

# La ricerca diretta dell'Higgs SM

I dati sperimentali testano il SM al livello del **per mille**

L'esistenza dell'Higgs e' ben supportata dai dati  
sulle correzioni radiative

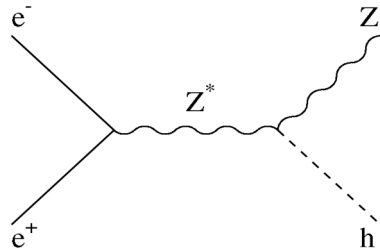
Il bosone di Higgs non e' pero' ancora stato scoperto

**a LEP si e' cercato in modo diretto**

Le misure di precisione hanno posto limiti sulla sua massa  
+ la teoria limita la sua massa

# LEP: la macchina ideale

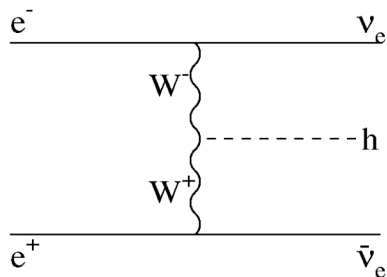
## Higgsstrahlung



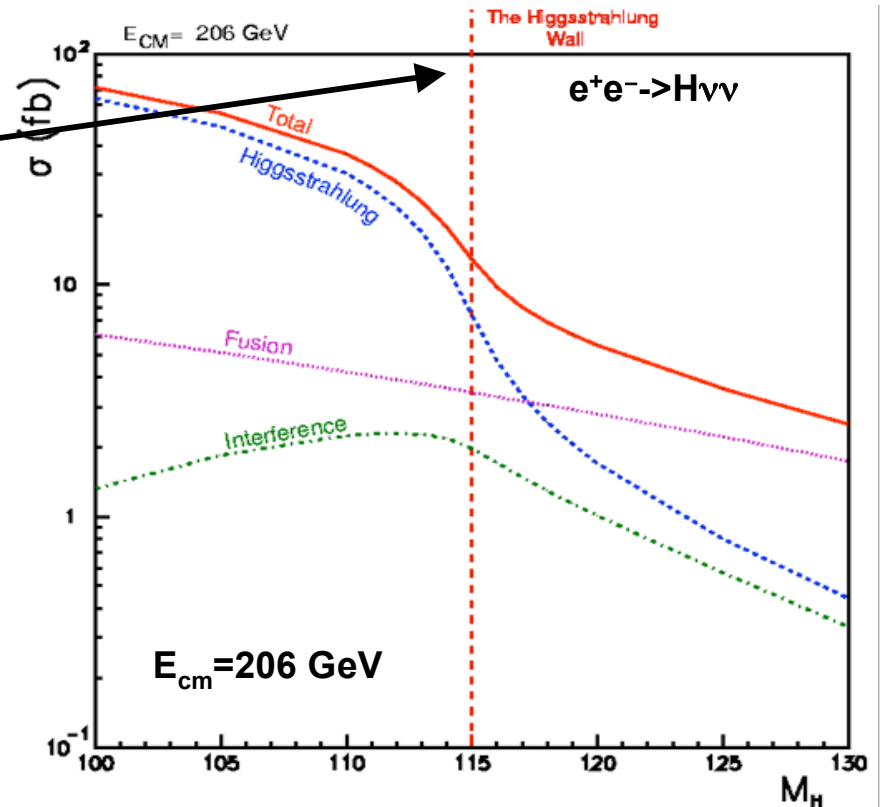
Modo dominante  
 $m(H) \leq \sqrt{s} - m(Z)$

+  
 Interferenza  
 positiva

## WW fusion

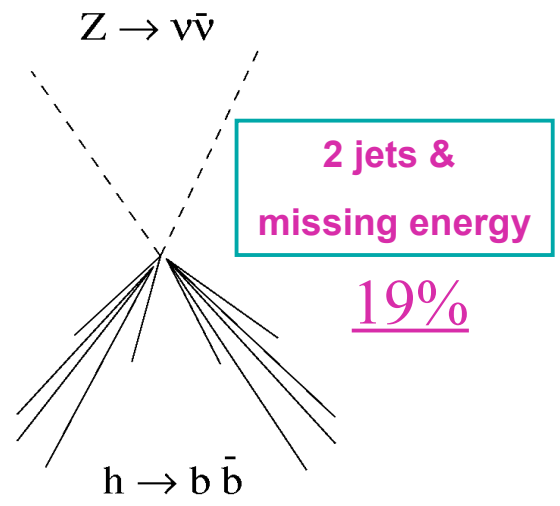
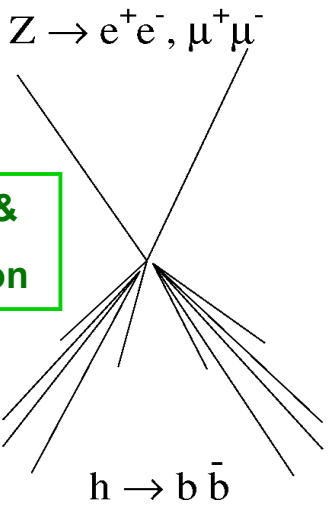
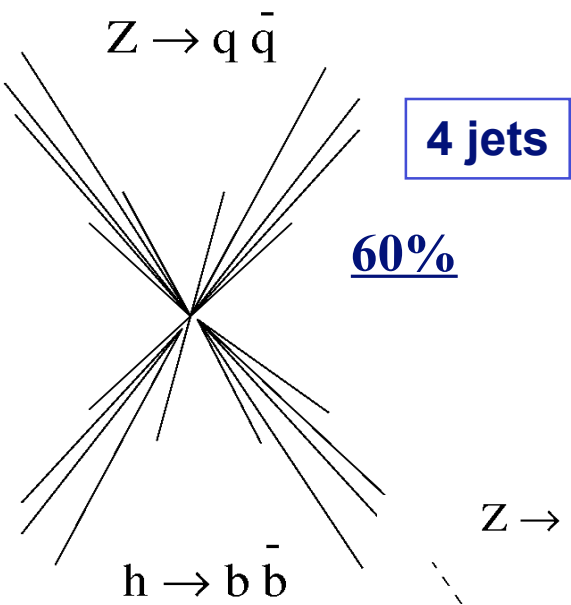
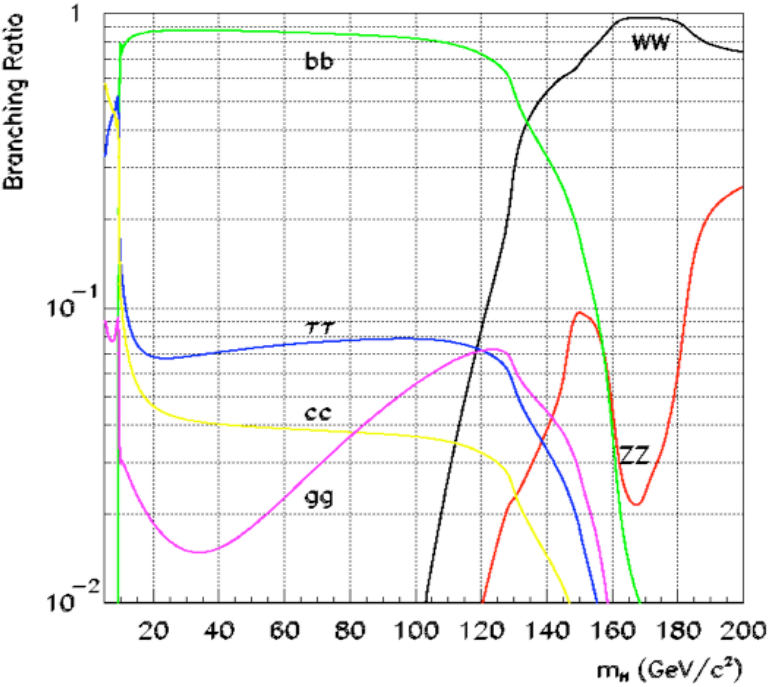


La sola possibilita' di andare oltre !



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

# LEP: la macchina ideale (2)



Or a  $\tau$  instead of the b

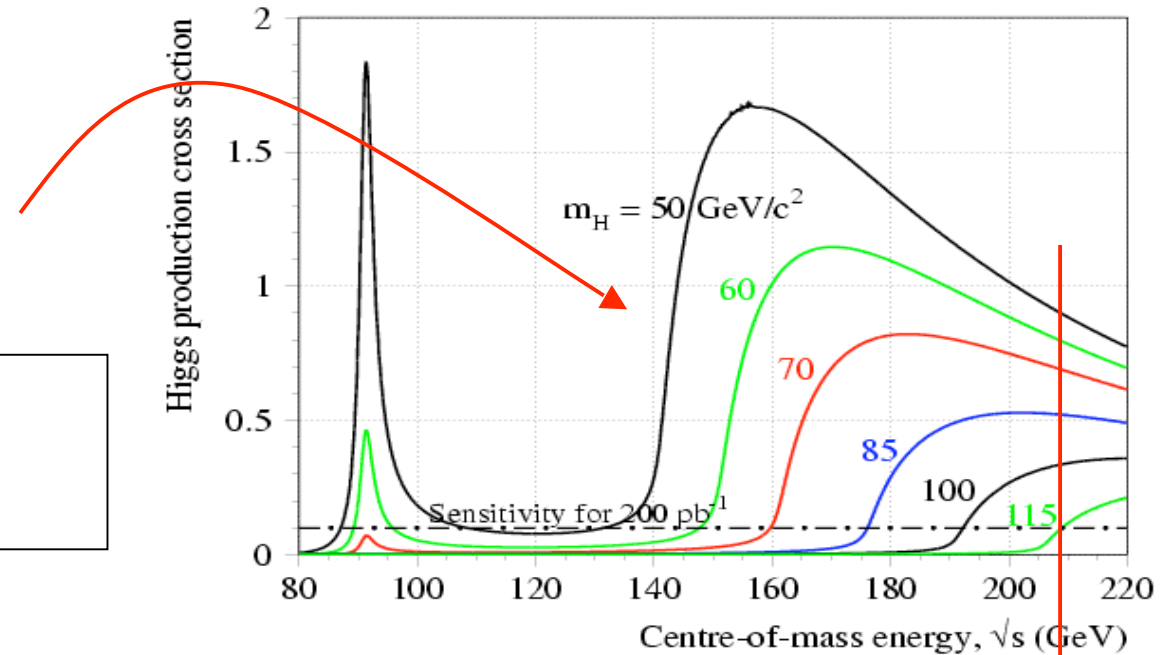
# LEP: la macchina ideale (3)

## Ricerche dirette:

LEP e' la macchina perfetta per la ricerca dell'Higgs

$$SE \ m(\text{Higgs}) < E_{\text{cm}} - Mz$$

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



**A LEP2 : 1995-2000,  $E_{\text{cm}} = 130 - 209 \text{ GeV}$**   
 **$\mathcal{L} > 2.5 \text{ fb}^{-1}$  @  $E_{\text{cm}} > 187 \text{ GeV}$**

## Ricerche Indirette:

Informazione dalle misure di precisione a LEP:

$$m(H) = 91^{+58}_{-37} \text{ GeV}/c^2$$

$$m(H) < 211 \text{ GeV}/c^2 \text{ at } 95\%CL$$

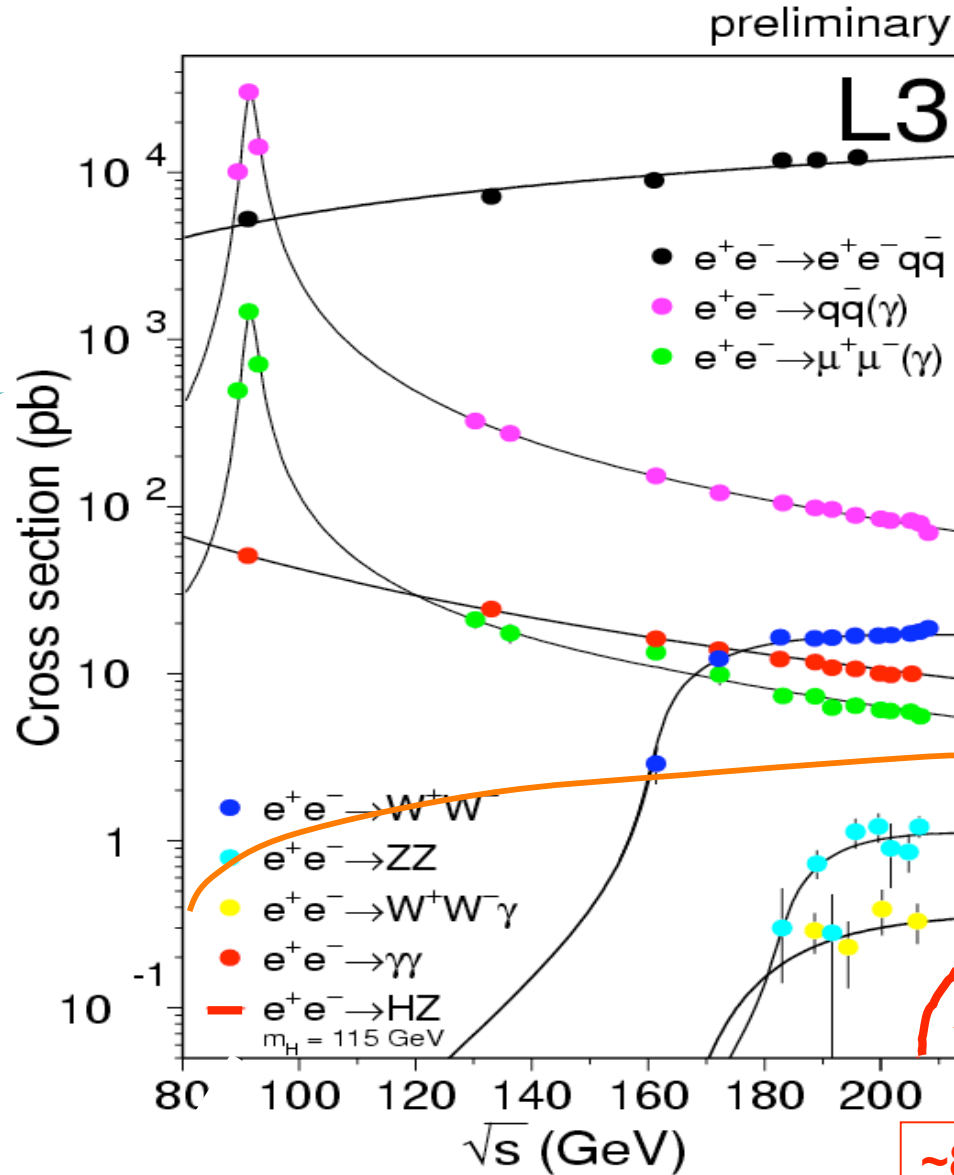
# Ma... una sezione d'urto molto piccola

$qq(\gamma) e'$   
 la  $\sigma$  dominante  
 Ma facile da ridurre  
 a eccezione....

Ermeticita'

$eeZ$   
 $evW$   
 missing energy

Energy flow



$WW e'$   
 dominante  
 in 4-jet

massa

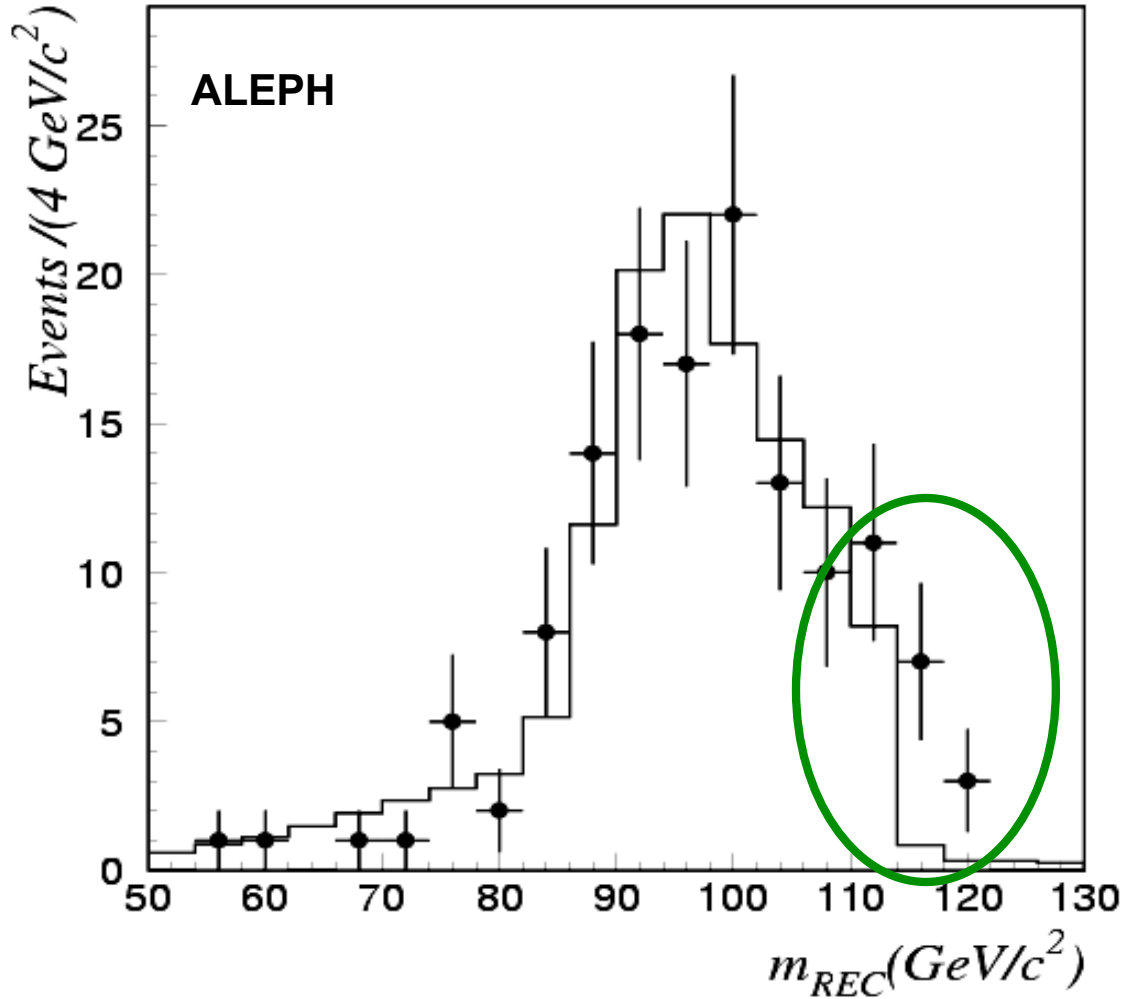
$ZZ e'$   
 Qualche volta  
 irreducibile

Higgs di  
 115  $\text{GeV}/c^2$

~8 eventi per esp

# La sfida della ricerca: il controllo delle code

Pre-selection level



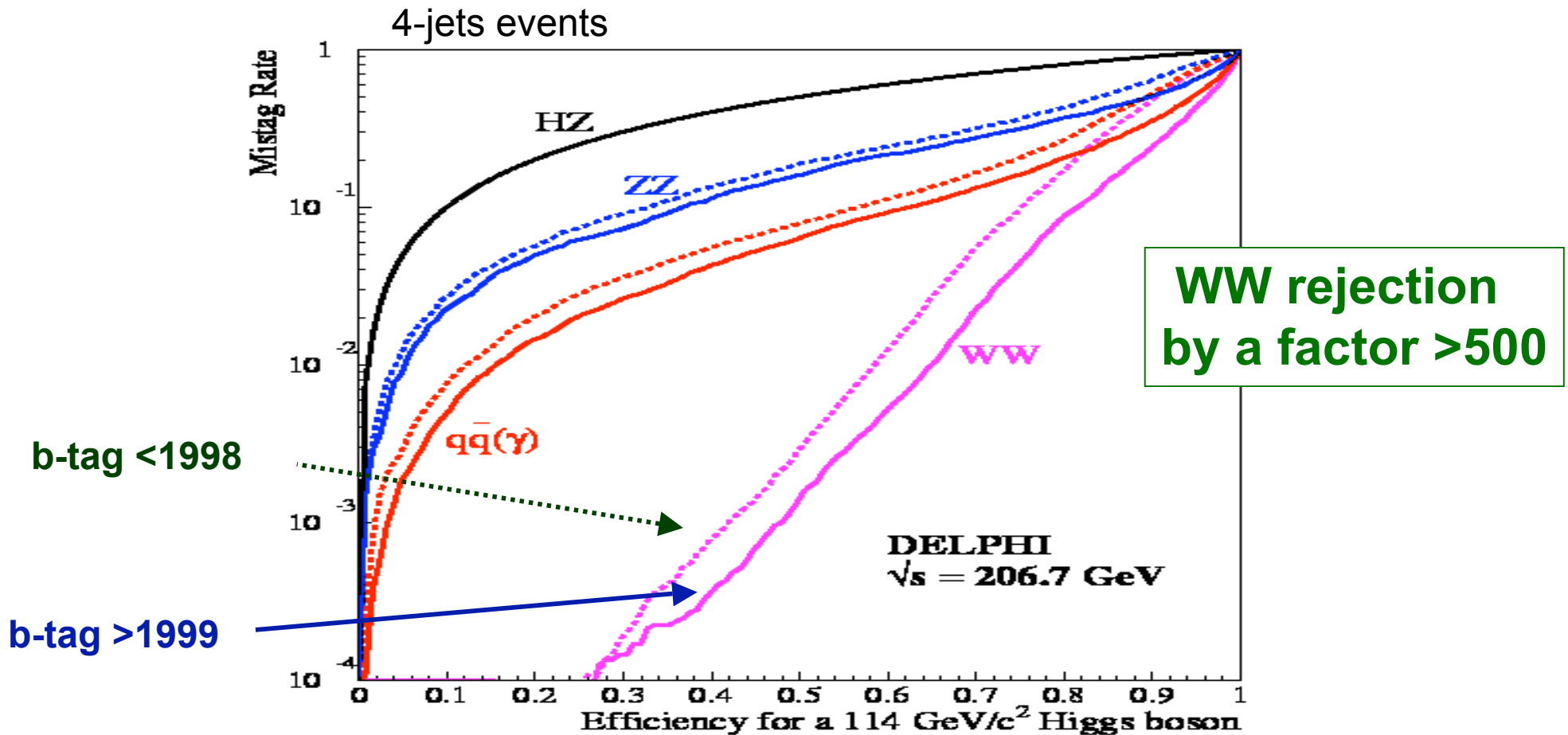
Tutte le variabili significative  
devono essere ben capite

La ricostruzione della massa  
dipende pesantemente sulla buona  
calibrazione dei rivelatori  
(tracciatori, calorimetri.)  
E sulle tecniche di software.

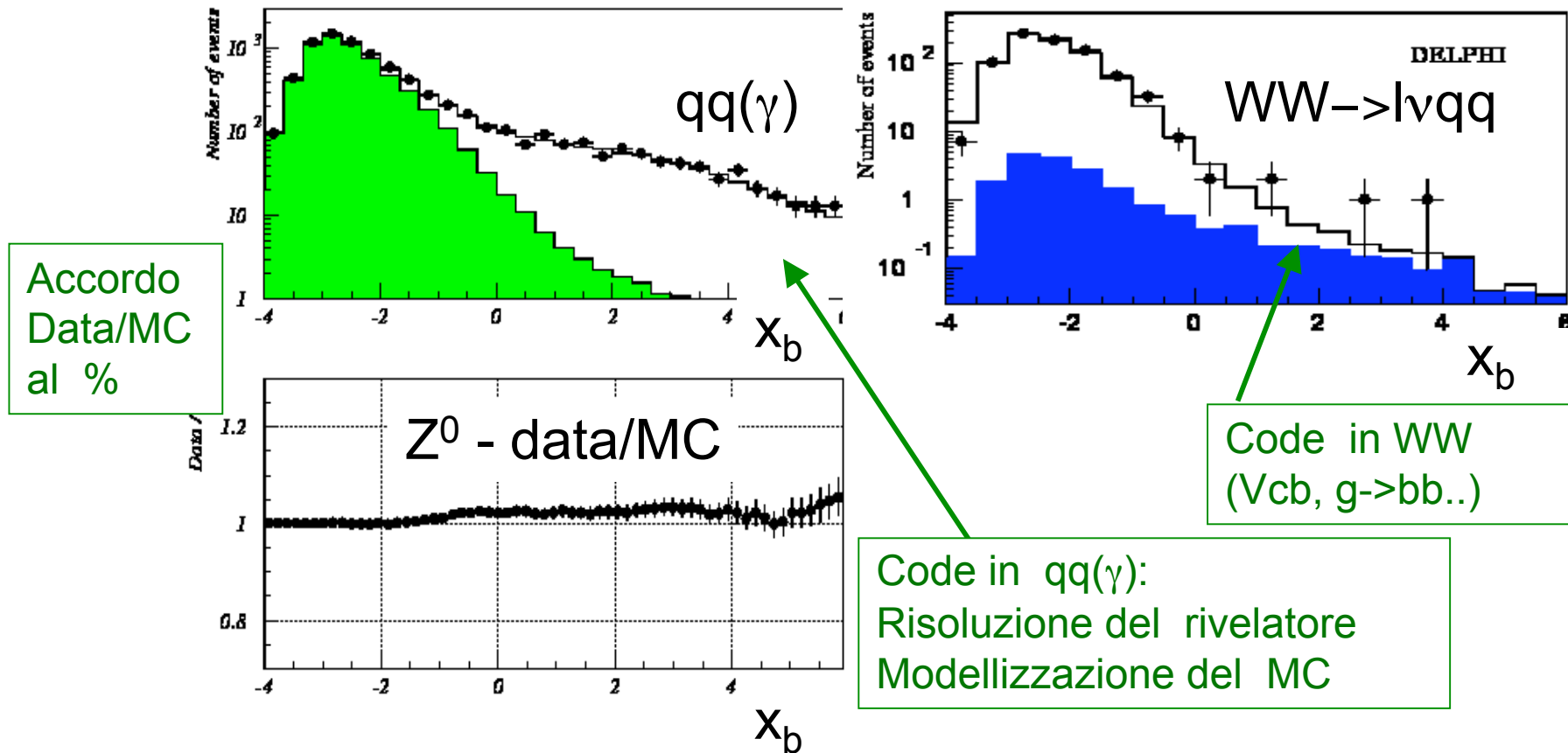
# ... e il b-tagging

Dalla "potenza" dei micro-vertici alle tecniche di software

Tutto quello che abbiamo imparato in 10 anni e' usato nella ricerca dell'Higgs



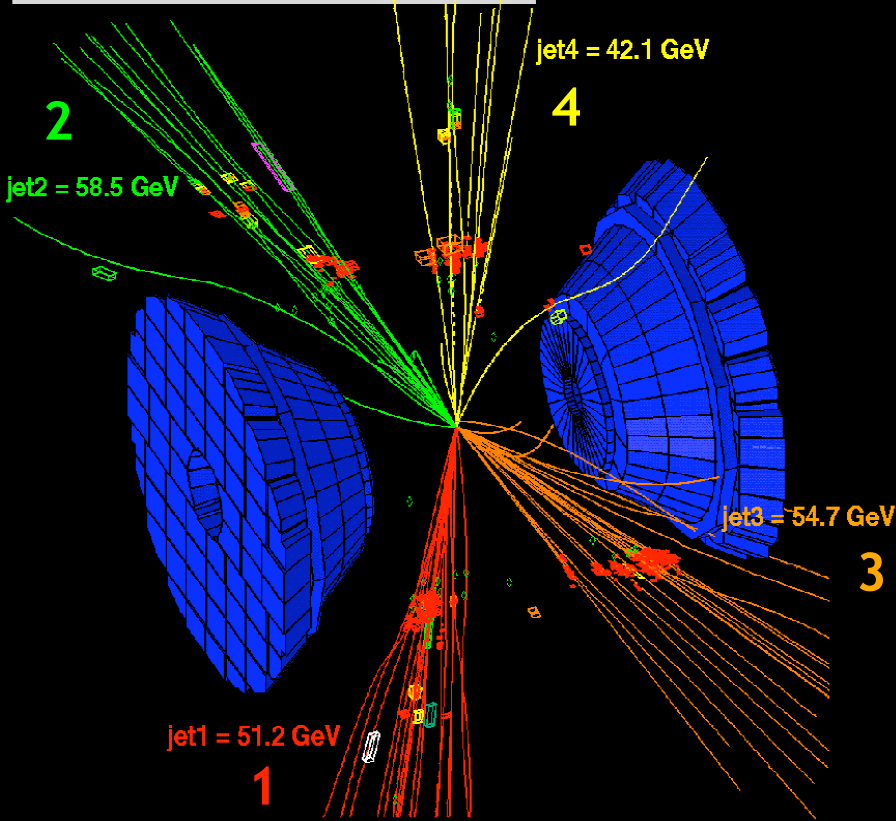
# ... e il b-tagging



La ricerca dello SM Higgs  $\Rightarrow$  una "misura di precisione"



DELPHI Run: 114574 Evt: 5797  
 Beam: 103.3 GeV Proc: 24-Aug-2000  
 DAS: 24-Aug-2000 Scan: 26-Aug-2000  
 17:50:05 Tau+DST



4C fit :

$M_{j_1 j_2} = 101.7 \text{ GeV}/c^2$

b-tag ( $j_1, j_2$ ) = +7.26

5C fit Z mass :

$M_{j_1 j_2} = 97.4 \text{ GeV}/c^2$

$M_{j_3 j_4} = 86.4 \text{ GeV}/c^2$

b-tag ( $j_3, j_4$ ) = -0.16

$M_{j_3 j_4} = M_Z$

$M_{j_1 j_4} = 98.9 \text{ GeV}/c^2$

b-tag ( $j_1, j_4$ ) = +1.43

$M_{j_1 j_4} = M_Z$

$M_{j_2 j_3} = 105.9 \text{ GeV}/c^2$

b-tag ( $j_2, j_3$ ) = + 5.67

$M_{j_2 j_3} = 113.4 \text{ GeV}/c^2$

1<sup>st</sup> pairing hypothesis

2<sup>nd</sup> pairing hypothesis

# Il canale a 4 jets: coppie & ricostruzione della massa

sei possibili coppie:

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 <sub>Z</sub> B=-0.5	(2,4)	(2,3)	(1,4) M=M <sub>Z</sub> B=2.0	(1,3)	(1,2)

•Per ogni coppia,  
fit a 5C con  $M_{ij} = M_Z$   
& likelihood includendo la probabilita' che gli altri 2 jet b-tagati vengano dal decadimento dell'Higgs.

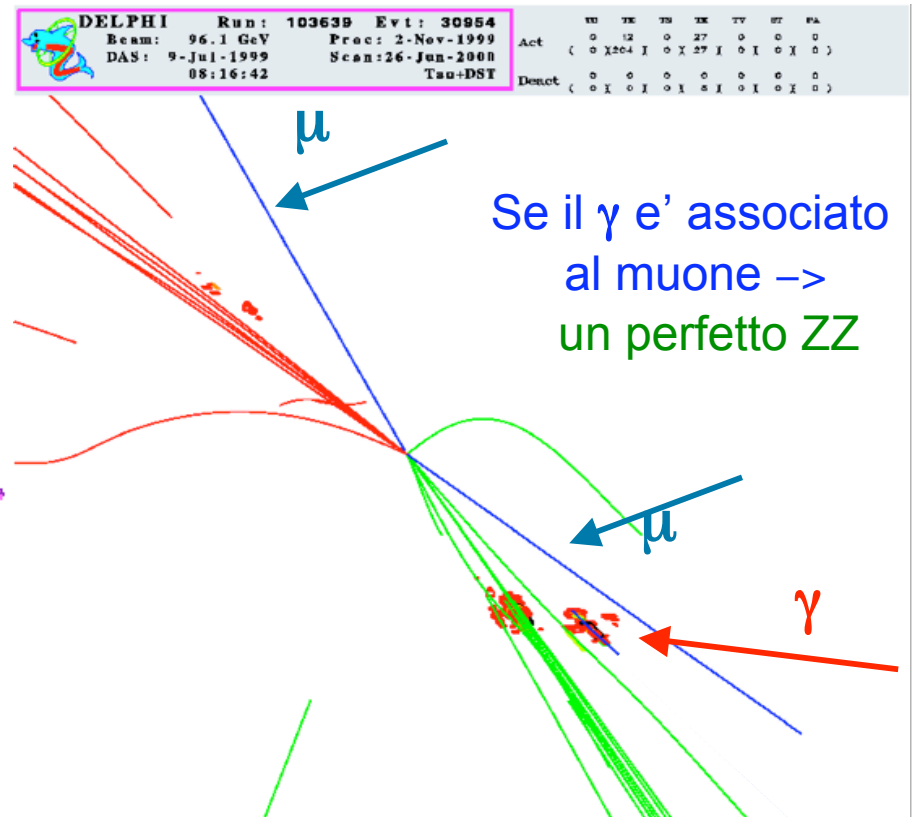
•Un solo valore di massa viene scelto

da Jesus Marco, Budapest

# Il canale leptonic

**the golden candidates!**  
 ma BR = 3 % per ogni sapore...

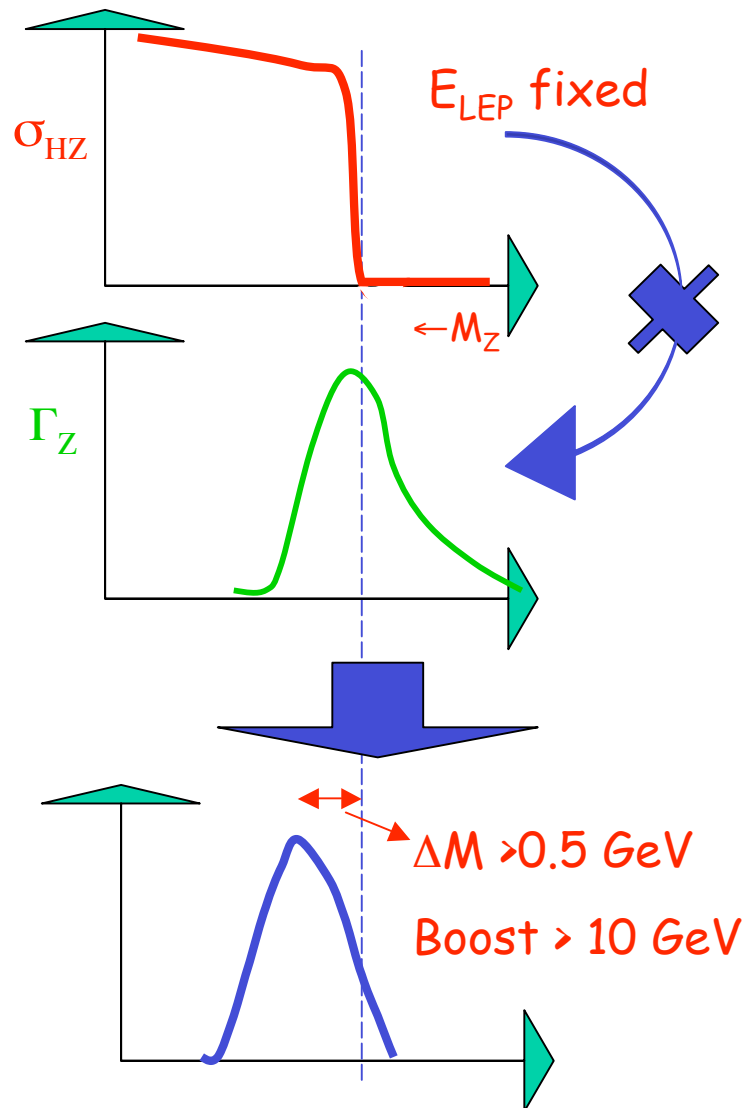
ma...i fotoni radiati



fondo  
 $llqq$

L3  $eeqq$ ,  $E_{cm} = 206$  GeV  
 $M(ee) = 89$  GeV/c<sup>2</sup>  
 $M(qq) = 108$  GeV/c<sup>2</sup>

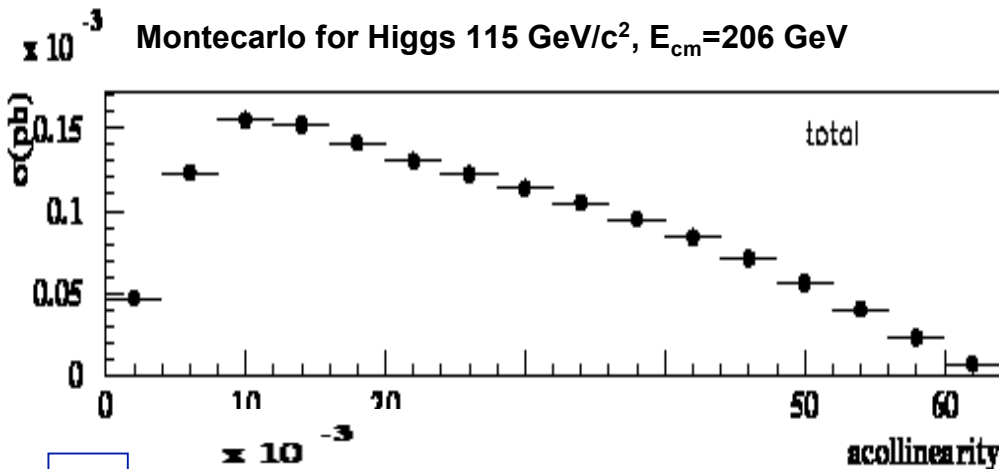
# H $\nu\nu$ : un fondo irreducibile, ee $\rightarrow$ bb



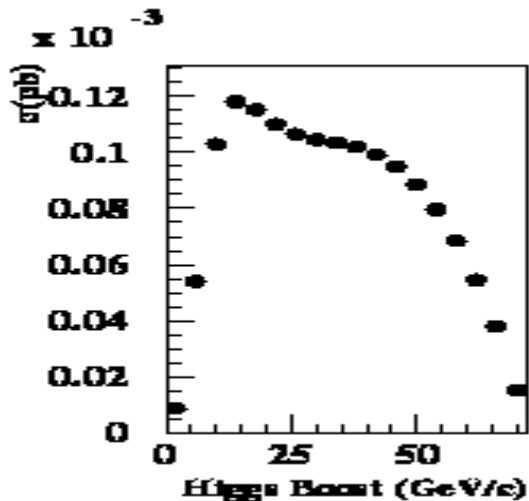
# H $\nu\nu$ : un fondo irreducibile, ee $\rightarrow$ bb

Il segnale non e' collineare !

per acollinearita' < 5°  
 5% di Higgs  $\sigma \sim 0.015$  pb  
 30% di qq( $\gamma$ )  $\sigma \sim 80$  pb



WPHACT



Gli eventi collineari sono:

- Z $\gamma\gamma$  doppi ritorni radiativi alla Z (visible mass  $\sim M(Z)$ )
- qq dove l'energia e' persa in  $\nu$  o per problemi di rivelatori, (alta massa visibile)

a 206 GeV  $6 \times 10^{-4}$  ee  $\rightarrow$  qq  
 $5 \times 10^{-4}$  ee  $\rightarrow$  bb  
 perdono > 60 GeV in neutrini:



Nel 2000 per L= 220 pb<sup>-1</sup>, ogni exp. ha ~10 events ee  $\rightarrow$ bb che perdono piu' di 60 GeV in neutrini

Di questi 10 evts , 80% hanno p<sub>T</sub>>10 GeV

# I nuovi risultati

Tutti i 4 esperimenti hanno implementato varie modifiche per  
Migliorare la sensibilita' e/o il miglior controllo dei fondi

- Processamento di tutti i dati: calibrazioni finali, allineamenti, b-tag...
- Nuovi generatori MC (DELPHI), piu' statistica di MC (tutti)
- Valori finali dell'energia del CM a LEP (tutti)
- Miglioramento di alcune analisi:
  - Nuove analisi con miglior sensibilita' (OPAL):  
nuovo jet pairing (4- jet), e  $L \rightarrow NN(\text{miss.ener})$
  - Miglior reiezione del fondo della macchina (ALEPH)
  - Analisi estese fino alla soglia bb (DELPHI)

**L3:** risultato finale gia' nel 2001 :

**pochi candidati compatibili con l'ipotesi di Higgs**

**ALEPH:** eccesso di eventi rispetto a quello che ci si aspetta dai fondi SM  
che suggerisce la produzione di un Higgs di mass  $m_H \sim 114 \text{ GeV}/c^2$

**DELPHI:** Nessuna evidenza di segnale di Higgs, limite a  $m_H > 114.1 \text{ GeV}/c^2$

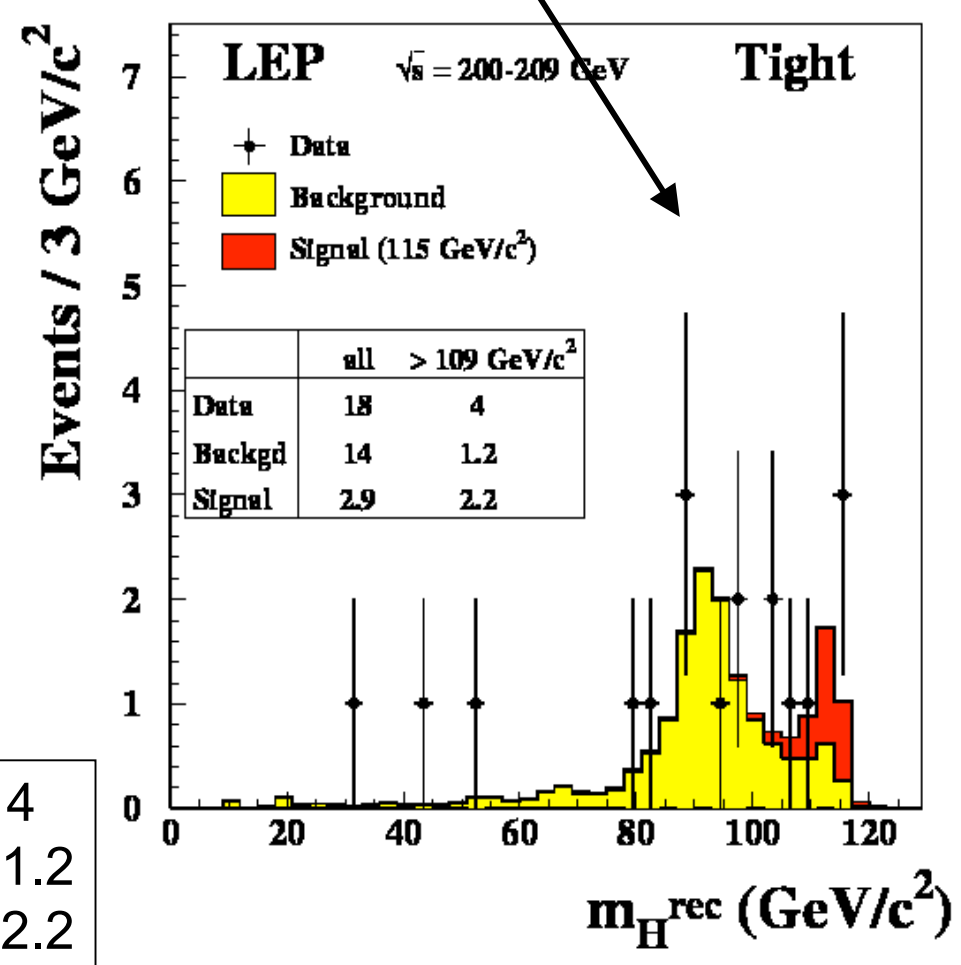
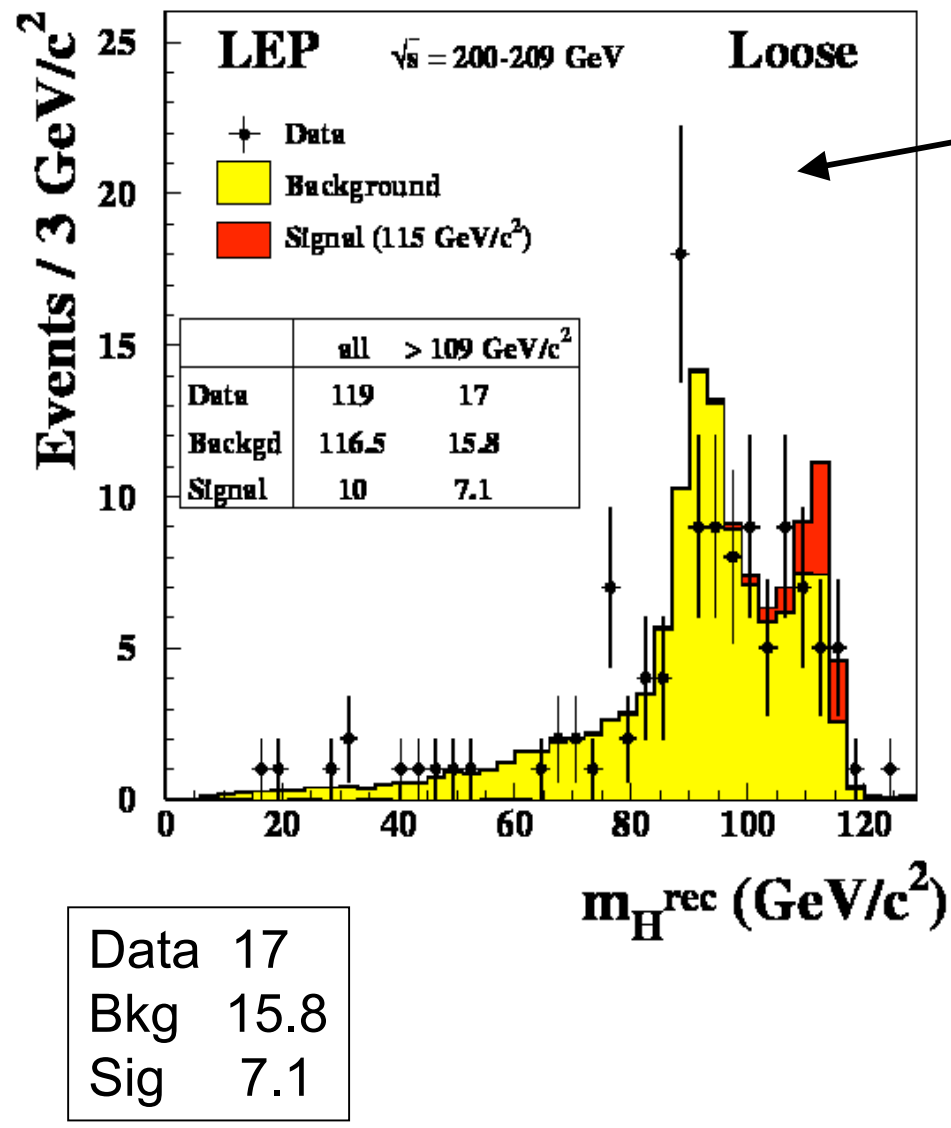
**OPAL:** Nessuna evidenza di segnale di Higgs, limite a  $m_H > 112.7 \text{ GeV}/c^2$

# Il plot di massa combinato

S/N per  $m(H) > 109 \text{ GeV}/c^2$

$> 0.5$

$> 2$



# La procedura statistica

LEP HIGGS WG

I data da tutti i canali (Hqq, Hvv, Hll, qqττ) e a tutte le  $E_{cm}$  sono combinati in uno spazio bi-Dimensionale:

- la massa ricostruita dell'Higgs  $M_H^{rec}$
- variabile discriminante  $G$  (b-tag, kinematical info..)

In ogni bin di  $M_H^{rec}$  e  $G$ :

- Background (MC)  $b_i$
- Segnale (MC)  $s_i$
- Num. di candidati  $N_i$

Per ogni "test mass"  $m(H)$

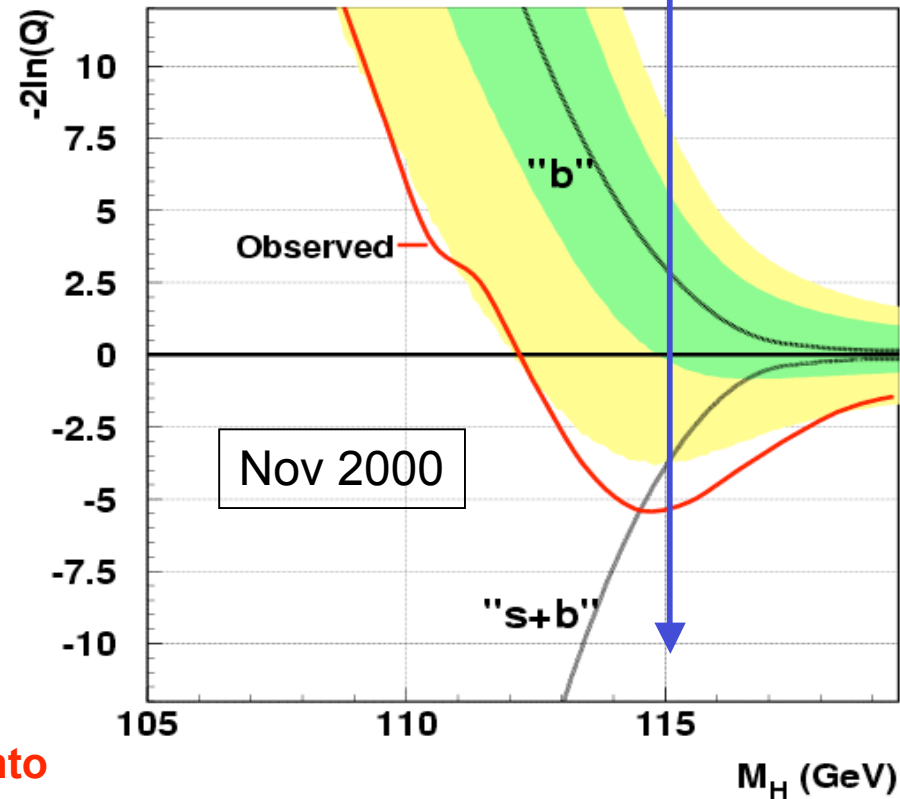
## LIKELIHOOD TEST :

"sig+bkgr"  $\Leftrightarrow$  "bkgr"

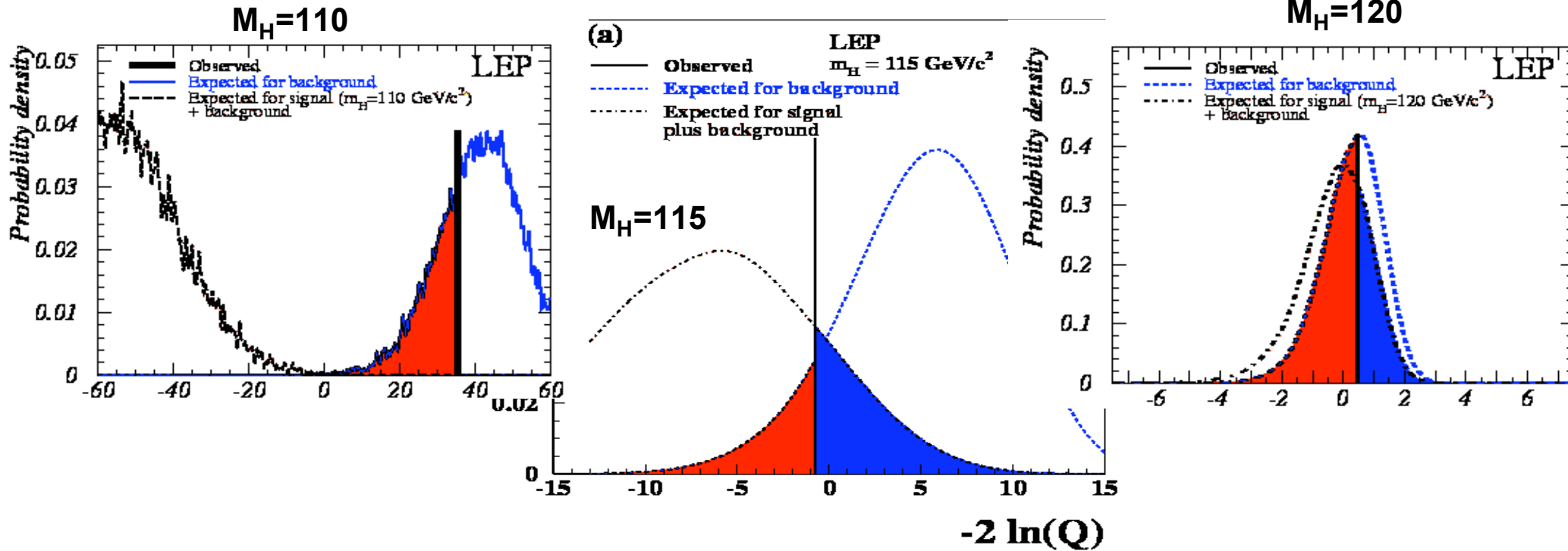
$$\ln Q(m(H)) = -S_{tot} + \sum N_i \ln[1 + s_i(m(H)) / b_i]$$

$W_i$  dell' evento

$$Q(m(H)) = \mathcal{L}(s + b) / \mathcal{L}(b) \quad \text{"test statistic"}$$



# I livelli di confidenza



$\lambda$   $1 - CL_b$  : una misura di incompatibilita' con "b"

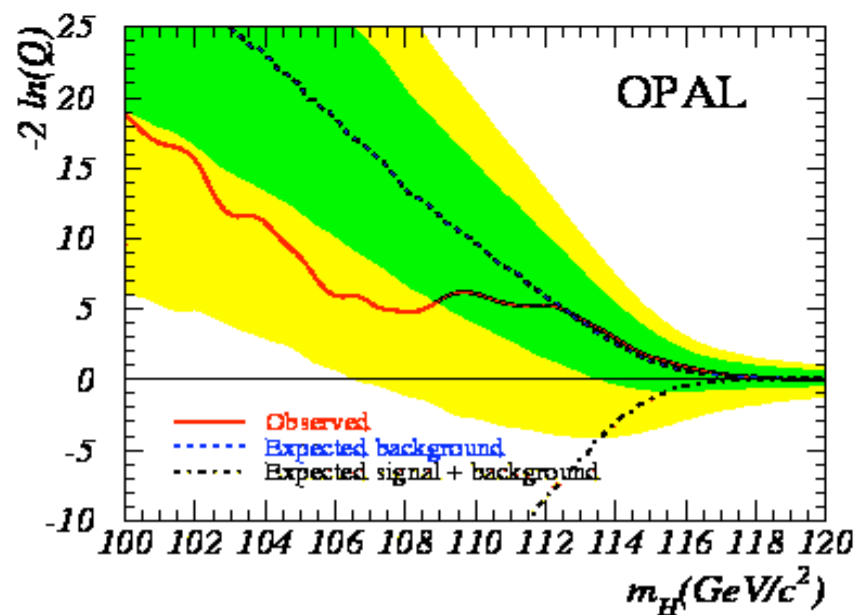
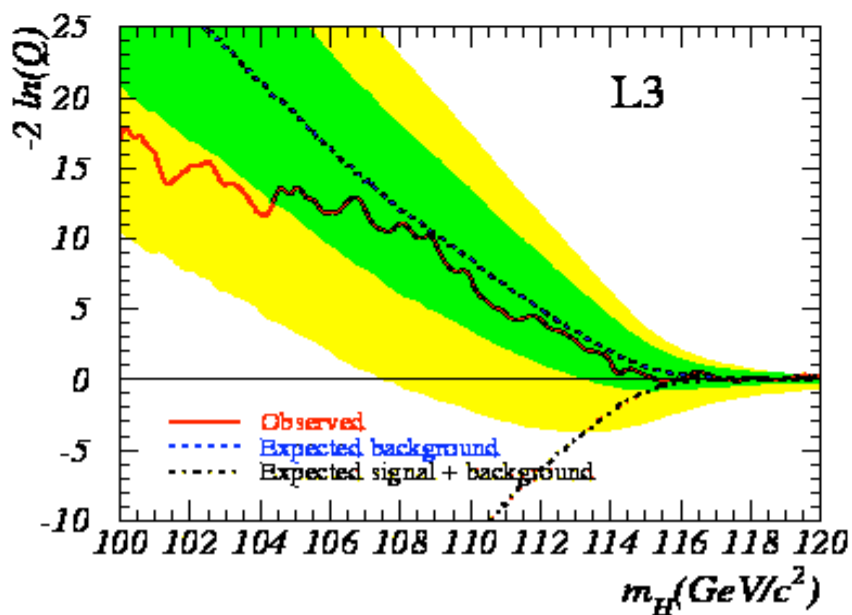
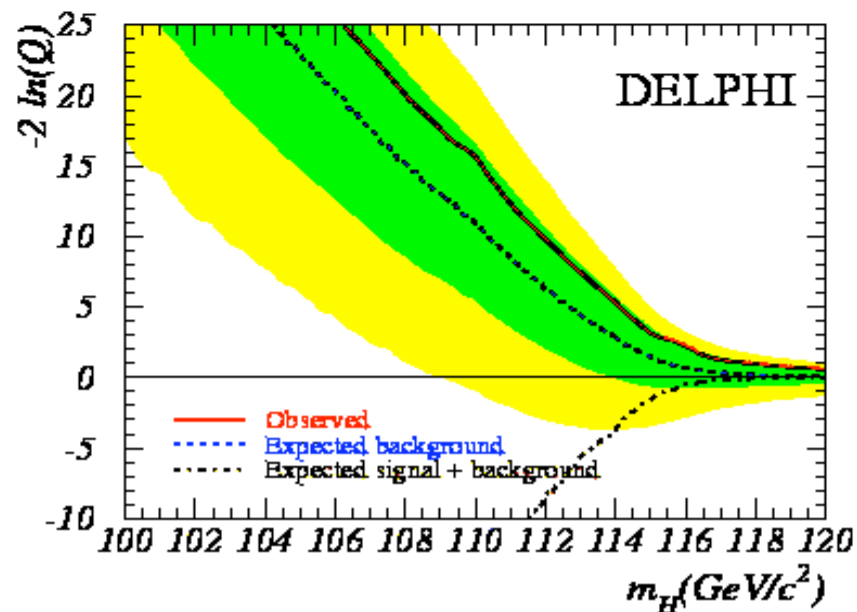
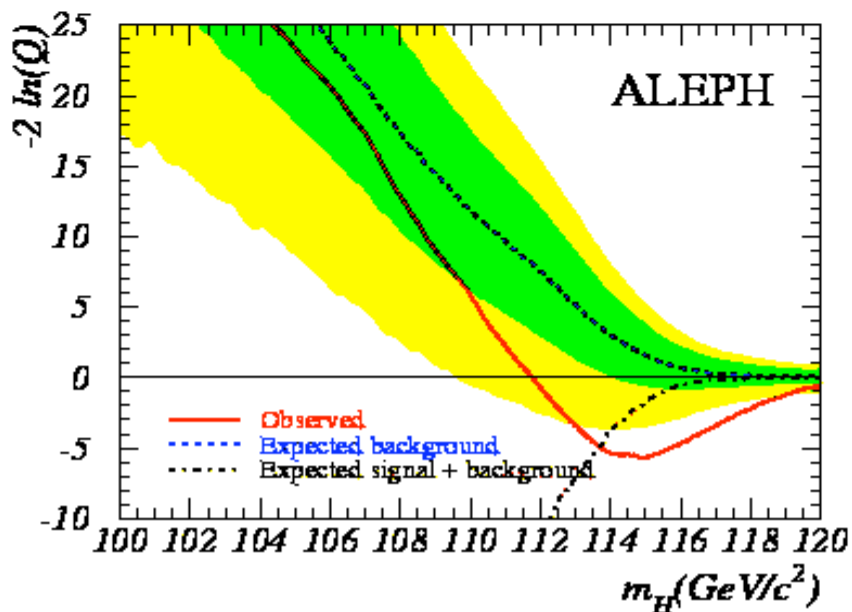
$1 - CL_b$	0.32	0.064	$2.7 \times 10^{-3}$	$6.3 \times 10^{-5}$	$5.7 \times 10^{-7}$
	$1\sigma$	$2\sigma$	$3\sigma$	$4\sigma$	$5\sigma$

$\lambda$   $CL_{s+b}$  : una misura di compatibilita' con "s+b"

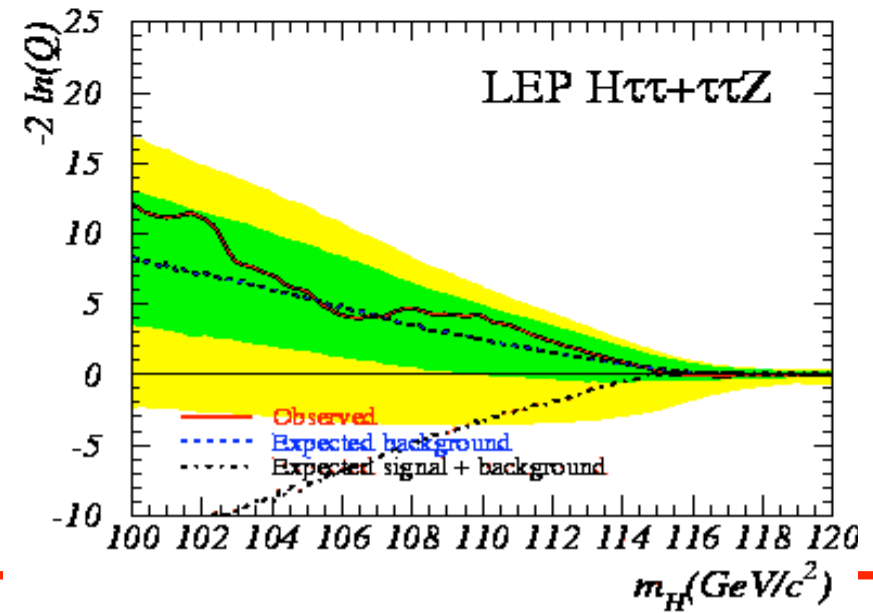
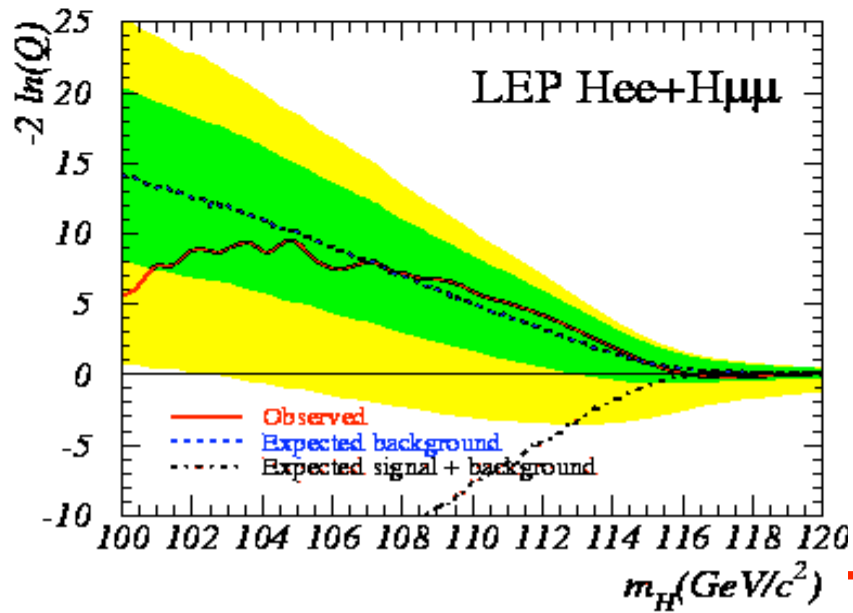
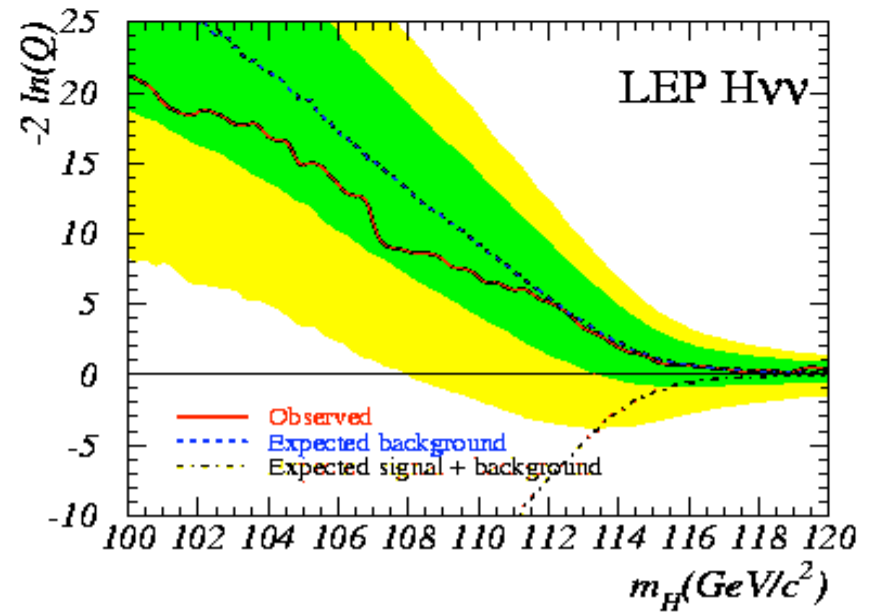
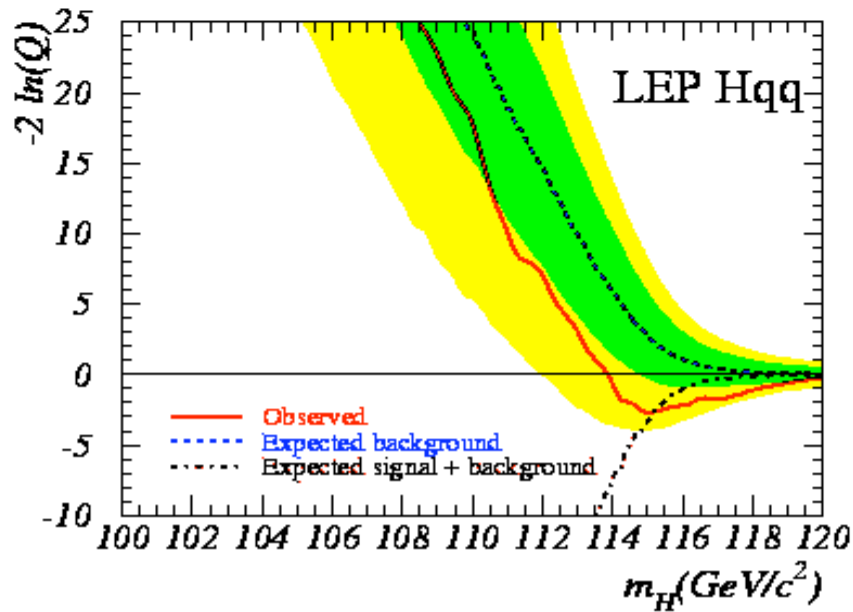
$\lambda$   $CL_s = CL_{s+b} / CL_b$  da il limite inferiore sulla massa dell' Higgs



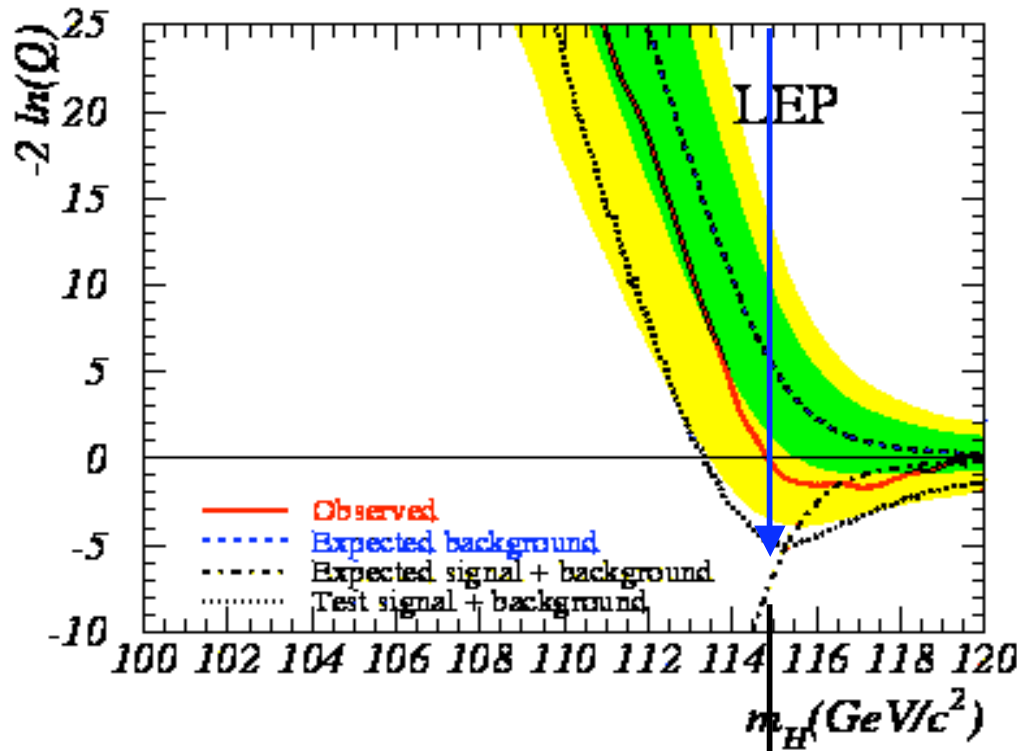
# I risultati dei singoli esperimenti



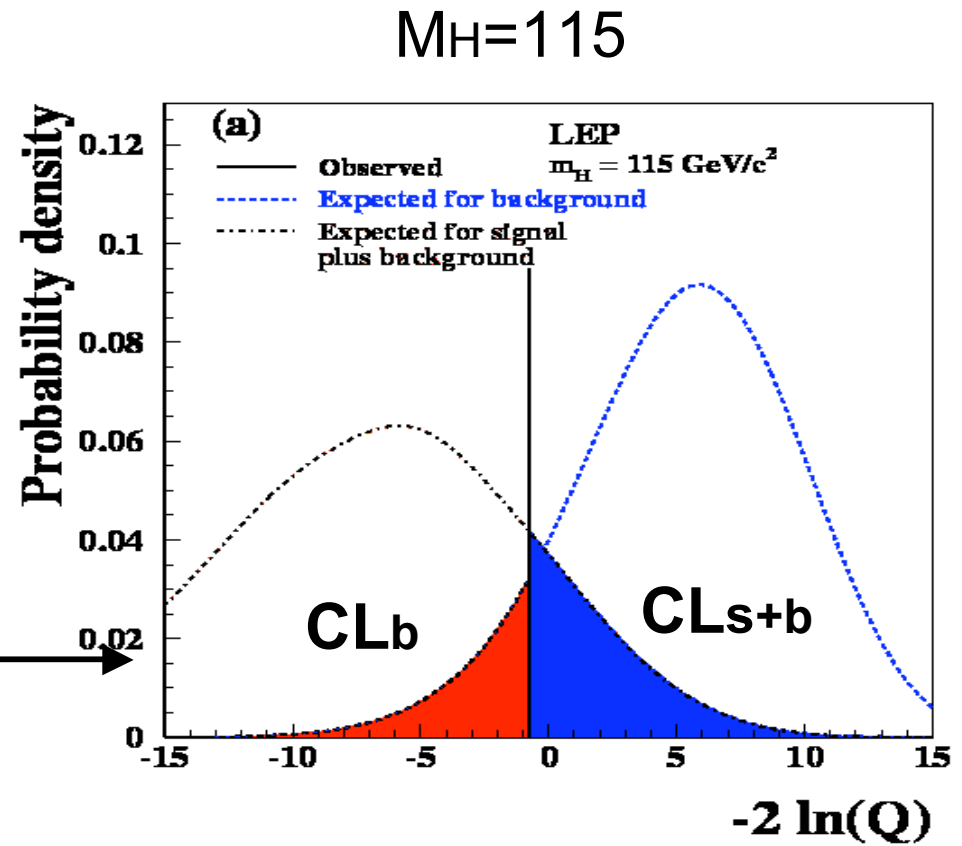
# I risultati per i singoli canali



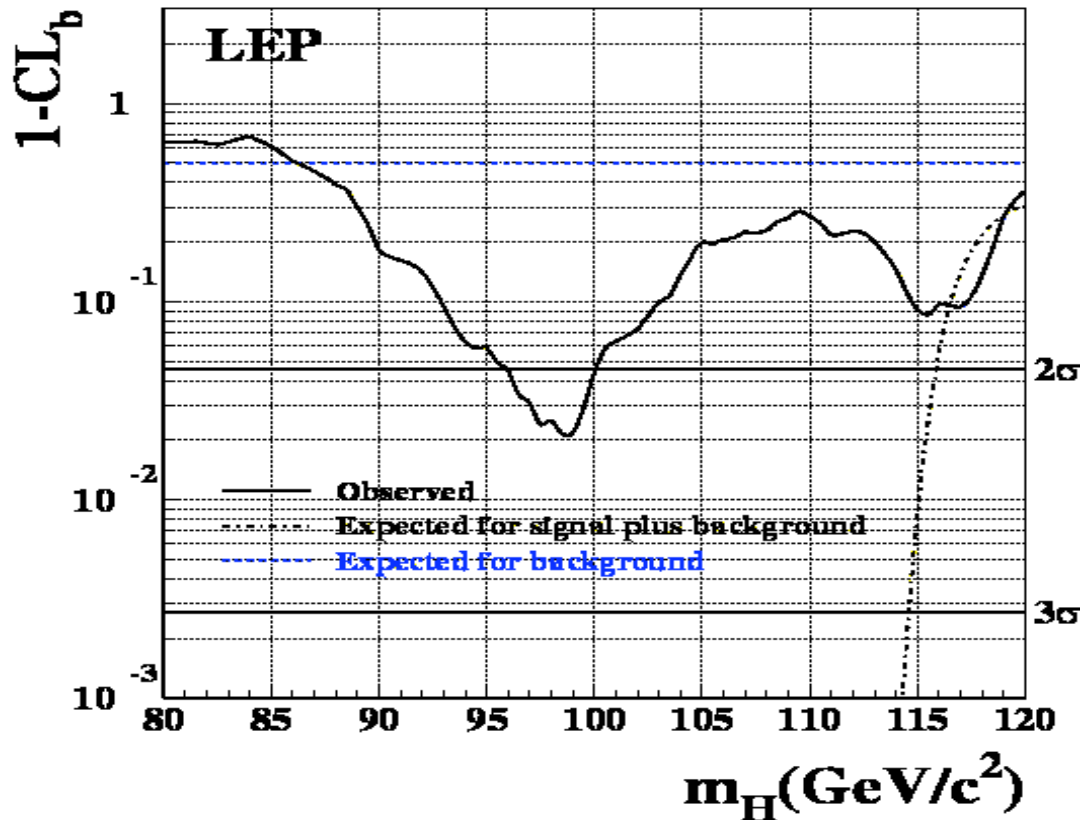
# Il risultato combinato di LEP



Slice a  $M_H = 115 \text{ GeV}$



# Compatibilita' con il fondo



**$1-CL_b$  @  $M_H=115$  GeV/c<sup>2</sup>**

**ALEPH**       **$3.3 \times 10^{-3}$**

**DELPHI**      **0.79**

**L3**      **0.33**

**OPAL**      **0.50**

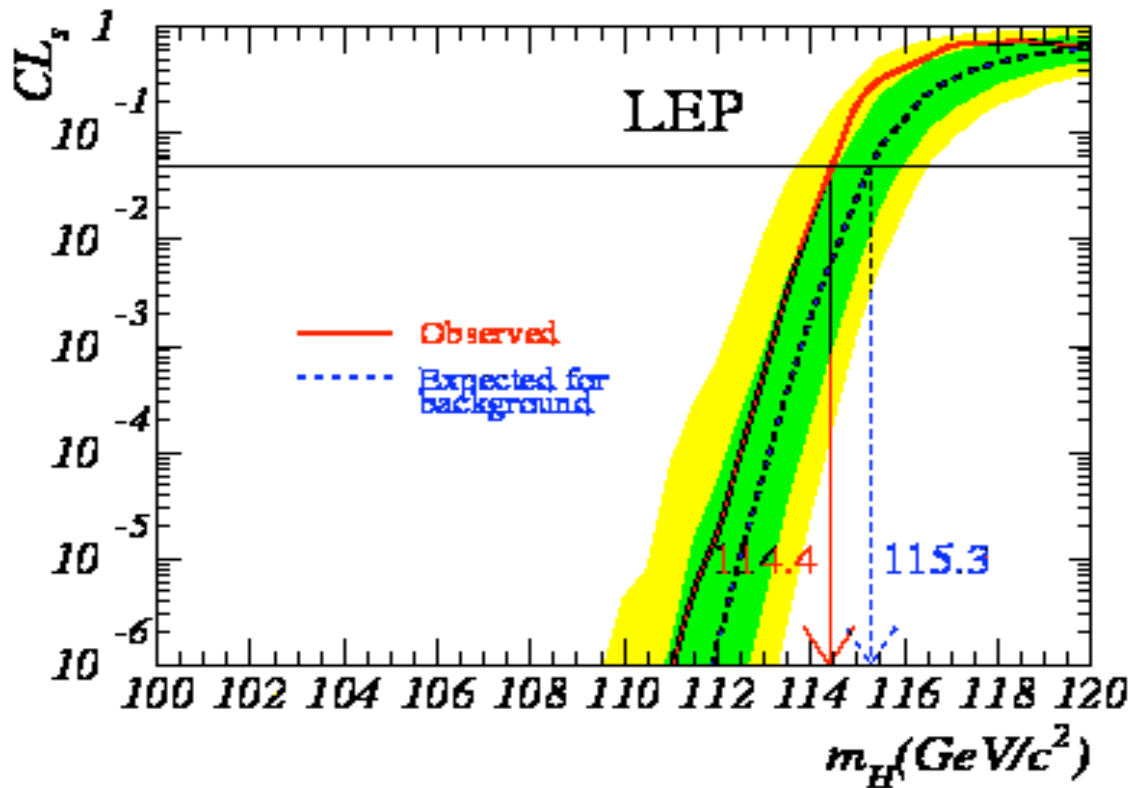
**LEP**      **0.09**

**4-jets**      **0.05**

**$l+\nu+\tau$**       **0.37**

**$CL_{s+b}$  ( $M_h=115$ ) = 0.15**

## Il limite combinato



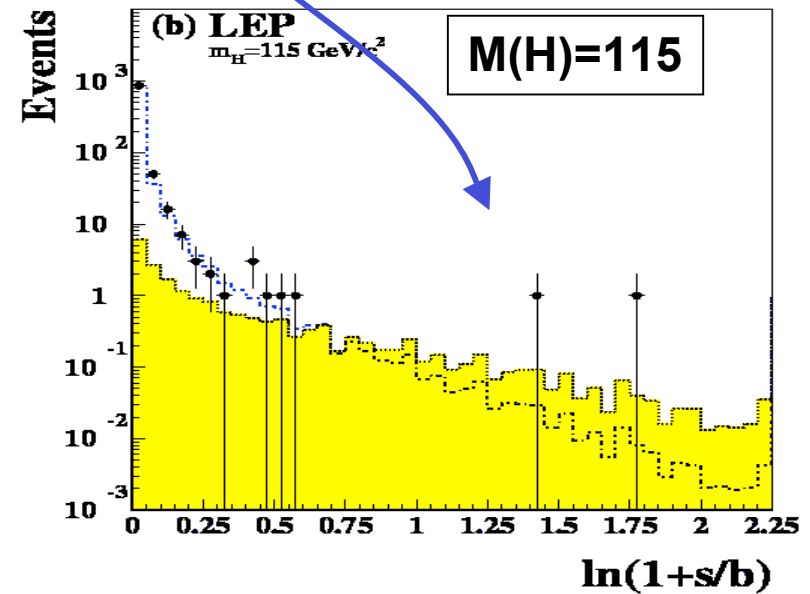
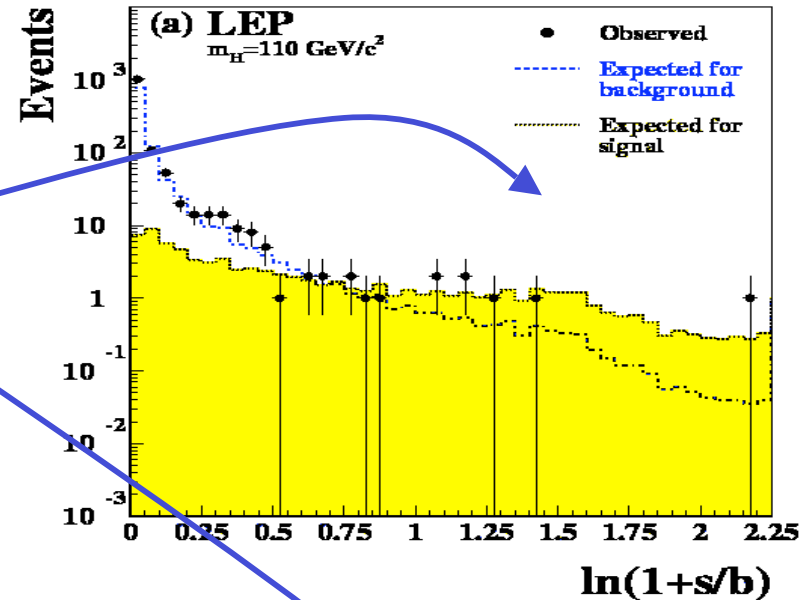
	Exp	Obs
ALEPH	113.5	111.5
DELPHI	113.3	114.1
L3	112.4	112.0
OPAL	112.7	112.7
<b>LEP</b>	<b>115.3</b>	<b>114.4</b>
4-jets	114.5	113.3
l+v+τ	114.2	114.2

# Gli eventi

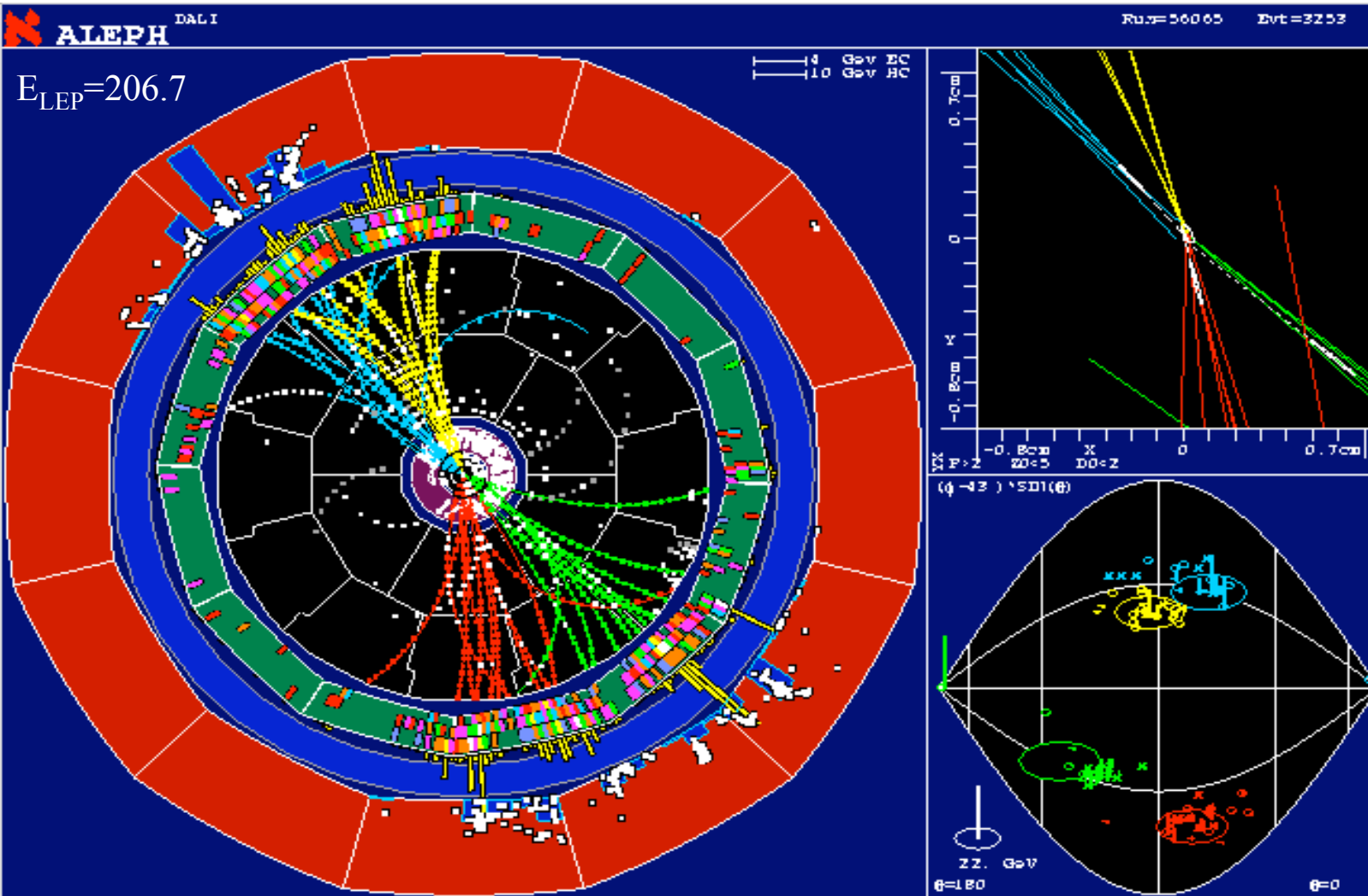
	Expt	$E_{cm}$	channel	$M^{rec}$ (GeV)	$\ln(1 + s/b)$ @ 115 GeV	prev. rank.
1	A	206.6	4 jet	114.1	1.76	1
2	A	206.6	4 jet	114.4	1.44	2
3	A	206.4	4 jet	109.9	0.59	3
4	L	206.4	Emiss	115.0	0.53	4
5	A	205.1	Lept.	117.3	0.49	7
6	A	206.5	Tau	115.2	0.45	8
7	O	206.4	4 jet	108.2	0.43	5
8	A	206.4	4 jet	114.4	0.41	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	

I primi 4 eventi mantengono  
il peso piu' alto anche nelle analisi finali

$M(H)=110$



# Uno degli eventi di Aleph- 1



4 b cand.

HZ hyp.

$m_H = 114.4$  GeV/c<sup>2</sup>

NN = 0.997

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

Uno sciame di 22 GeV nel SICAL che dava  $E_{vis} = 252$  GeV  
 e' ora sottratto da un miglior algoritmo:  $m_H = 112.8 \rightarrow m_H = 114.4$

# Uno degli eventi di Aleph-2

2 b cand.

HZ hyp.  
 $m_H = 114 \text{ GeV}$   
 $\pm 3 \text{ GeV}$

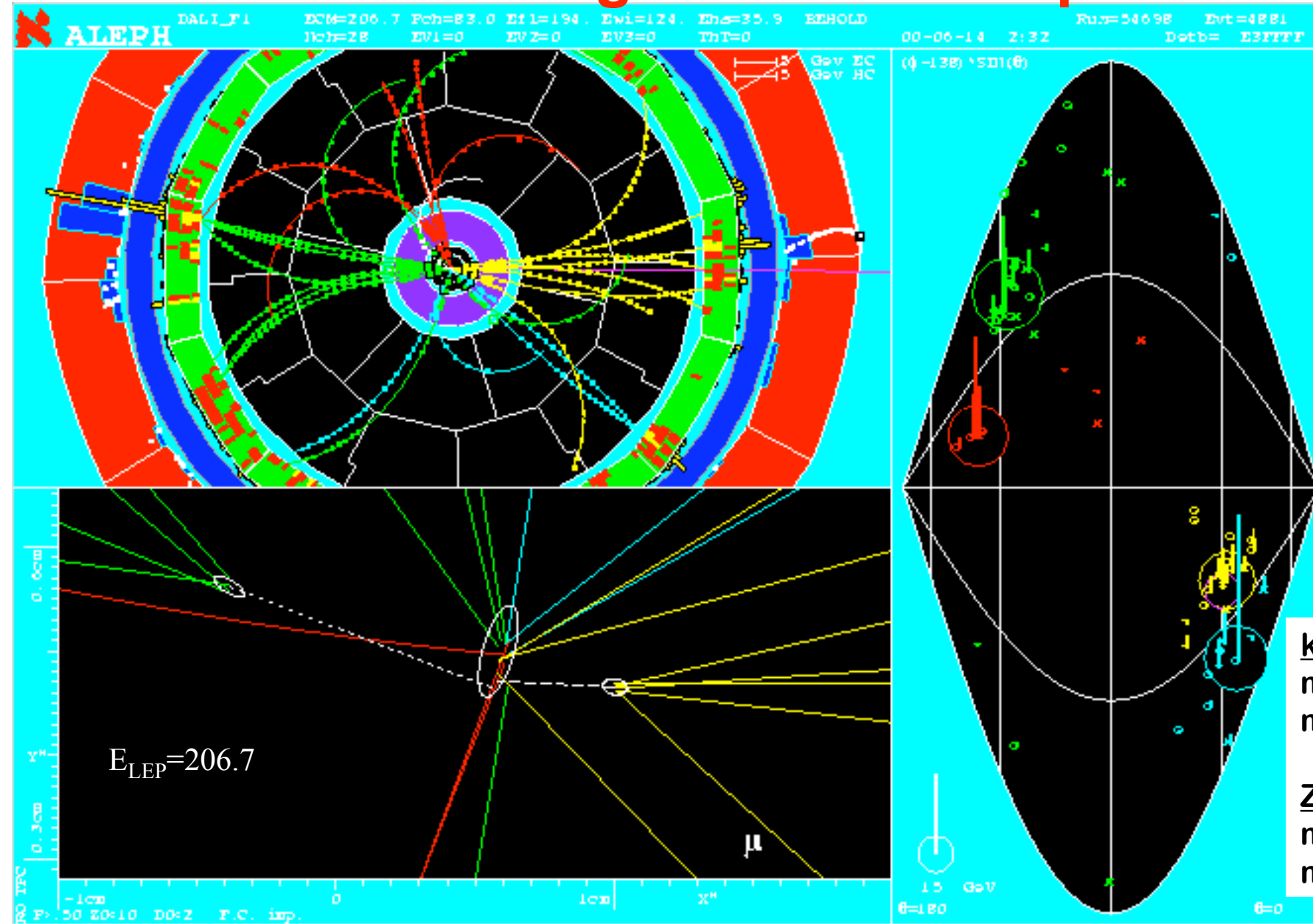
NN = 0.996

jet b-tag:

	Z	H
1	0.14	
2	0.01	
3		0.99
4		0.99

kin. mass fit  
 $m_H = 112.4 \text{ GeV}$   
 $m_Z = 93.3 \text{ GeV}$

ZZ hyp.  
 $m_Z = 102 \text{ GeV}$   
 $m_Z = 91.7 \text{ GeV}$





# Uno degli eventi di Aleph-3

4 b cand.

$m_H = 110 \text{ GeV} \pm 3 \text{ GeV}$

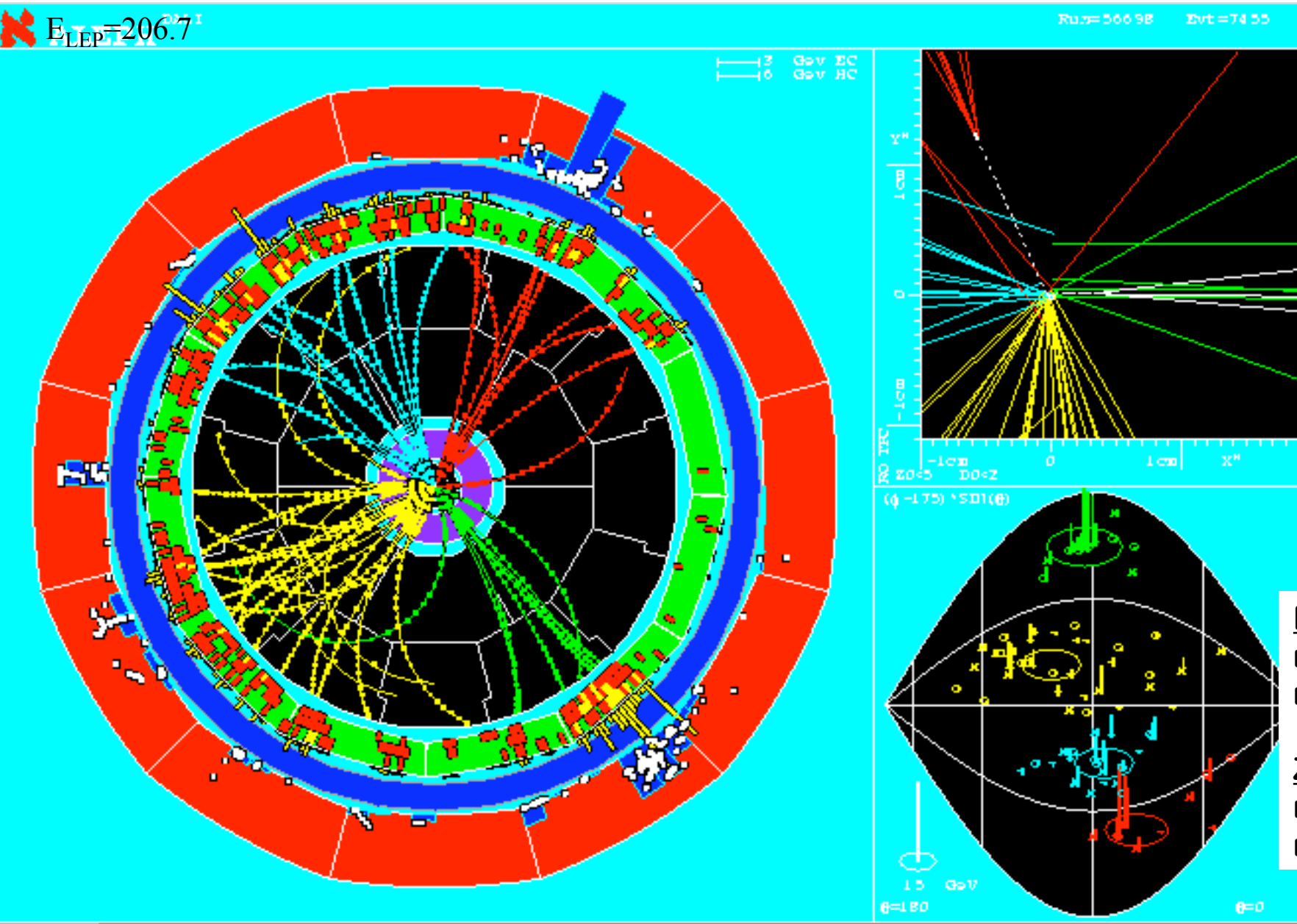
NN = 0.999

jet b-tag:

	Z	H
1	0.99	
2	0.84	
3		0.99
4		0.21

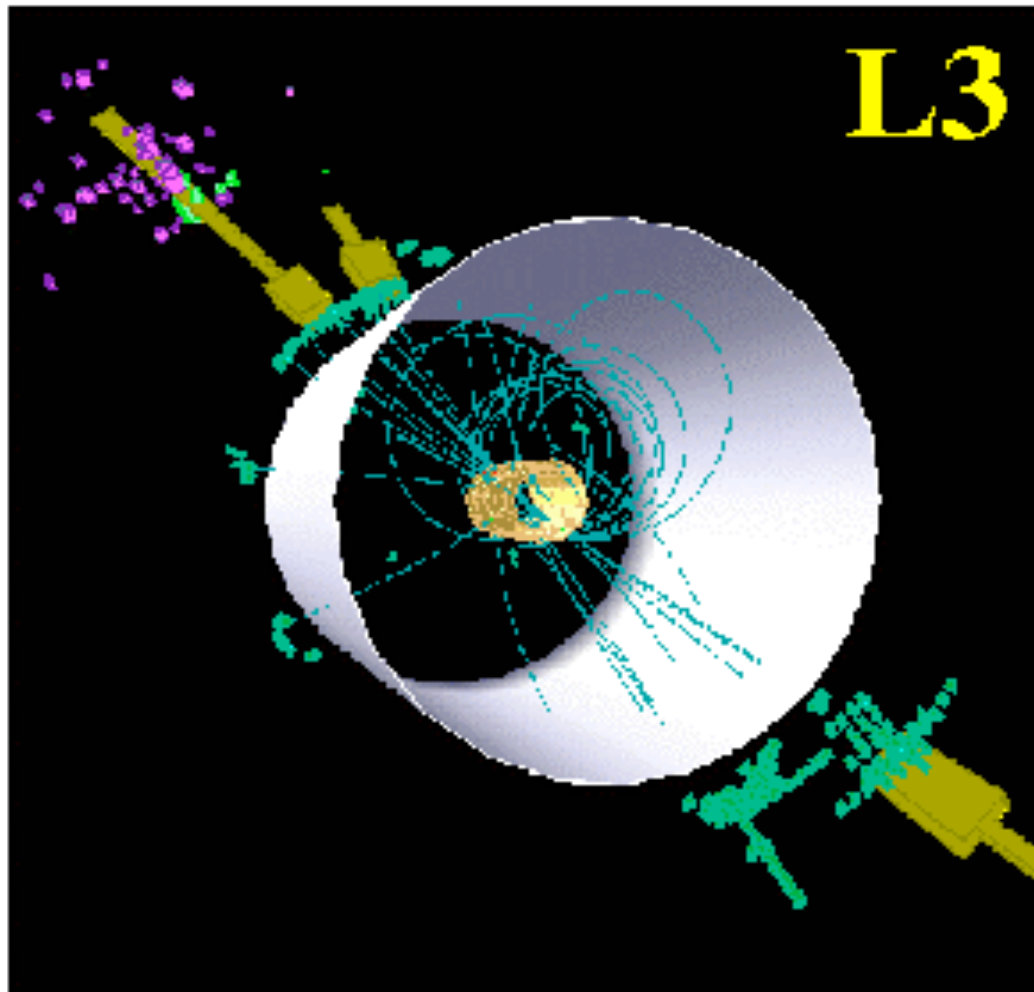
kin. mass fit  
 $m_H = 109.1 \text{ GeV}$   
 $m_Z = 92.3 \text{ GeV}$

ZZ hyp.  
 $m_Z = 100 \text{ GeV}$   
 $m_Z = 99 \text{ GeV}$



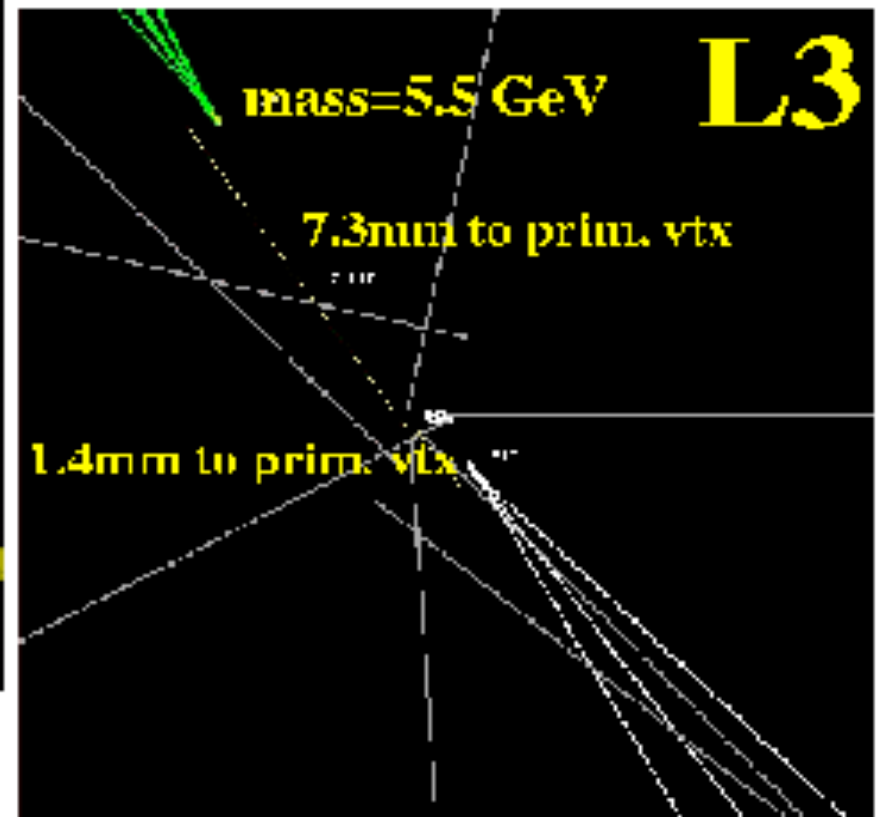
most significant  $H\nu\nu$  candidate

L'evento di L3

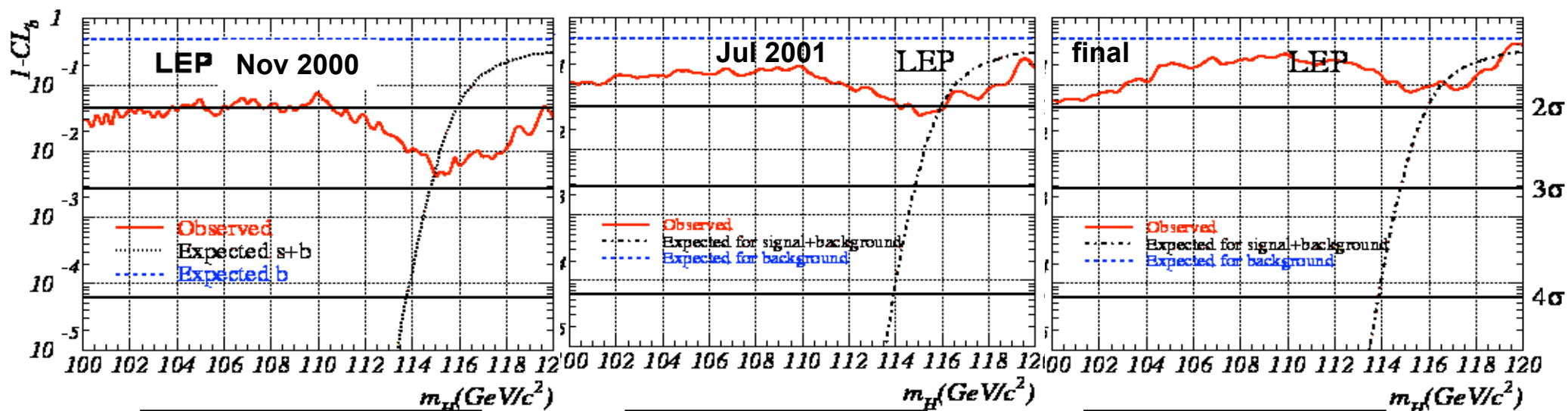


measured  $H$  mass = 114.4 GeV  
 $H$  mass resolution  $\sim 3$  GeV

Secondary vtx's view



# La scoperta dell'Higgs? dalla fine del 2000 al risultato finale



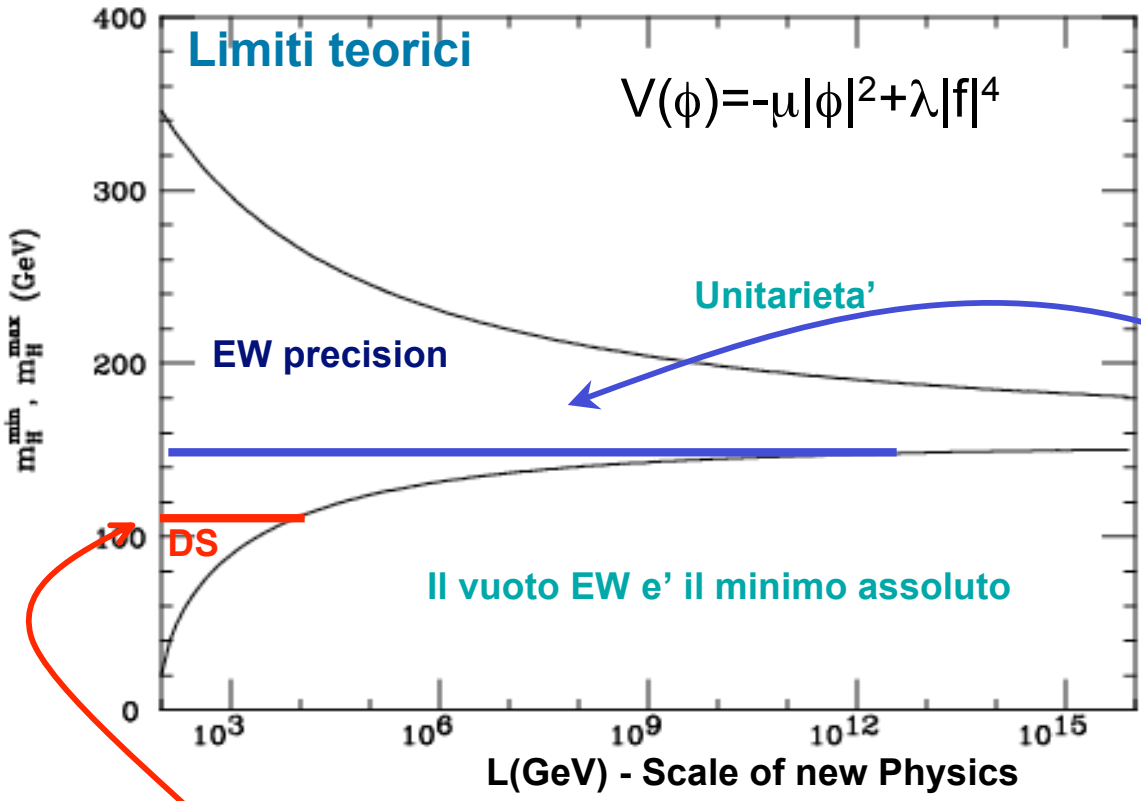
**$4.2 \times 10^{-3}$**   
 $m_H > 113.5$   
 (115.3 expected)

**$\sim 0.03$**   
 $m_H > 114.1$   
 (115.4 expected)

**$\sim 0.09$**   
 $m_H > 114.4$   
 (115.3 expected)

Cambiamenti:	Probabilità del fondo $1-CL_b$ ( $m_H=115$ )		
	Nov 2000	→ Luglio 2001	→ finale
ALEPH:	0.00065 (to HWG) 0.0011 (publ.)	→ 0.0015	→ 0.0024
DELPHI:	0.68	→ 0.77	→ 0.73
L3:	0.068	→ 0.32	→ 0.32
OPAL:	0.19	→ 0.20	→ 0.50

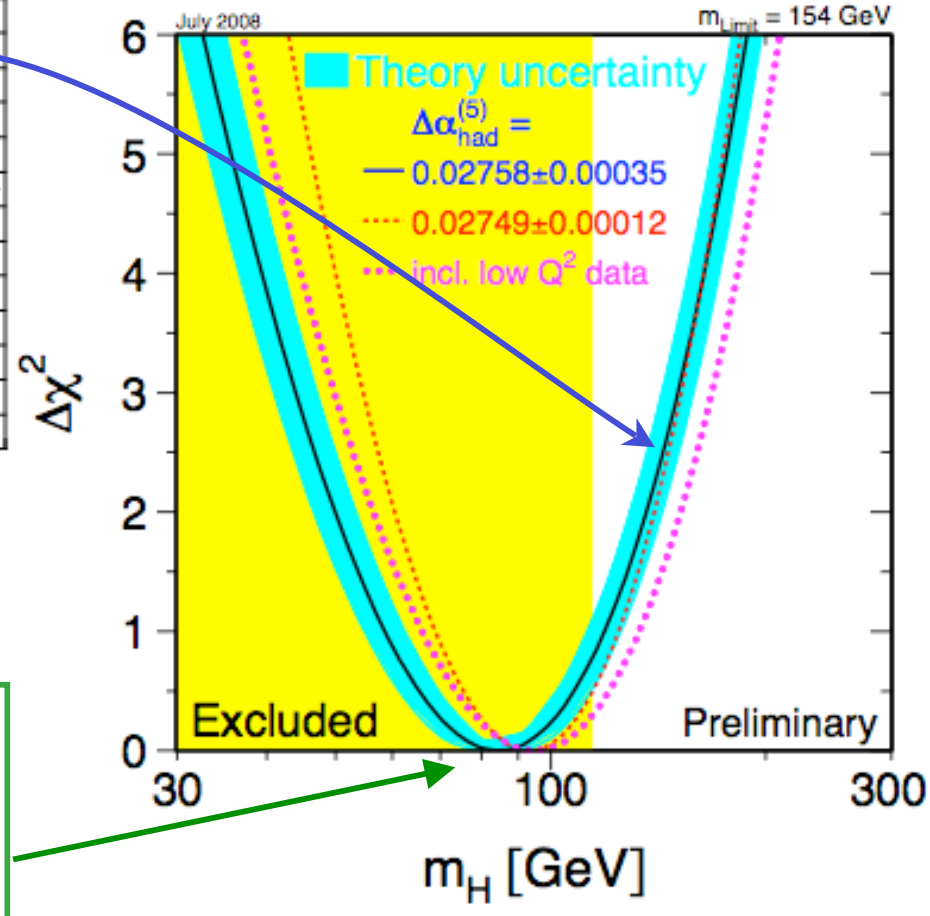
# L'Higgs Standard Model Higgs oggi



**Ricerca diretta**  
 $m(H) \geq 114.4 \text{ GeV}/c^2$   
 at 95% CL

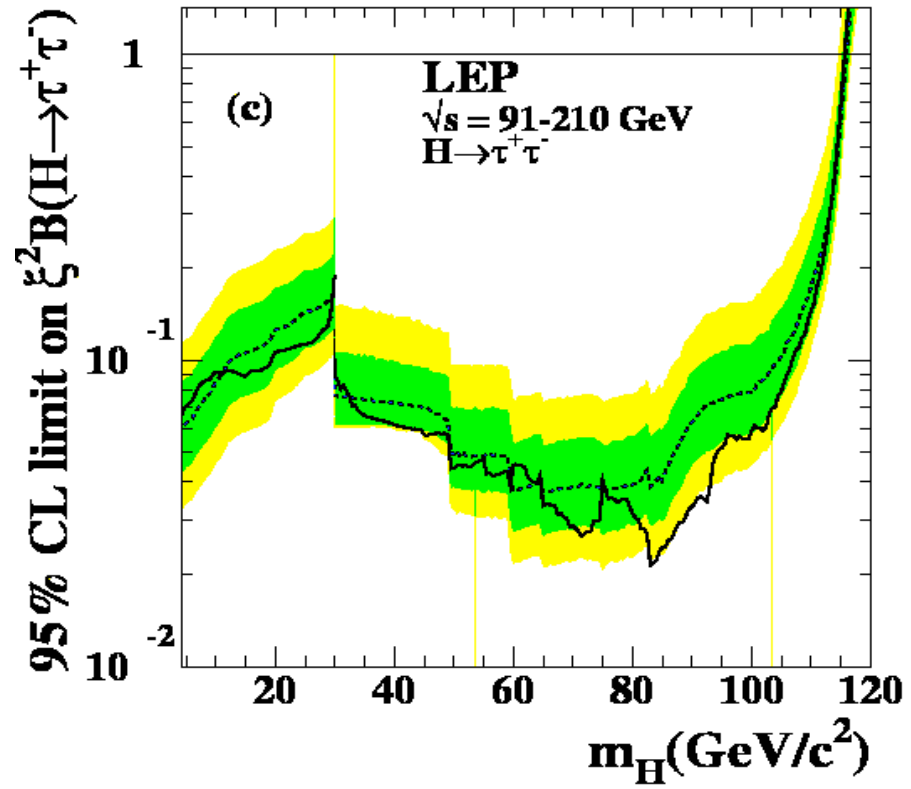
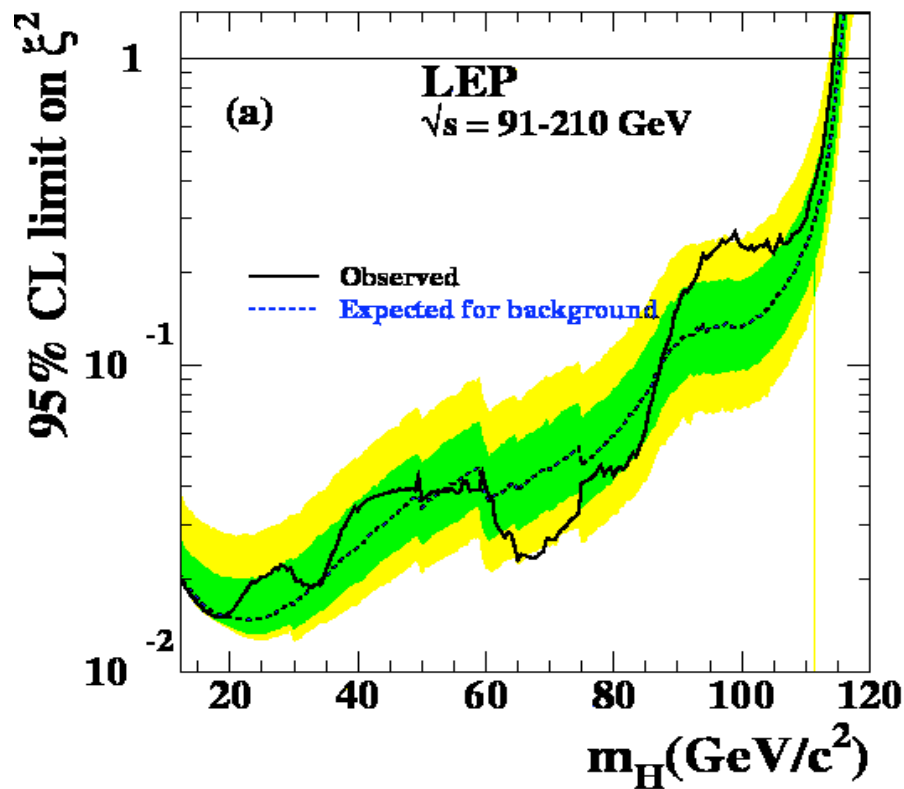
**EW precision measurements**  
 $m(H) = 84^{+34}_{-26} \text{ GeV}/c^2$

$m(H) \leq 154 \text{ GeV}/c^2$   
 at 95% CL



# L'accoppiamento HZZ

Il limite superiore al 95%CL su  $(g_{HZZ}/g_{HZZ}^{SM})^2$ :  
i.e. l'accoppiamento HZZ rispetto all'accoppiamento SM



Da 10 a 85 GeV la  $\sigma_{obs}$  e' ~20 volte piu' piccola di quella del SM