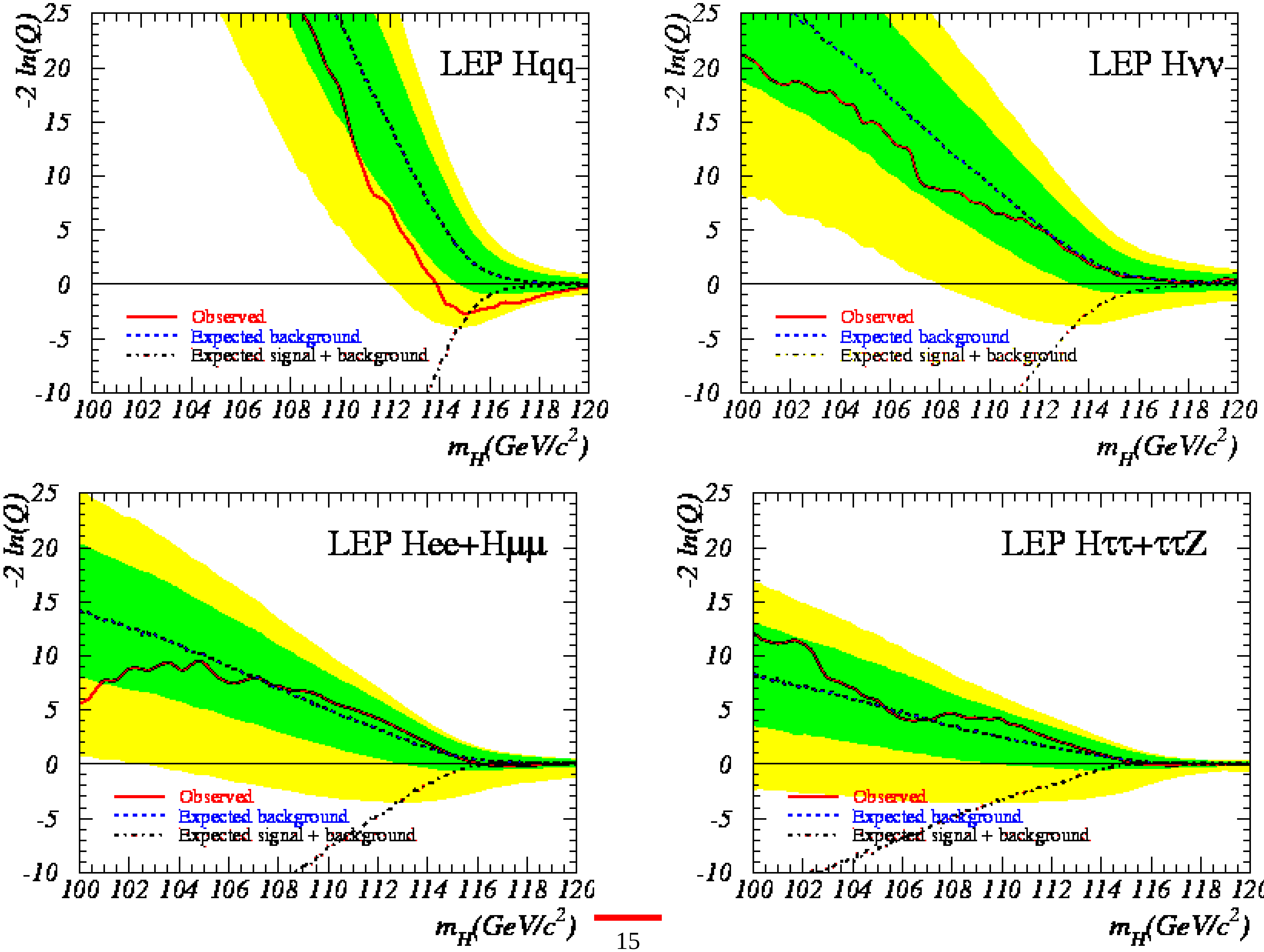
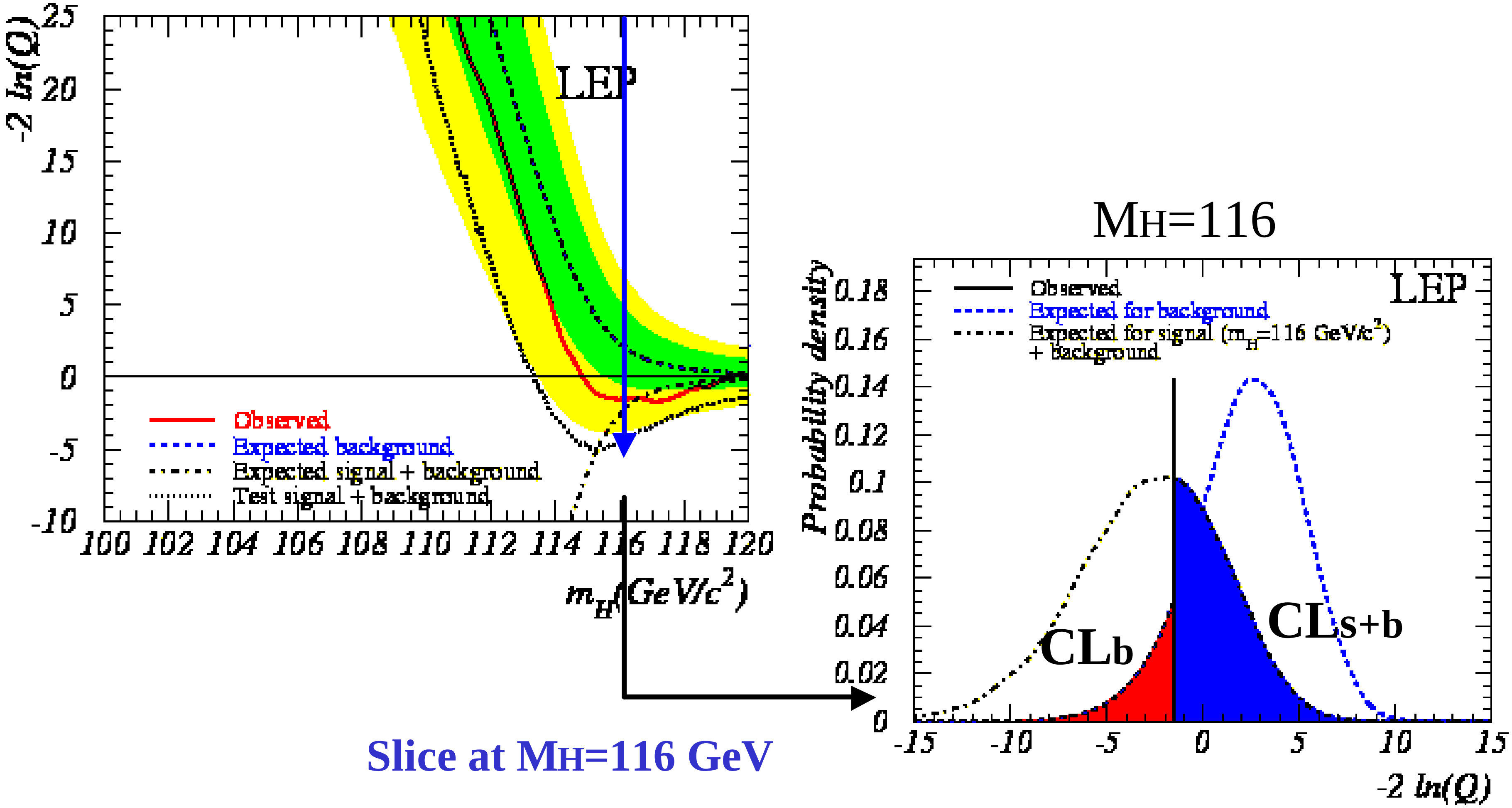
The results of each experiment



The results per channel

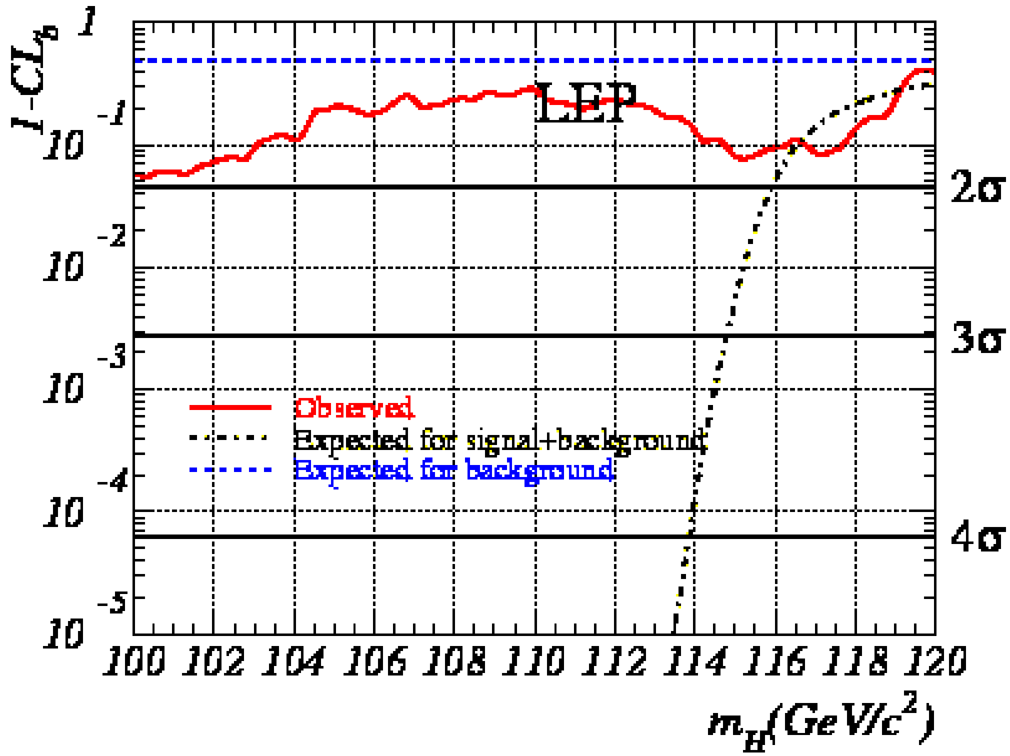


The combined LEP result



Slice at MH=116 GeV

Compatibility with the background



$1\text{-}CL_b$ @ M_H=116 GeV/c^2

ALEPH	**2.4×10^{-3}**
DELPHI	**0.874**
L3	**0.348**
OPAL	**0.543**
LEP	**0.099**

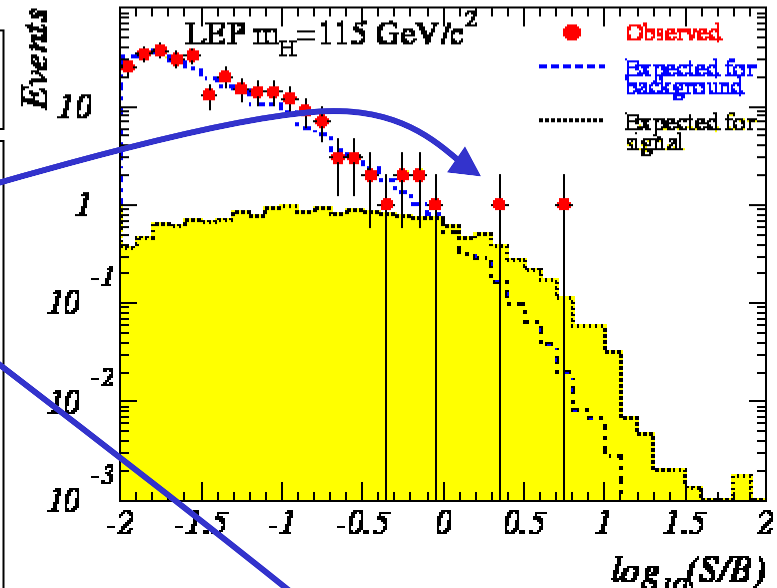
4-jets	**5.7×10^{-3}**
l+n+t	**0.368**

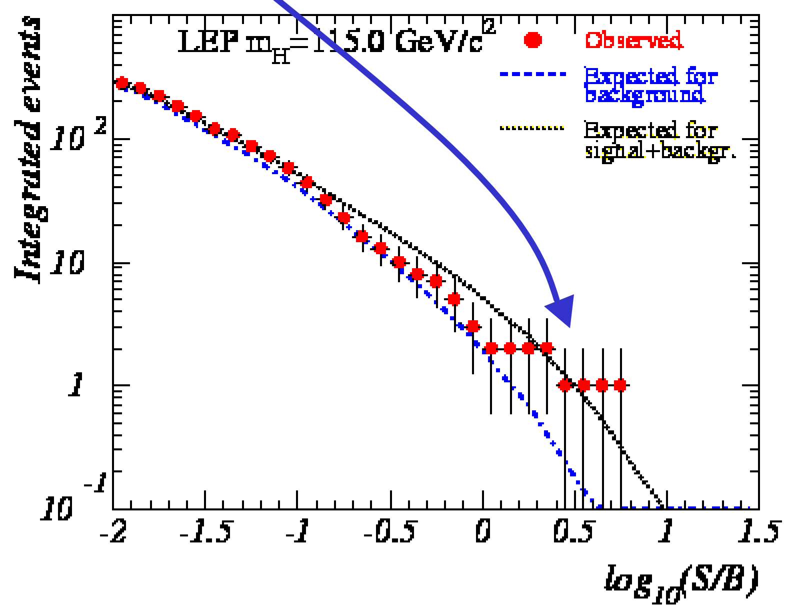
Neutrinos	**0.474**
Leptons	**0.275**
Taus	**0.255**

CL_{s+b} (Mh=116) = 0.37

The events

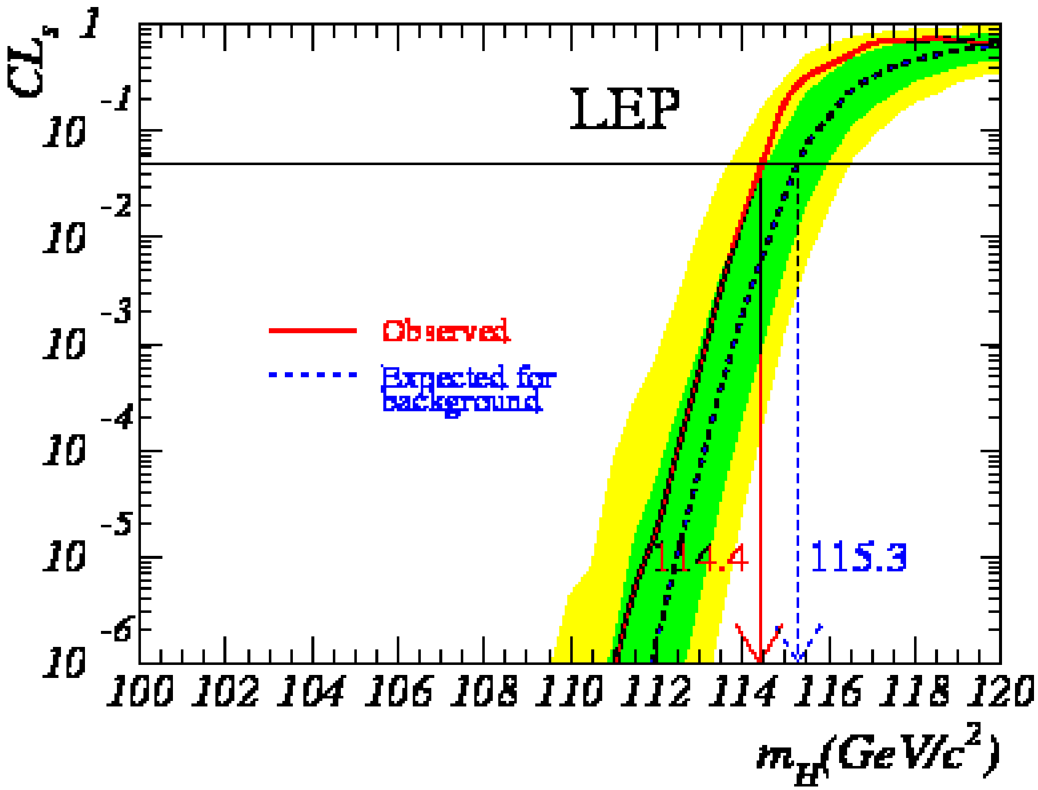
	Expt	E_{cm}	channel	M^{rec} (GeV)	$\ln(1+s/b)$ @ 115 GeV	prev. rank.
1	A	206.6	4 jet	114.1	1.76	1
2	A	206.6	4 jet	114.4	1.44	2
3	A	206.4	4 jet	109.9	0.59	3
4	L	206.4	Emiss	115.0	0.53	4
5	A	205.1	Lept.	117.3	0.49	7
6	A	206.5	Tau	115.2	0.45	8
7	O	206.4	4 jet	108.2	0.43	5
8	A	206.4	4 jet	114.4	0.41	9
9	L	206.4	4 jet	108.3	0.30	12
10	D	206.6	4 jet	110.7	0.28	
11	A	207.4	4 jet	102.8	0.27	14
12	D	206.6	4 jet	97.4	0.23	11
13	O	201.5	Emiss	111.2	0.22	
14	L	206.0	Emiss	110.1	0.21	17
15	A	206.5	4 jet	114.2	0.19	
16	D	206.6	4 jet	108.2	0.19	
17	L	207.0	4 jet	109.6	0.18	





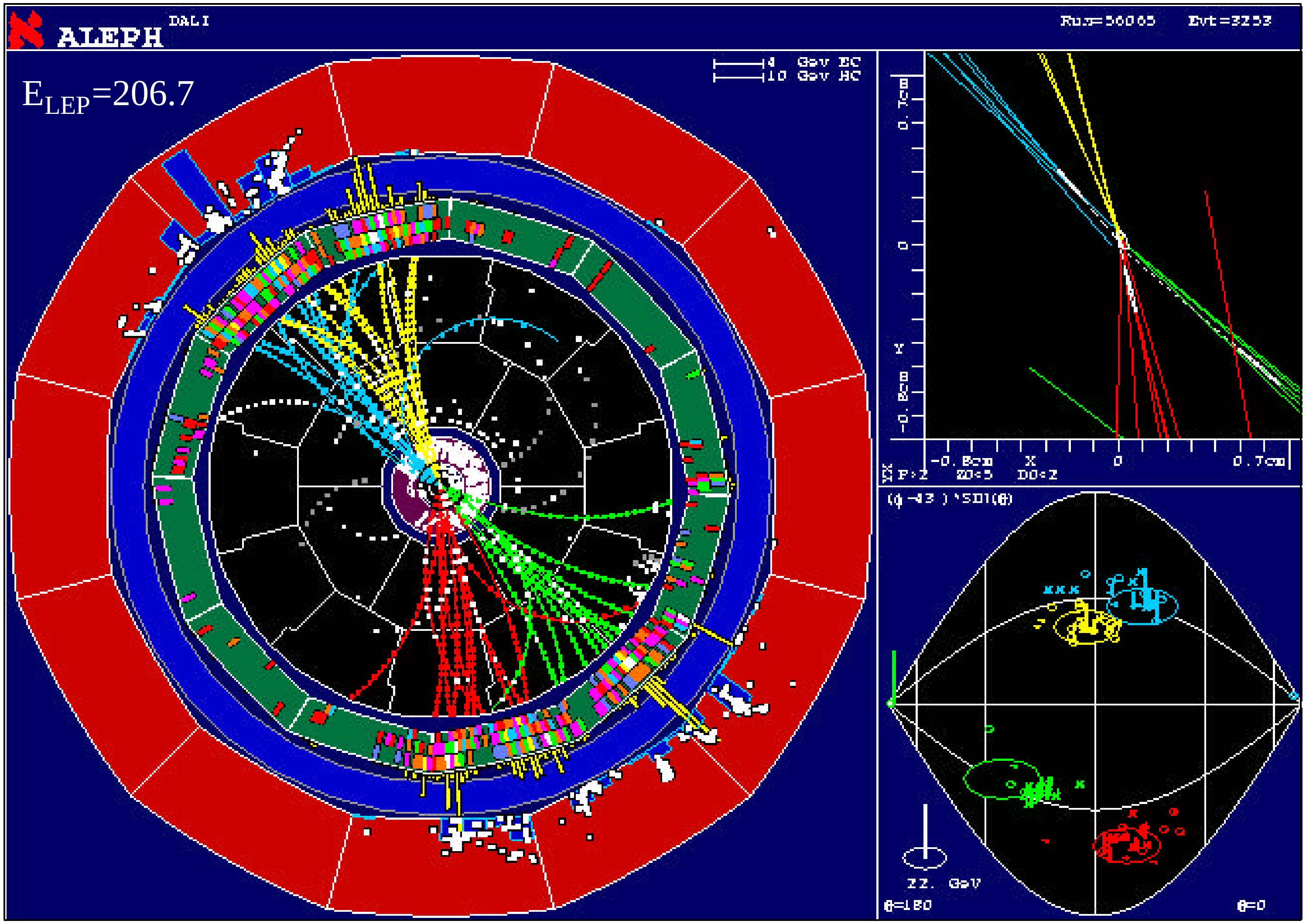
The first 4 events maintain the highest weight in the final analyses

The combined limit



	Exp	Obs
ALEPH	113.5	111.5
DELPHI	113.3	114.1
L3	112.4	112.0
OPAL	112.7	112.7
LEP	**115.3**	**114.4**
4-jets	114.5	113.3
l+n+t	114.2	114.2

One of the 3 Aleph events



4 b cand.

HZ hyp.
m_H=114.4 GeV/c^2

NN = 0.997

jet b-tag:

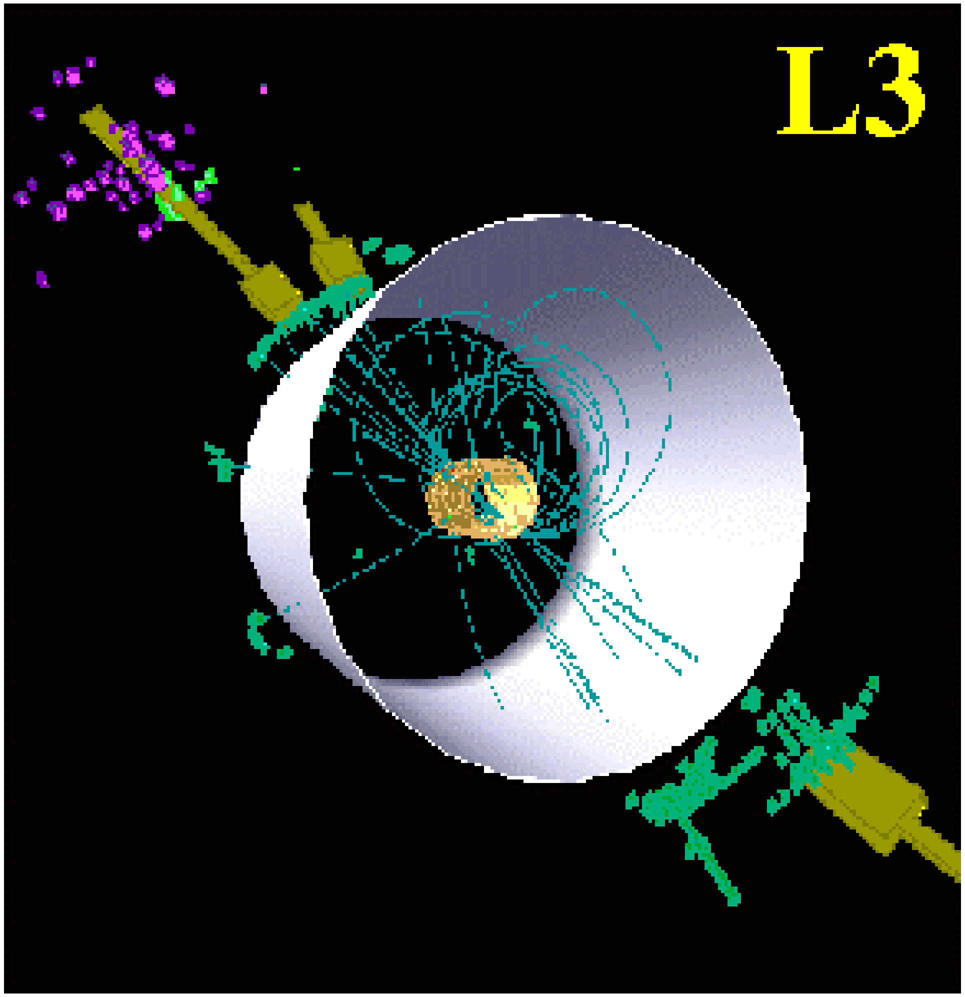
jet	b-tag
Z	
1	0.994
2	0.78
H	
3	0.993
4	0.999

ZZ hyp.
m_Z=97 GeV
m_Z=94 GeV

A 22 GeV shower in SICAL that was giving Evis = 252 GeV is rejected by a better algorithm : m_H= 112.8 -> m_H=114.4

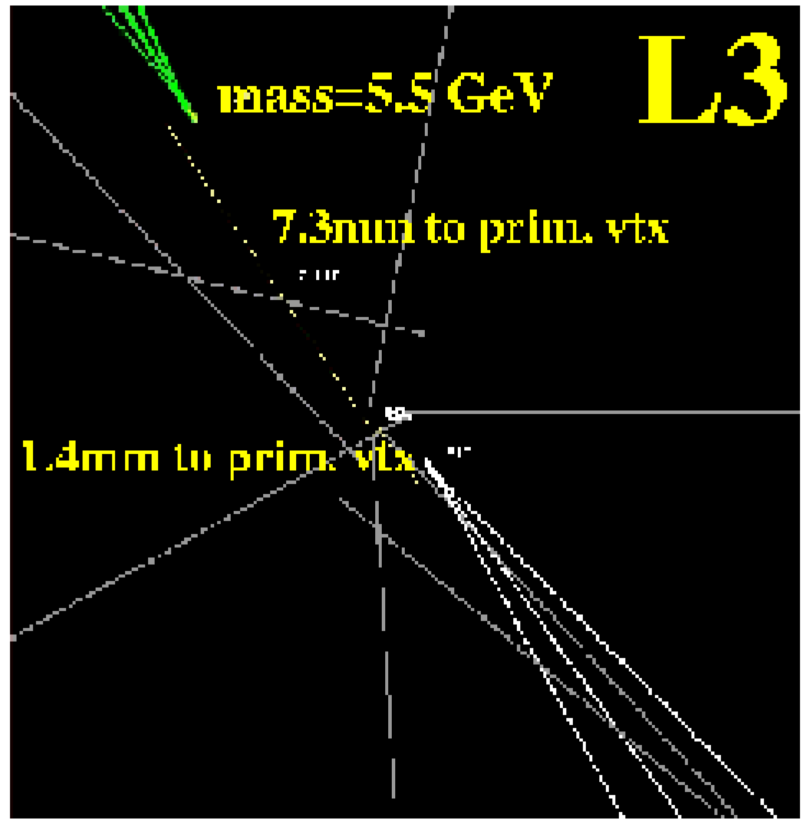
most significant Hνν candidate

The L3 event

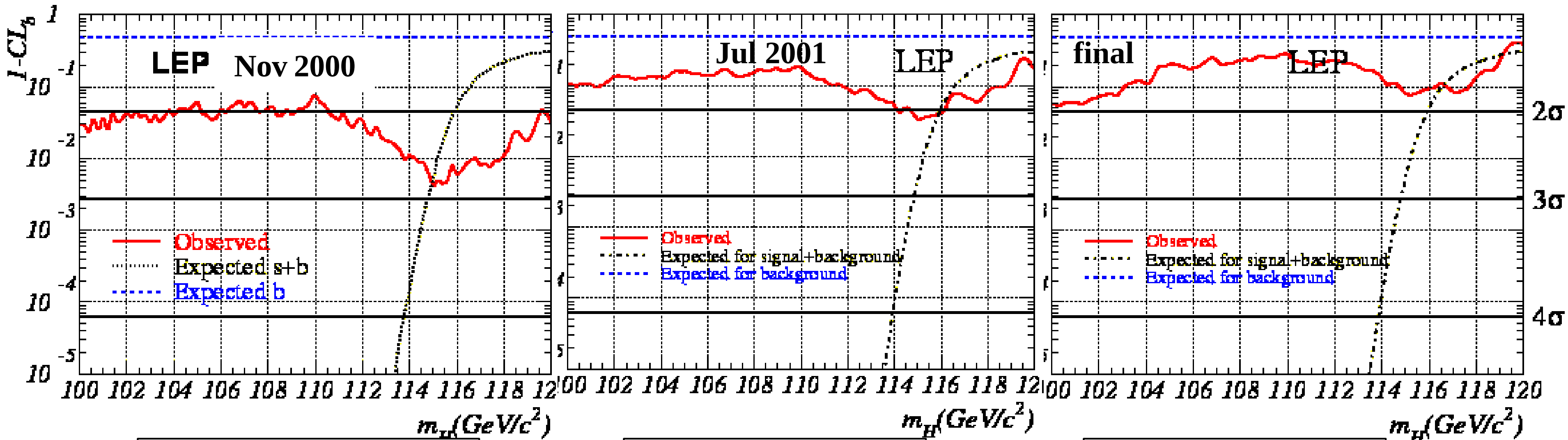


measured ll mass=114.4 GeV
ll mass resolution ~3 GeV

Secondary vtx's view



Higgs discovery?
from end of 2000 to the final results…



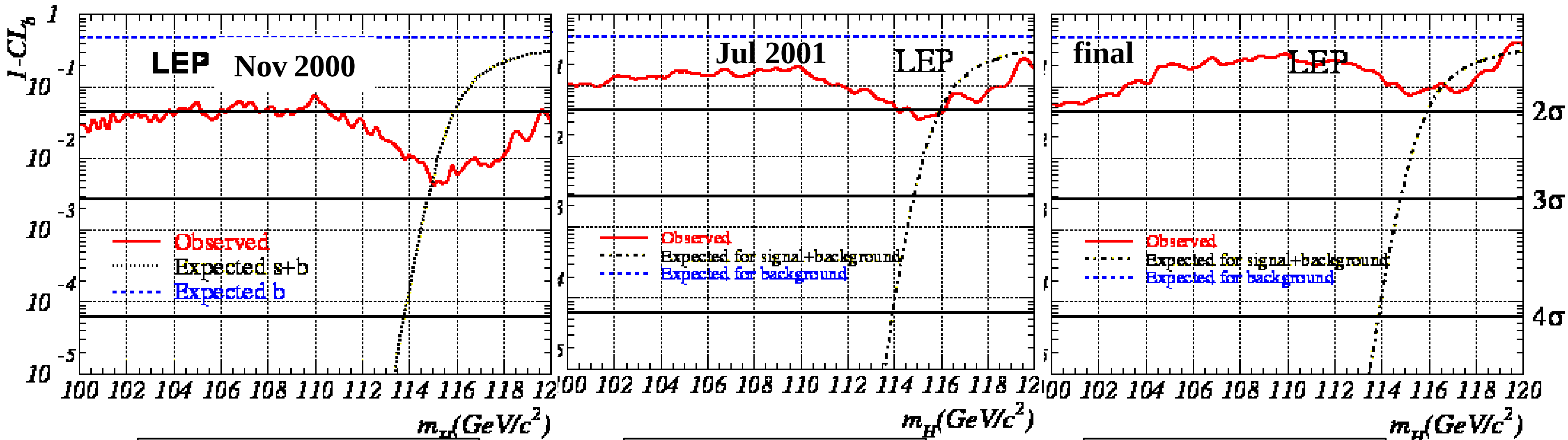
4.2 x 10^{-3}	~0.03	~ 0.09
m_H>113.5	m_H>114.1	m_H>114.4
(115.3 expected)	(115.4 expected)	(115.3 expected)

Changes: +10% L @ 206 final Ebeam

final detector calibrations

Aleph	2D correlation in Hqq	
Delphi	Hee optimized	New MC for sig and bkg
L3	more MC	
OPAL	better bgk estim.	New analyses, new mass rec.

Higgs discovery?
from end of 2000 to the final results…



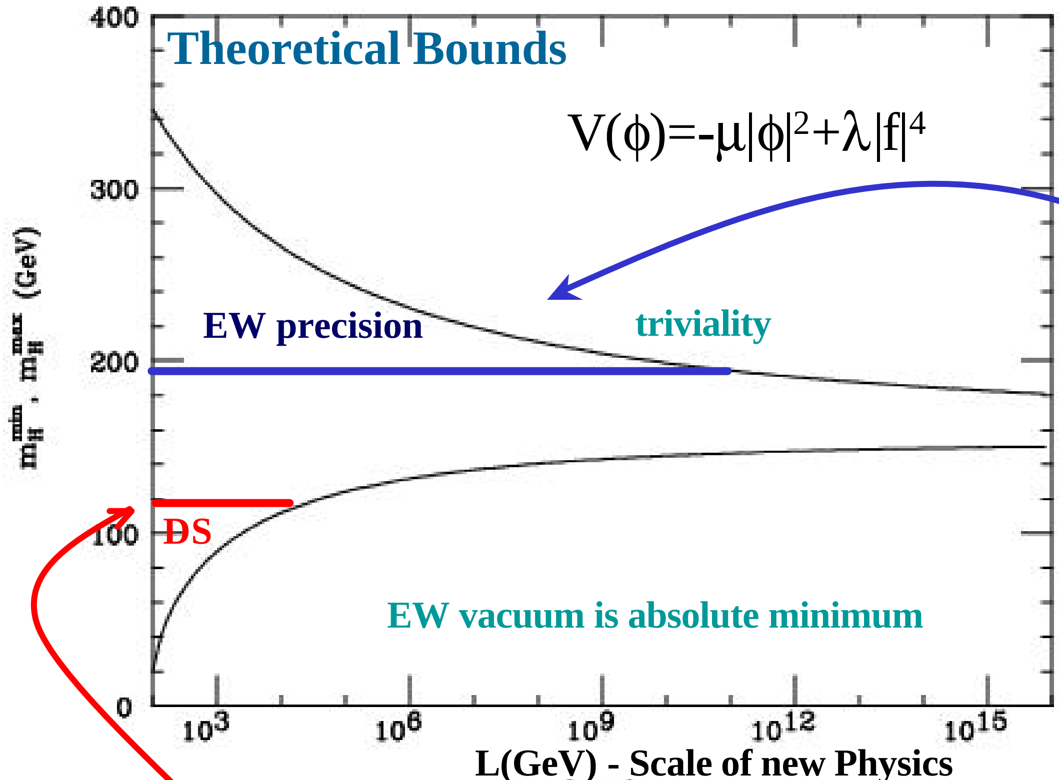
4.2 x 10^{-3}	~0.03	~ 0.09
m_H>113.5	m_H>114.1	m_H>114.4
(115.3 expected)	(115.4 expected)	(115.3 expected)

Changes:

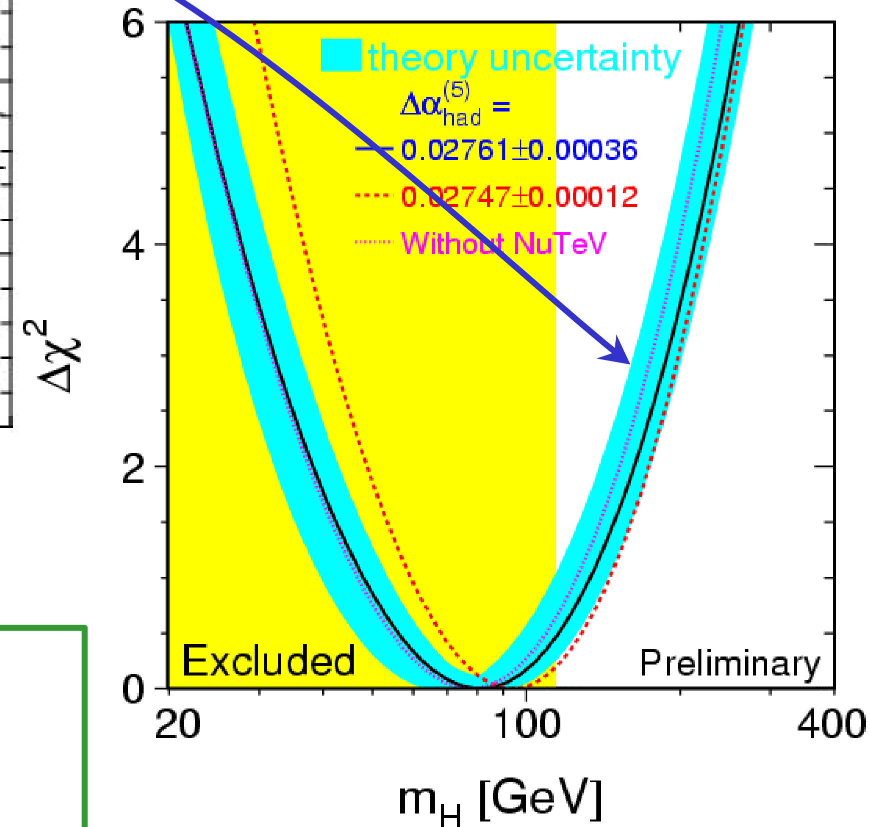
Background Probabilities 1-CL_b (m_H=115)

	Nov 2000	→	July 2001	→	final
ALEPH:	0.00065 (to HWG)	→	0.0015	→	0.0024
	0.0011 (publ.)				
DELPHI:	0.68	→	0.77	→	0.73
L3:	0.068	→	0.32	→	0.32
OPAL:	0.19	→	0.20	→	0.50

Standard Model Higgs as of today



m(H)£ 193 GeV/c^2
at 95% CL



Direct Search
m(H) ³ 114.3 GeV/c^2
at 95% CL

EW precision measurements

$m(H)=81^{+52}_{-33}$ GeV/c^2

backup

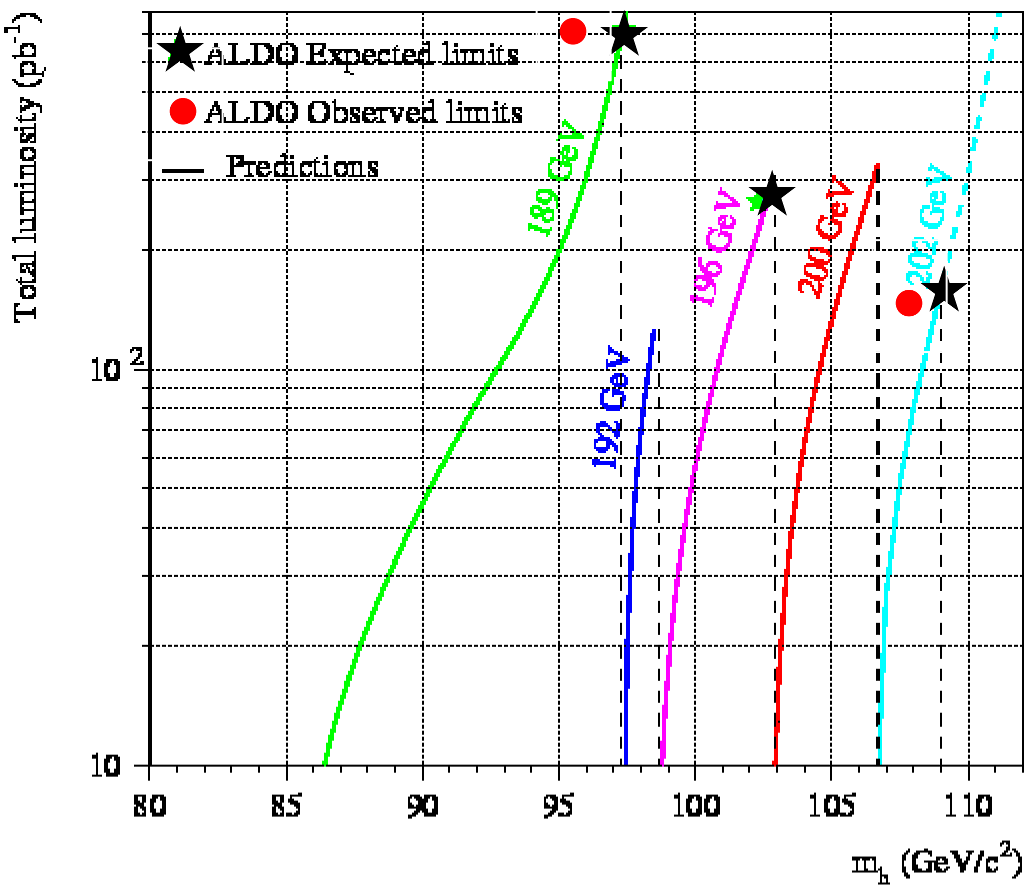
LEP: a successful performance

LEP1 + LEP2

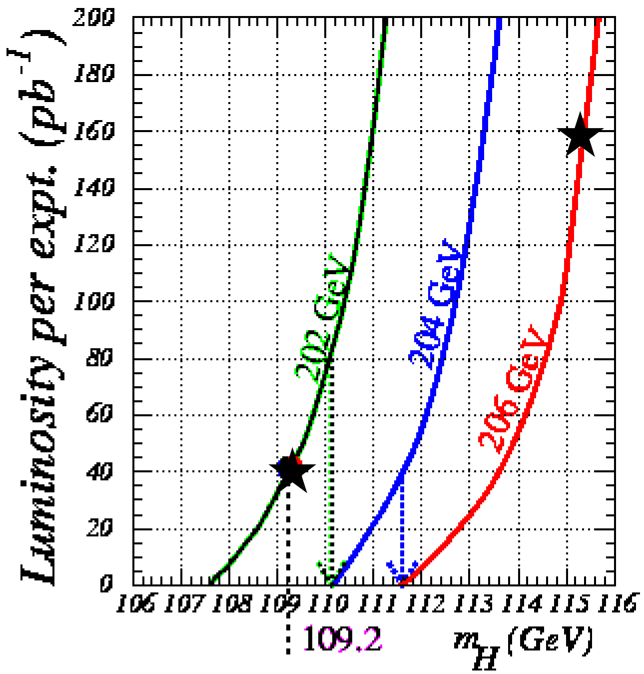
1989-1995 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000

E_{cm}(GeV)	91	130	136	161	172	183	189	192	196	200	202	204-209
Lum(pb^{-1}) per exp.	175	2.5	2.5	11	11	55	160	30	80	80	40	225

L > 2.5 fb^{-1} @ E_{cm}> 189 GeV



LEP exclusion potential



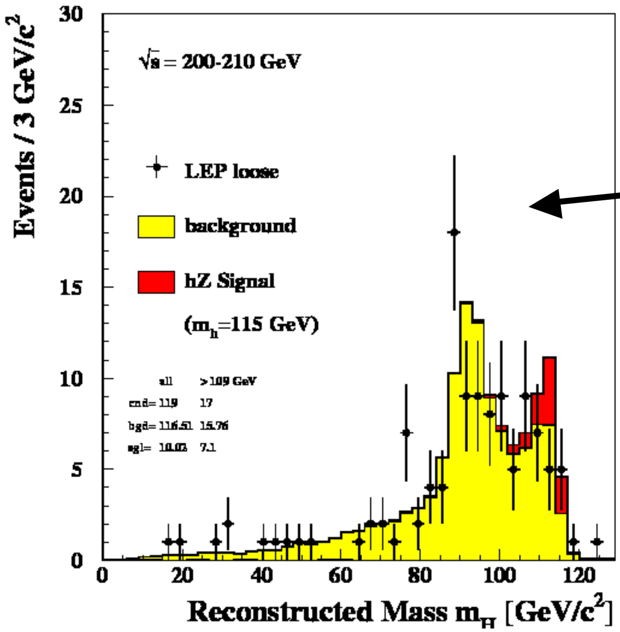
Chiara MARIOTTI, CERN

backup

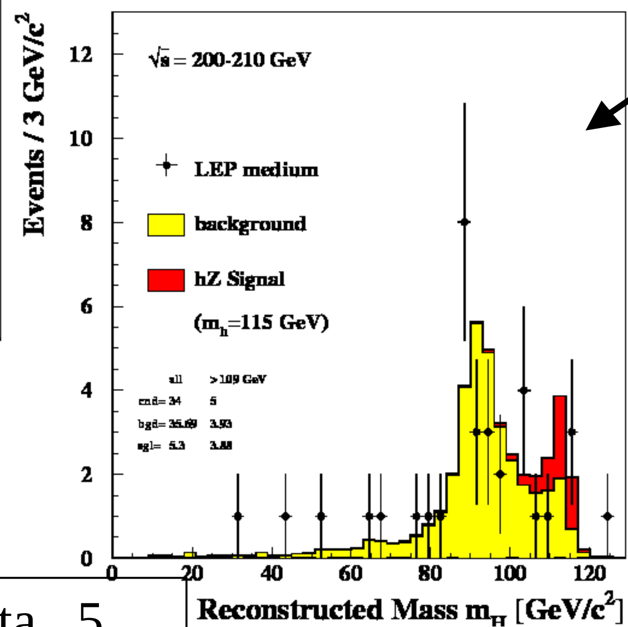
The combined mass plot

S/N for m(H) > 109 GeV/c²

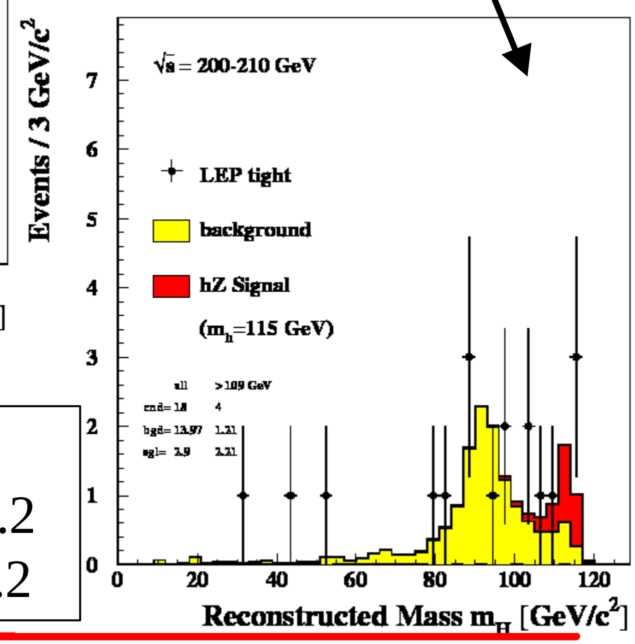
> 0.5 >1 >2



Data	17
Bkg	15.8
Sig	7.1



Data	5
Bkg	3.9
Sig	3.8



Data	4
Bkg	1.2
Sig	2.2

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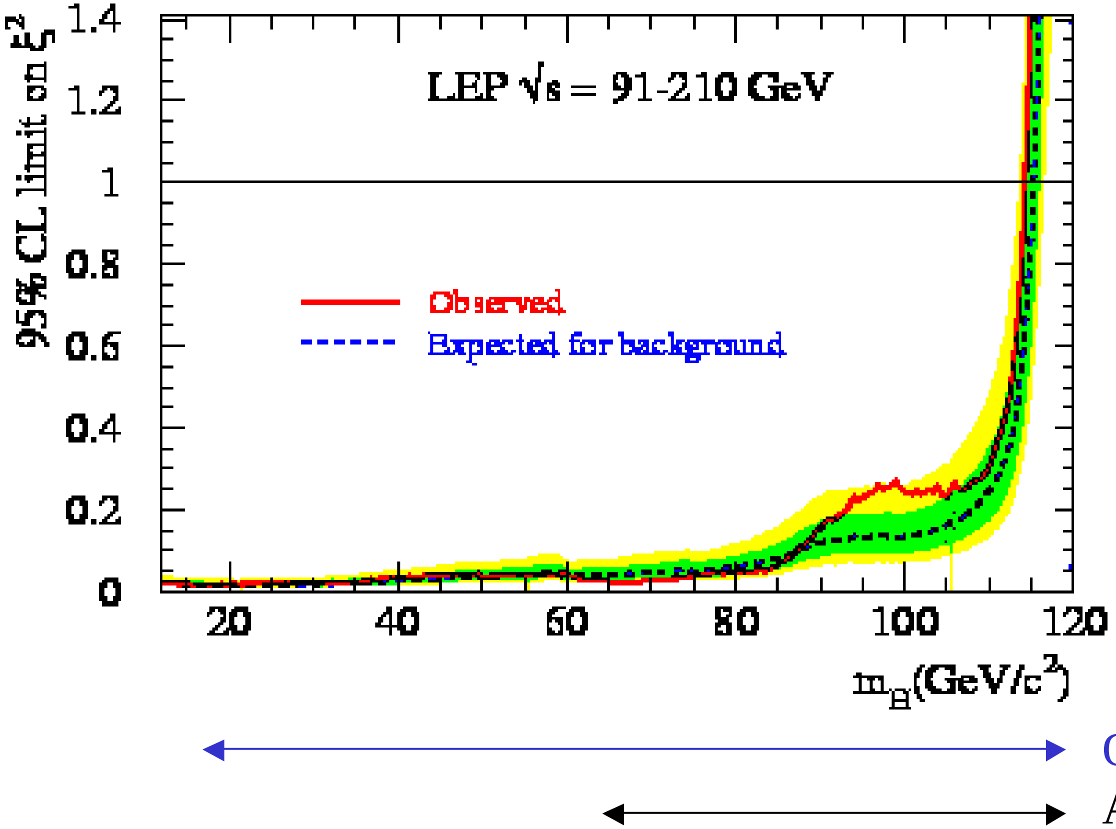
The HZZ coupling

The 95%CL upper-bound on **$(gHZZ/gHZZ(SM))^2$:**

i.e. the HZZ coupling relative to the SM coupling



OPAL, DELPHI

ALEPH, L3

From 10 to 85 GeV the s_{obs} is ~20 times smaller than the SM.