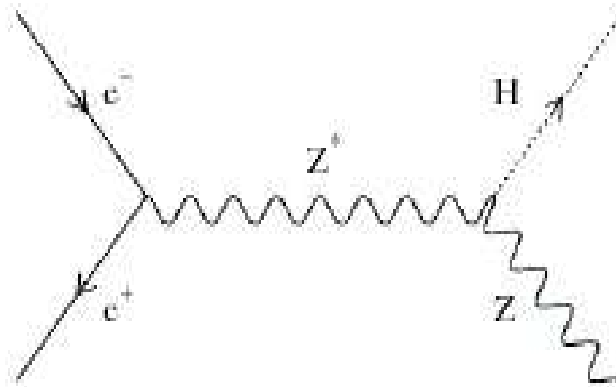


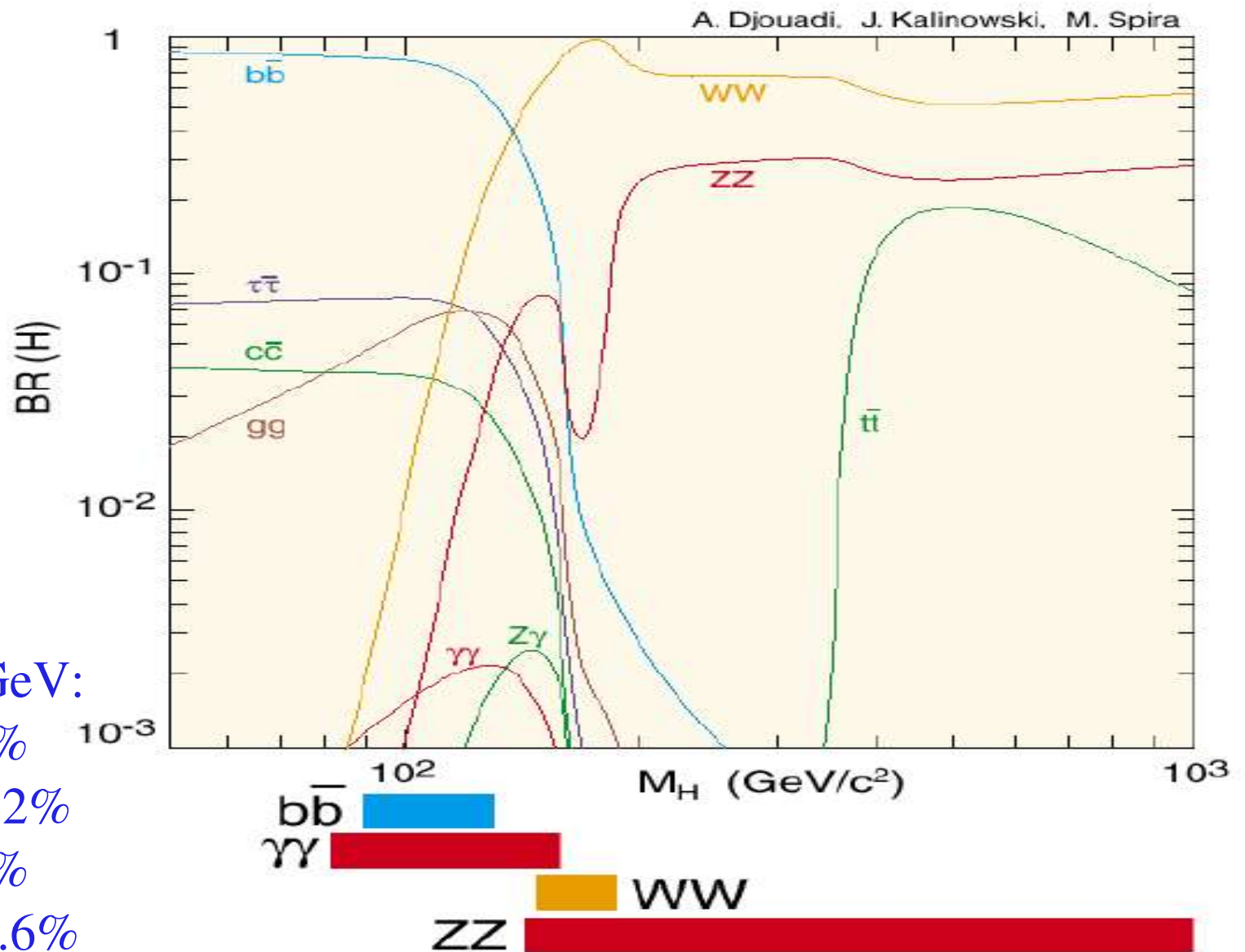
# Search for the Standard Model Higgs Boson at LEP

combined results from ALEPH, DELPHI, L3, and OPAL collaborations  
references: results of Higgs working group on the web, CERN-EP/2003-001  
combined luminosity of  $3 \text{ fb}^{-1}$  for cm energies 189 – 209 GeV  
running up to end 2000



dominant process: Higgs strahlung

**decay of Higgs:** dominantly in the heaviest fermion pair possible  
for masses accessible at LEP this means  $b\bar{b}$



for Higgs of 115 GeV:

H  $\rightarrow$   $b\bar{b}$  74%

H  $\rightarrow$   $\tau^+\tau^-$  7.2%

H  $\rightarrow$   $W^+W^-$  7%

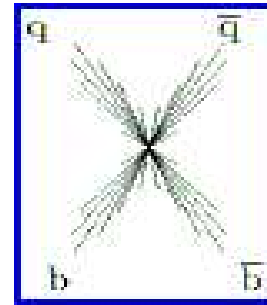
H  $\rightarrow$   $g\bar{g}$  6.6%

H  $\rightarrow$   $c\bar{c}$  3.3%

final state topologies investigated at LEP:

four jet final state

$$(H \rightarrow b\bar{b})(Z \rightarrow q\bar{q})$$



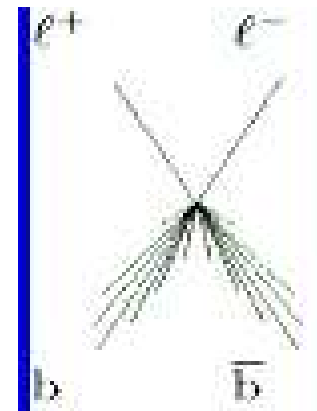
missing energy final state

$$(H \rightarrow b\bar{b})(Z \rightarrow \nu\bar{\nu})$$



leptonic final state  
(ee or mu mu)

$$(H \rightarrow b\bar{b})(Z \rightarrow \ell^+ \ell^-)$$



tau-leptonic final state

$$(H \rightarrow b\bar{b})(Z \rightarrow \tau^+ \tau^-)$$
$$(H \rightarrow \tau^+ \tau^-)(Z \rightarrow q\bar{q})$$



the challenge: the predicted cross section for Higgs production is orders of magnitude smaller than the total e+e- cross section

- i) very good back-ground suppression needed
- ii) very good understanding of remaining background

at  $\sqrt{s} = 209 \text{ GeV}$

$\sigma(e+e- \rightarrow qq\bar{q}) = 100 \text{ pb}$

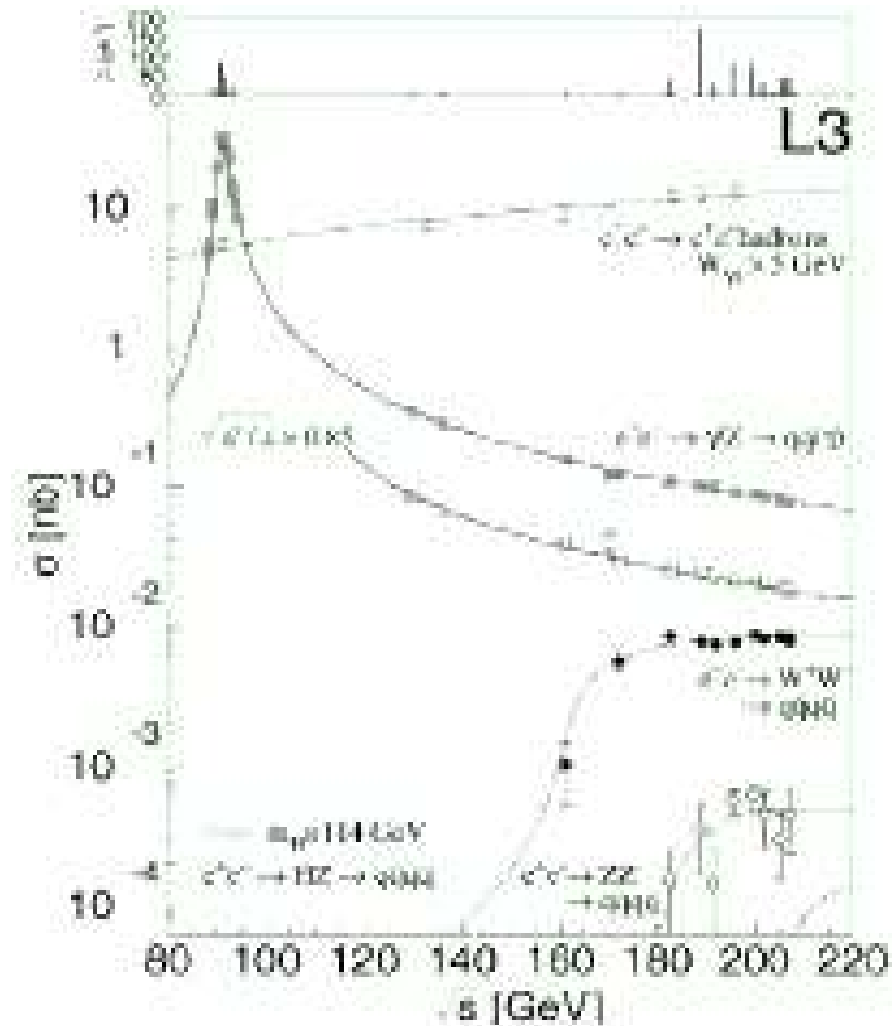
about 20 k events per year

$\sigma(e+e- \rightarrow HZ \rightarrow qq\bar{q}\bar{q}) = 0.1 \text{ pb}$   
for Higgs of 114 GeV

$\sigma(e+e- \rightarrow ZZ \rightarrow qq\bar{q}\bar{q}) = 10 \text{ pb}$

but: Higgs couples strongly to heavy quarks, crucial role of

“b-tagging”

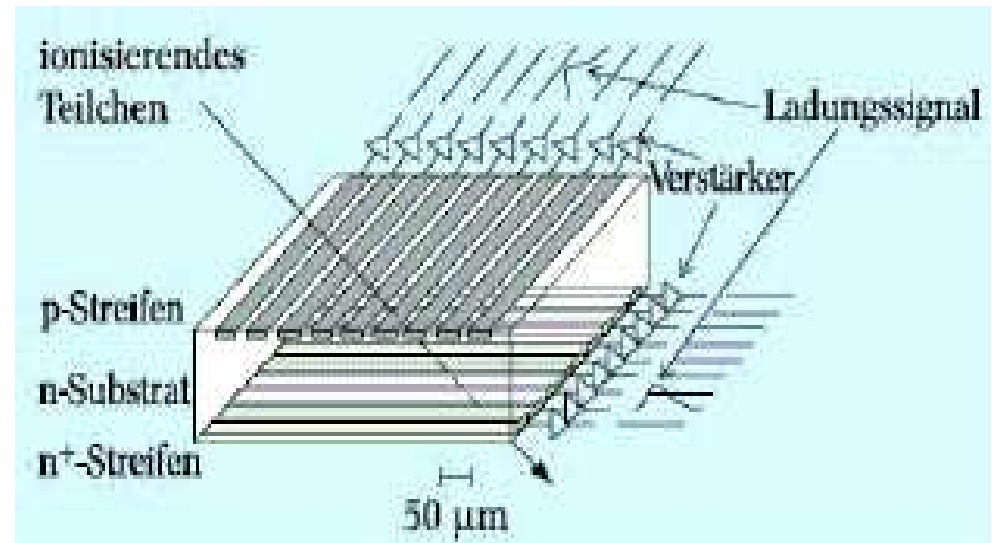


b-quark hadronizes into a jet containing a  $B^0$ -meson  
lifetime of  $B^0$ -meson 1.5 ps, typical momentum 5-10 GeV, it will fly mm  
before it decays

needed: precise vertex determination plus search for two jets each  
containing a secondary decay vertex (decay of  $B^0$ ) some distance away.

reconstruct invariant mass of these two jets (Higgs mass)  
and invariant mass of the other two jets (those need to give 90 GeV)

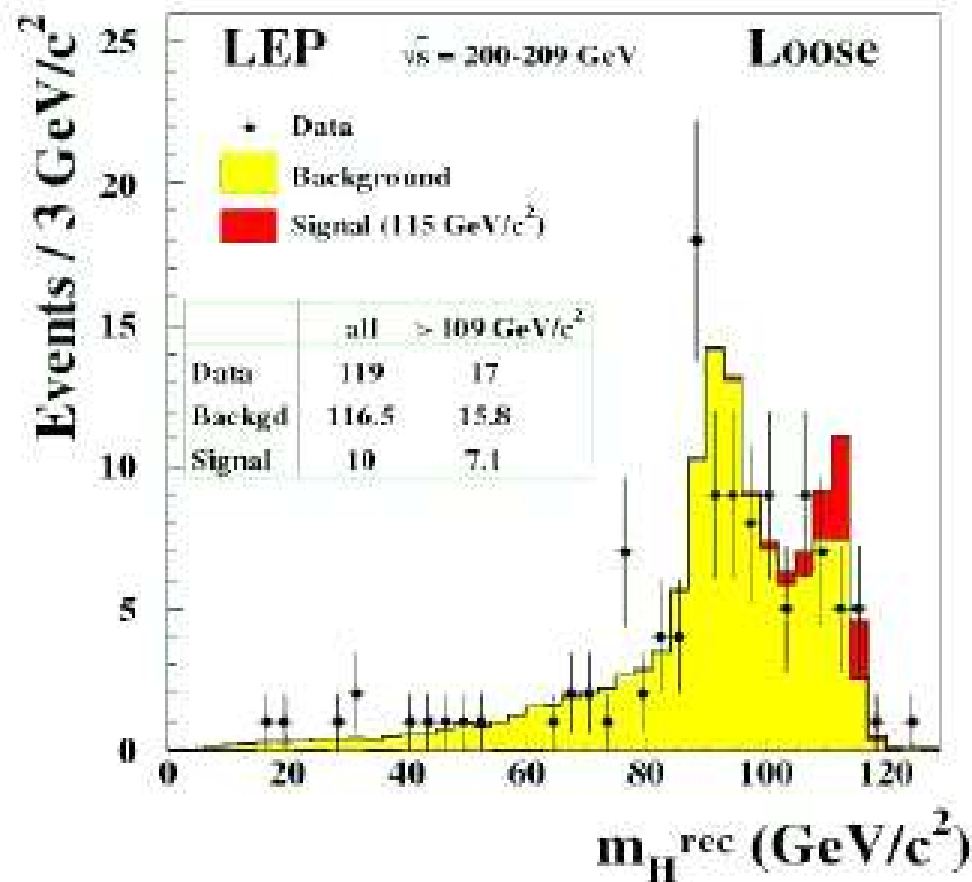
Si microstrip detectors with Si  
strips of 100  $\mu\text{m}$  pitch  $\rightarrow$  vertex  
resolution of order 10  $\mu\text{m}$



# combined resulting reconstructed Higgs mass distribution

obviously this plot is not  
conclusive  
data consistent with yellow or  
yellow + red

one can use sophisticated  
statistical method to obtain precise  
likelihood for Higgs of certain  
mass respectively an exclusion  
limit



background peaks at Z mass because of  
 $ZZ \rightarrow 4 \text{ jets}$

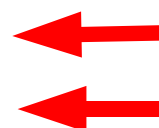
- for each channel (set of data): bin data in terms of 2 variables  
reconstructed Higgs mass  $m_H^{\text{rec}}$  and  
G (combines all important event features: tagging variables, likelihood functions,  
energy,...)

- for each channel and bin in the  $(m_H^{\text{rec}}, G)$  plane there exist

number of selected data events

number of expected background events

number of expected signal events for a  
set of hypothetical Higgs masses



from detailed Monte-Carlo  
simulations including syste-  
matic errors and their corr.

- observed data configuration in  $(m_H^{\text{rec}}, G)$  plane subjected to a likelihood ratio  
test of two hypothetical scenarios:

background scenario – assumes data receive contributions from background only

signal + background scenario – contributions from Standard Model Higgs assumed  
in addition to background

obtain likelihood ratio  $Q = \mathcal{L}_{s+b} / \mathcal{L}_b$  and use log. form  $-2 \ln Q$  as test statistic

approximately equal to difference in  $\chi^2$  when data configuration is compared to  
background or signal+background hypothesis

note: can evaluate this for individual events as well or for a small subset e.g. only L3

combined set of all channels and all experiments:

positive values: data more background like  
negative values: data more signal+background like  
for  $m > 115$  GeV hypothesis of SM Higgs of such a mass slightly more favored

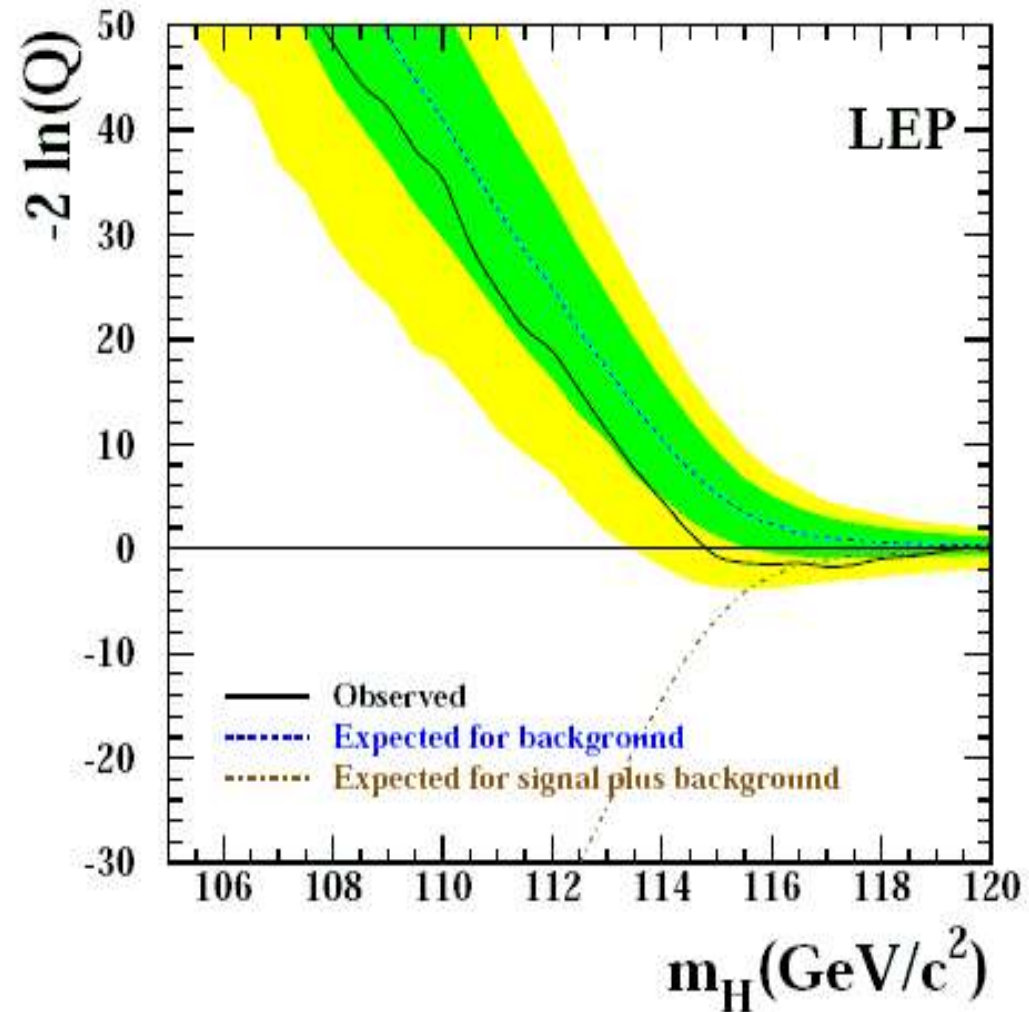


Figure 1: Observed and expected behaviour of the test statistic  $-2 \ln Q$  as a function of the test mass  $m_H$ , obtained by combining the data of the four LEP experiments. The full curve represents the observation; the dashed curve shows the median background expectation; the dark and light shaded bands represent the 68% and 95% probability bands about the median background expectation. The dash-dotted curve indicates the expectation for  $-2 \ln Q$ , given the signal plus background hypothesis, when the signal mass on the abscissa is tested. For the expected behaviours, the medians of the simulated distributions are shown.

now more differential:  
each experiment alone  
and four-jet as compared to  
the rest

result: signal-like deviation  
from background beyond 95%  
confidence level only observed  
by ALEPH

but beyond 114 GeV no  
individual exp. has power to  
distinguish at more than 2  
sigma level (look at simulated  
signal line diving into yellow  
band)

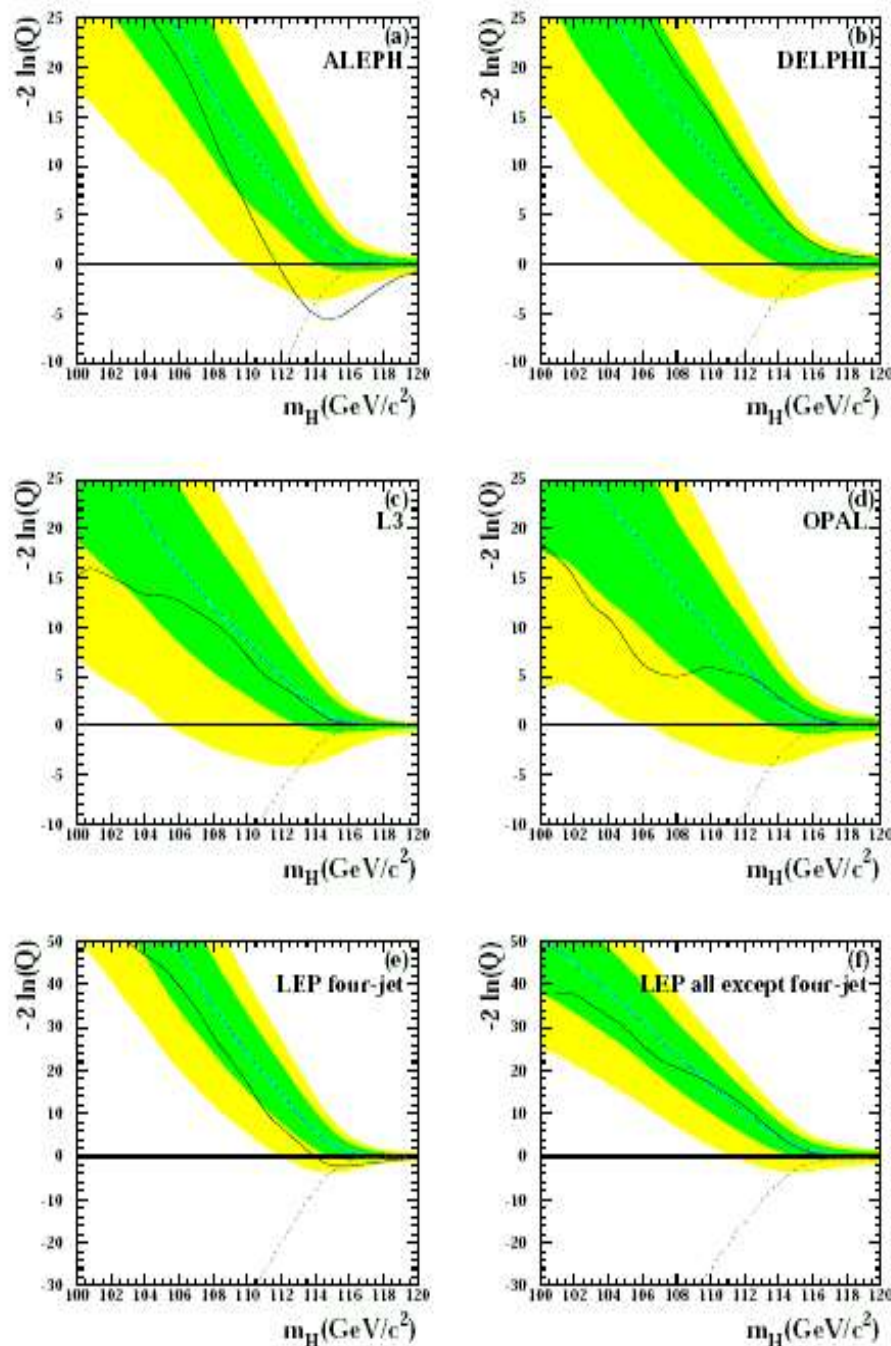


Figure 2: Observed and expected behaviour of the test statistic  $-2 \ln Q$  as a function of the test mass  $m_H$  when the combination procedure is applied to subsets of the LEP data. Plots (a) to (d): data sets from individual experiments; (e): the four-jet final state and (f): all except the four-jet final state, with the data of the four experiments combined. The same notation as in Figure 1 is used.

how do individual events contribute to the statistic measure  $-2 \ln Q$ ?  
 use binned likelihood function to get contribution as an event weight  
 (simplified  $\ln(1+s/b)$  where  $s$  and  $b$  are estimates for signal and background in each bin)

evaluated for candidate events with highest weight for test mass of 115 GeV

for this mass these events contribute together 40% of total weight of likelihood

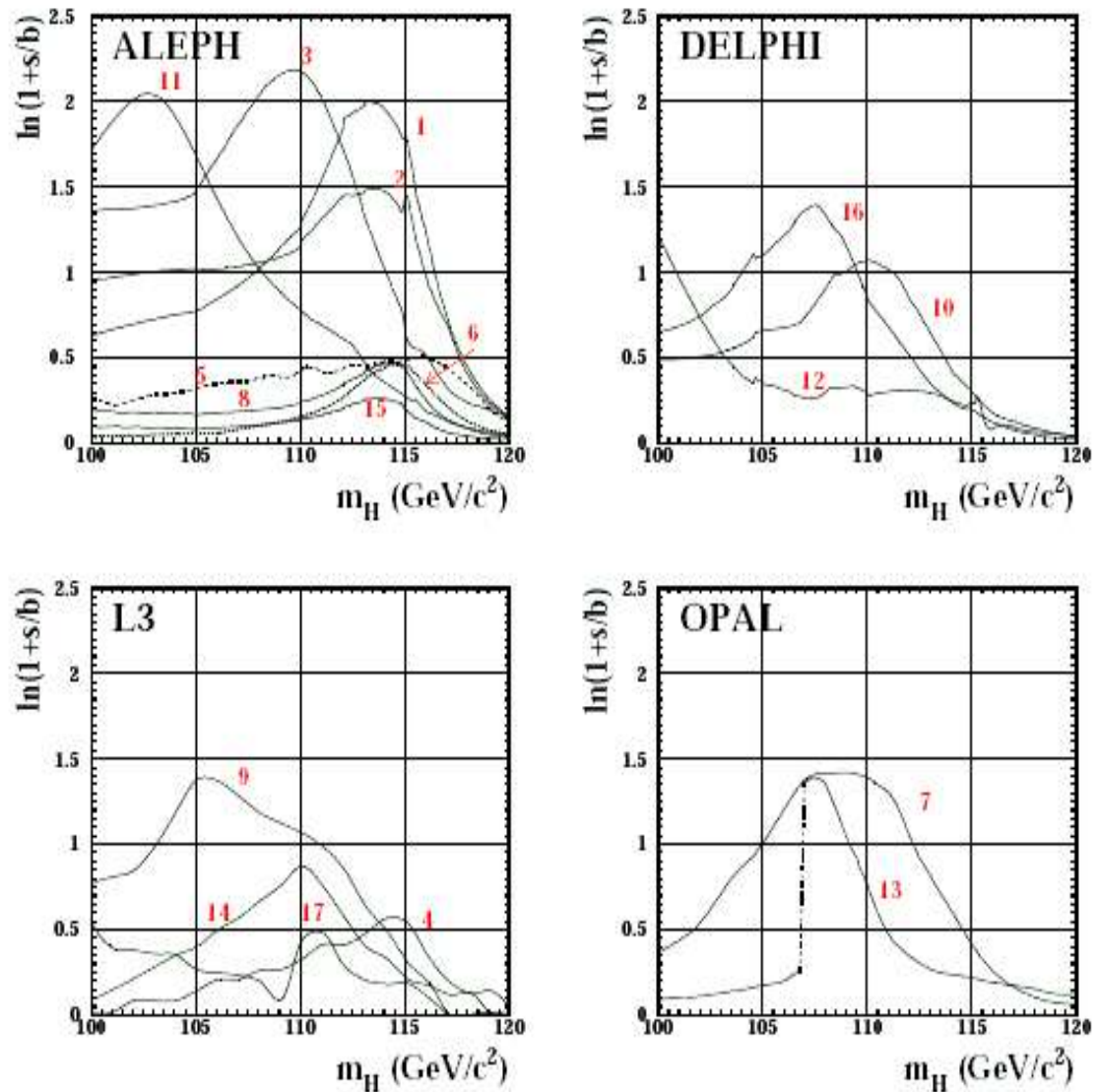
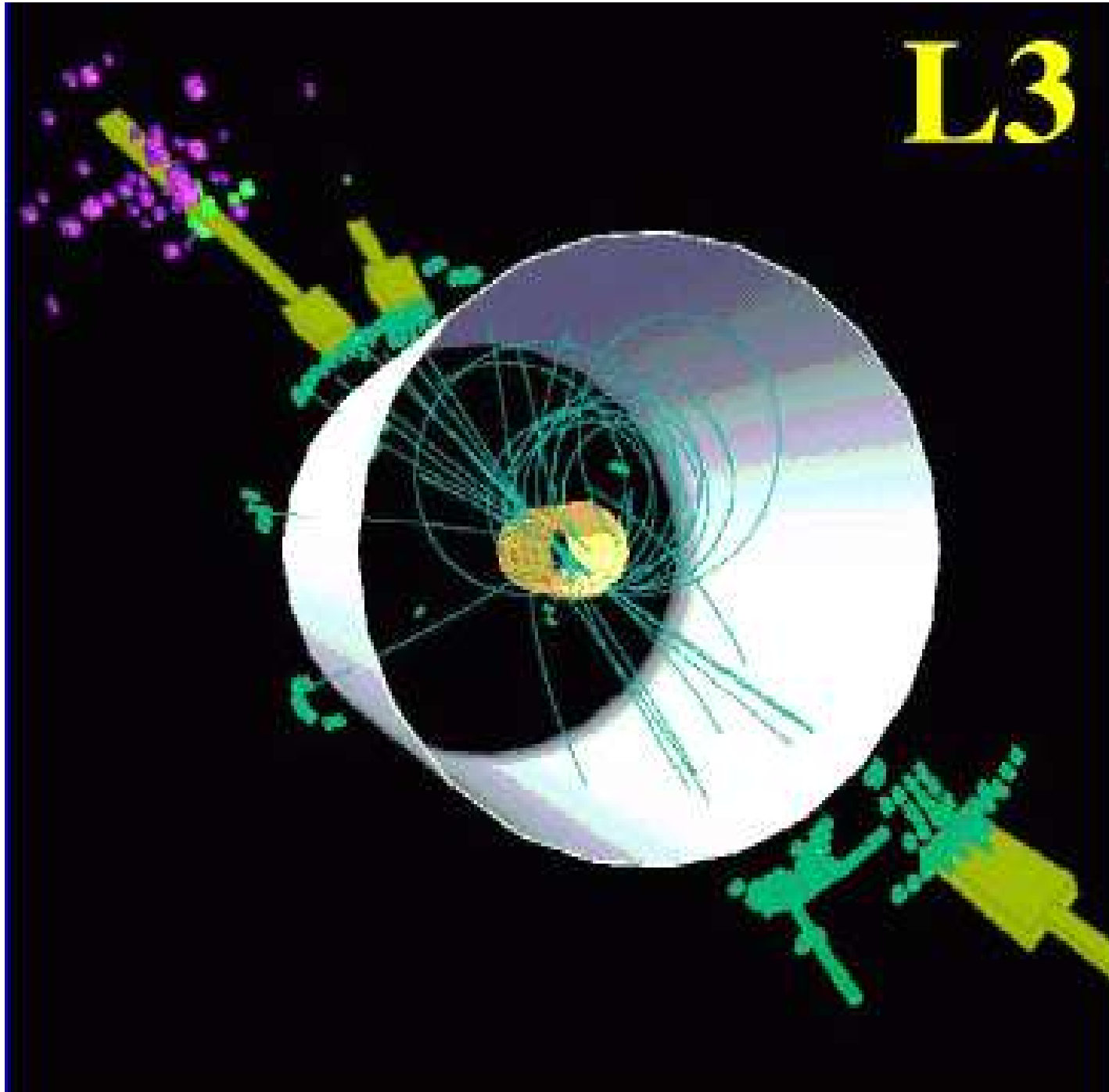


Figure 3: Evolution of the event weight  $\ln(1 + s/b)$  with test mass  $m_H$  for the events which have the largest contributions to  $-2 \ln Q$  at  $m_H = 115 \text{ GeV}/c^2$ . The labels correspond to the candidate numbers in the first column of Table 2. The sudden increase in the weight of the OPAL missing energy candidate labelled "13" at  $m_H = 107 \text{ GeV}/c^2$  is due to switching from the low-mass to high-mass optimization of the search at that mass. A similar increase is observed in the case of the L3 four-jet candidate labelled "17" which is due to the test mass dependent attribution of the jets to the Z and Higgs bosons.

	Experiment	$\sqrt{s}$ (GeV)	Final state topology	$m_{\text{H}}^{\text{rec}}$ (GeV/ $c^2$ )	$\ln(1 + s/b)$ at 115 GeV/ $c^2$
1	ALEPH	206.6	Four-jet	114.1	1.76
2	ALEPH	206.6	Four-jet	114.4	1.44
3	ALEPH	206.4	Four-jet	109.9	0.59
4	L3	206.4	Missing energy	115.0	0.53
5	ALEPH	205.1	Leptonic	117.3	0.49
6	ALEPH	208.0	Tau	115.2	0.45
7	OPAL	206.4	Four-jet	111.2	0.43
8	ALEPH	206.4	Four-jet	114.4	0.41
9	L3	206.4	Four-jet	108.3	0.30
10	DELPHI	206.6	Four-jet	110.7	0.28
11	ALEPH	207.4	Four-jet	102.8	0.27
12	DELPHI	206.6	Four-jet	97.4	0.23
13	OPAL	201.5	Missing energy	108.2	0.22
14	L3	206.4	Missing energy	110.1	0.21
15	ALEPH	206.5	Four-jet	114.2	0.19
16	DELPHI	206.6	Four-jet	108.2	0.19
17	L3	206.6	Four-jet	109.6	0.18

Table 2: Properties of the candidates with the largest contribution to  $-2 \ln Q$  at  $m_{\text{H}} = 115 \text{ GeV}/c^2$ . For each candidate, the experiment, the centre-of-mass energy, the final-state topology, the reconstructed Higgs boson mass and the weight at  $m_{\text{H}} = 115 \text{ GeV}/c^2$  are listed. The applied selection,  $\ln(1 + s/b) \geq 0.18$  (i.e.  $s/b \geq 0.2$ ) at  $m_{\text{H}} = 115 \text{ GeV}/c^2$ , retains 17 candidates while the expected numbers of signal and background events are 8.4 and 15.8, respectively.

most significant missing energy candidate of L3 - event 4 of table



distribution of event weights  
in agreement with  
background hypothesis

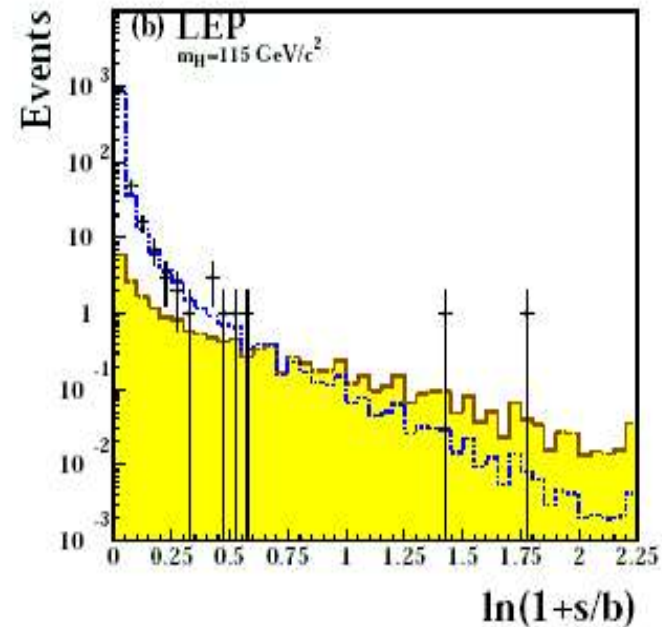
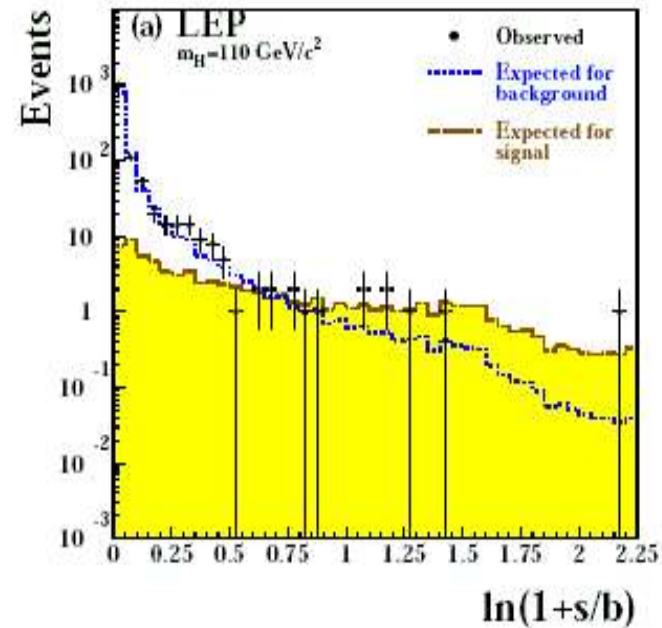


Figure 4: Expected and observed distributions of the event weight  $\ln(1 + s/b)$  for test masses  $m_H$  of (a) 110 and (b) 115  $\text{GeV}/c^2$ . Dashed line histograms: expected distributions for the background; shaded histograms: expected distributions for the signal; points with error bars: selected data.

## Results of hypothesis testing:

significant discriminating power  
for  $m=110$  GeV  
moderate for 115 GeV  
vanishing for 120 GeV

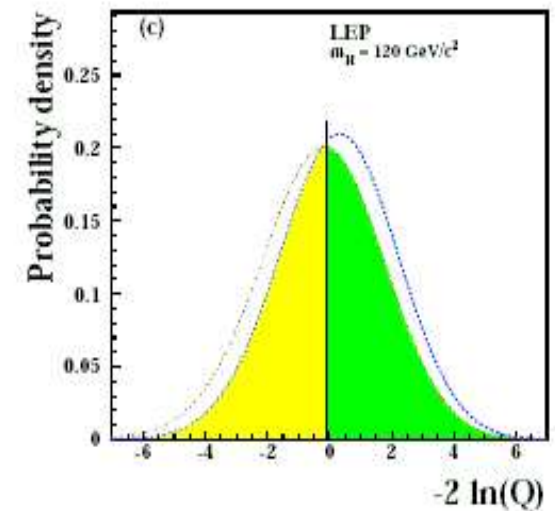
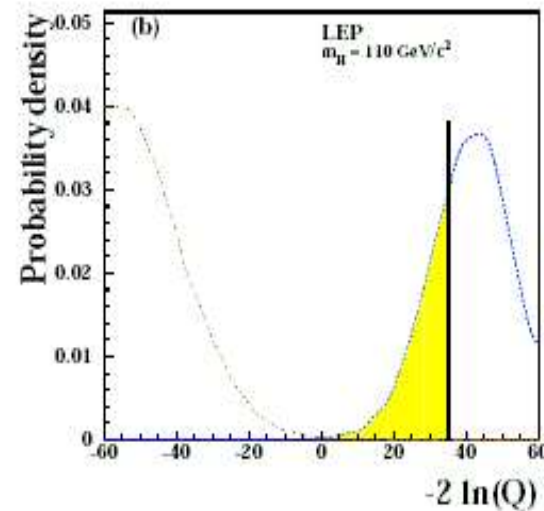
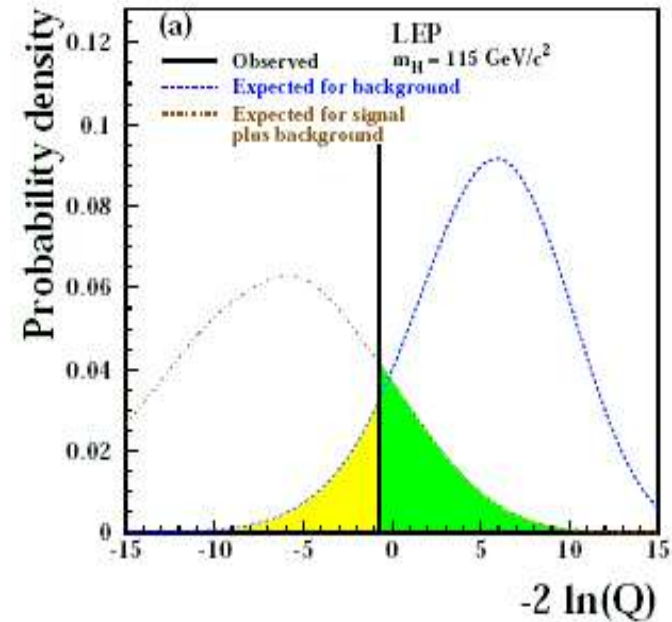


Figure 6: Probability density functions corresponding to fixed test masses  $m_H$ , for the background and signal plus background hypotheses. The observed values of the test statistic  $-2 \ln Q$  are indicated by the vertical lines. The light shaded areas,  $1 - \text{CL}_b$ , measure the confidence for the background hypothesis and the dark shaded areas,  $\text{CL}_{s+b}$ , the confidence for the signal plus background hypothesis. Plot (a): test mass  $m_H = 115 \text{ GeV}/c^2$ ; (b):  $m_H = 110 \text{ GeV}/c^2$ ; (c):  $m_H = 120 \text{ GeV}/c^2$ .

## background confidence:

value of 0.09 near  $m = 115$  GeV  
is 1.7 sigma from background  
hypothesis

note: at 98 GeV value of 0.02 is  
2.3 sigma from background but  
number of events that would  
reproduce this value is order of  
magnitude below value expected  
from SM Higgs.

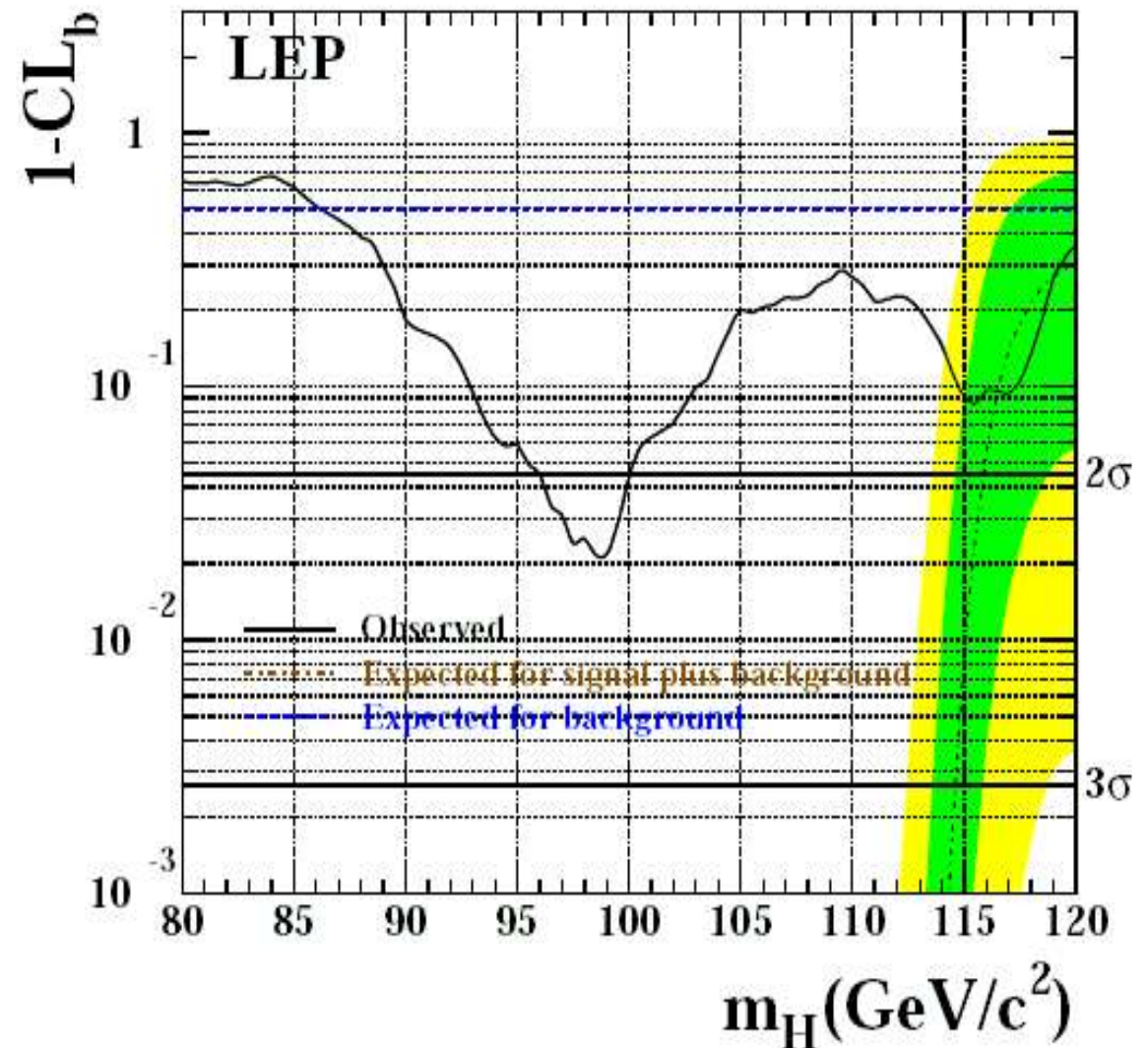


Figure 7: The background confidence  $1 - CL_b$  as a function of the test mass  $m_H$ . Full curve: observation; dashed curve: median expected background confidence. Dash-dotted line: the median expectation for  $1 - CL_b$ , given the signal plus background hypothesis, when the signal mass on the abscissa is tested; the dark and light shaded bands represent the 68% and 95% probability bands about the median expectation. The horizontal solid lines indicate the levels for  $2\sigma$  and  $3\sigma$  deviations from the background hypothesis (see the Appendix for the conversion).

## bounds for Higgs boson mass:

lower bound at 95%  
confidence level

experiments: 114.4 GeV  
expected: 115.3 reflecting a  
slight excess observed in the data  
w.r. to background expect. at  
high mass

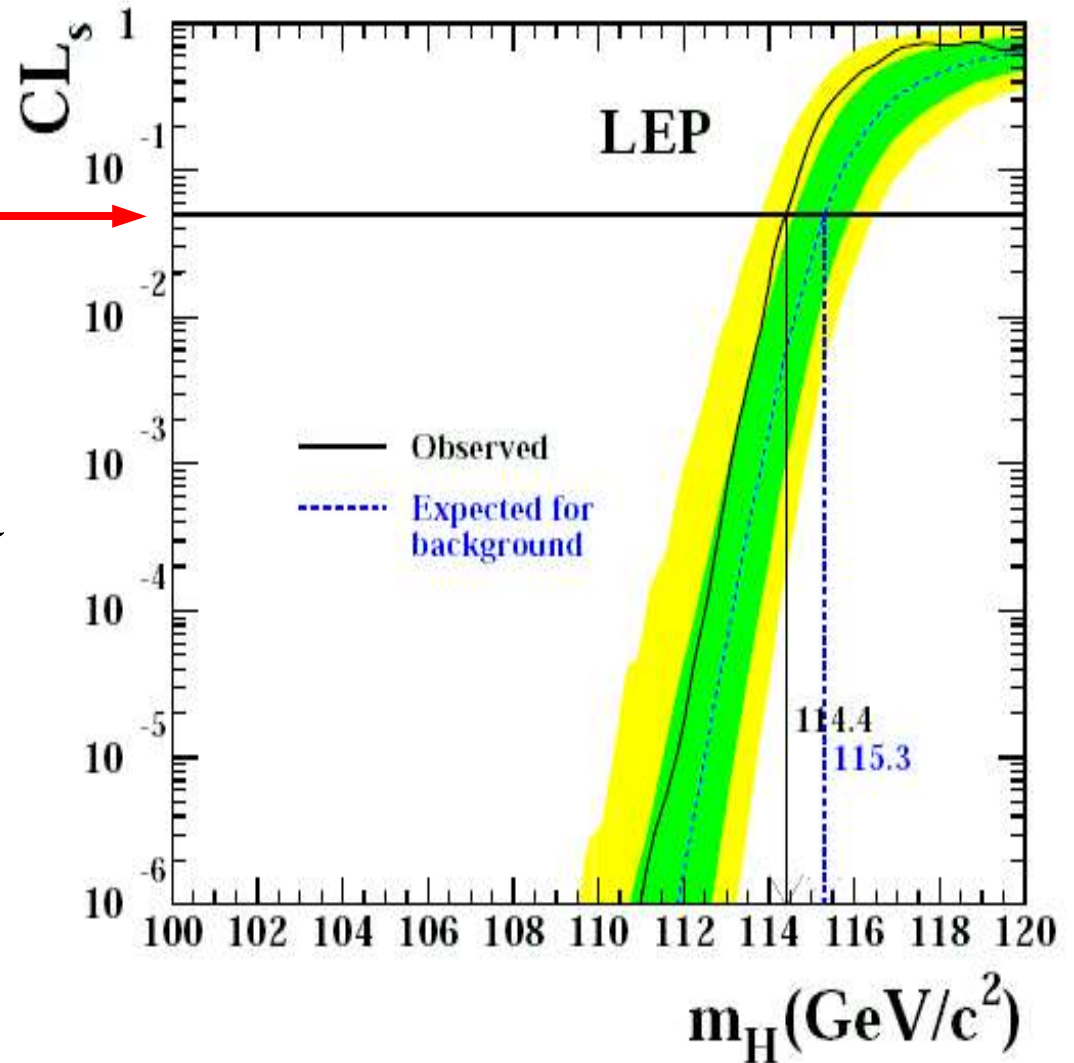


Figure 9: The ratio  $CL_s = CL_{s+b}/CL_b$  for the signal plus background hypothesis, as a function of the test mass  $m_H$ . Solid line: observation; dashed line: median background expectation. The dark and light shaded bands around the median expectation for the background hypothesis correspond to the 68% and 95% probability bands. The intersection of the horizontal line for  $CL_s = 0.05$  with the observed curve is used to define the 95% confidence level lower bound on the mass of the Standard Model Higgs boson.

# Higgs Boson search at LHC

(material from A. de Roeck, Valparaiso 06)

Process	Events/s	Events/year	Other machines
$W \rightarrow e\nu$	15	$10^8$	$10^4$ LEP / $10^7$ Tevatron
$Z \rightarrow ee$	1.5	$10^7$	$10^7$ LEP
$t\bar{t}$	0.8	$10^7$	$10^4$ Tevatron
$b\bar{b}$	$10^5$	$10^{12}$	$10^8$ Belle/BaBar
$\tilde{g}\tilde{g}$ ( $m=1$ TeV)	0.001	$10^4$	—
H ( $m=0.8$ TeV)	0.001	$10^4$	—
Black Holes $M_p=3$ TeV $n=4$	0.0001	$10^3$	

at LHC luminosity of  $10^{33}$   $\text{cm}^{-2}\text{s}^{-1}$  min bias rate:  $10^8$  /s = 2-4 / bunch cross.

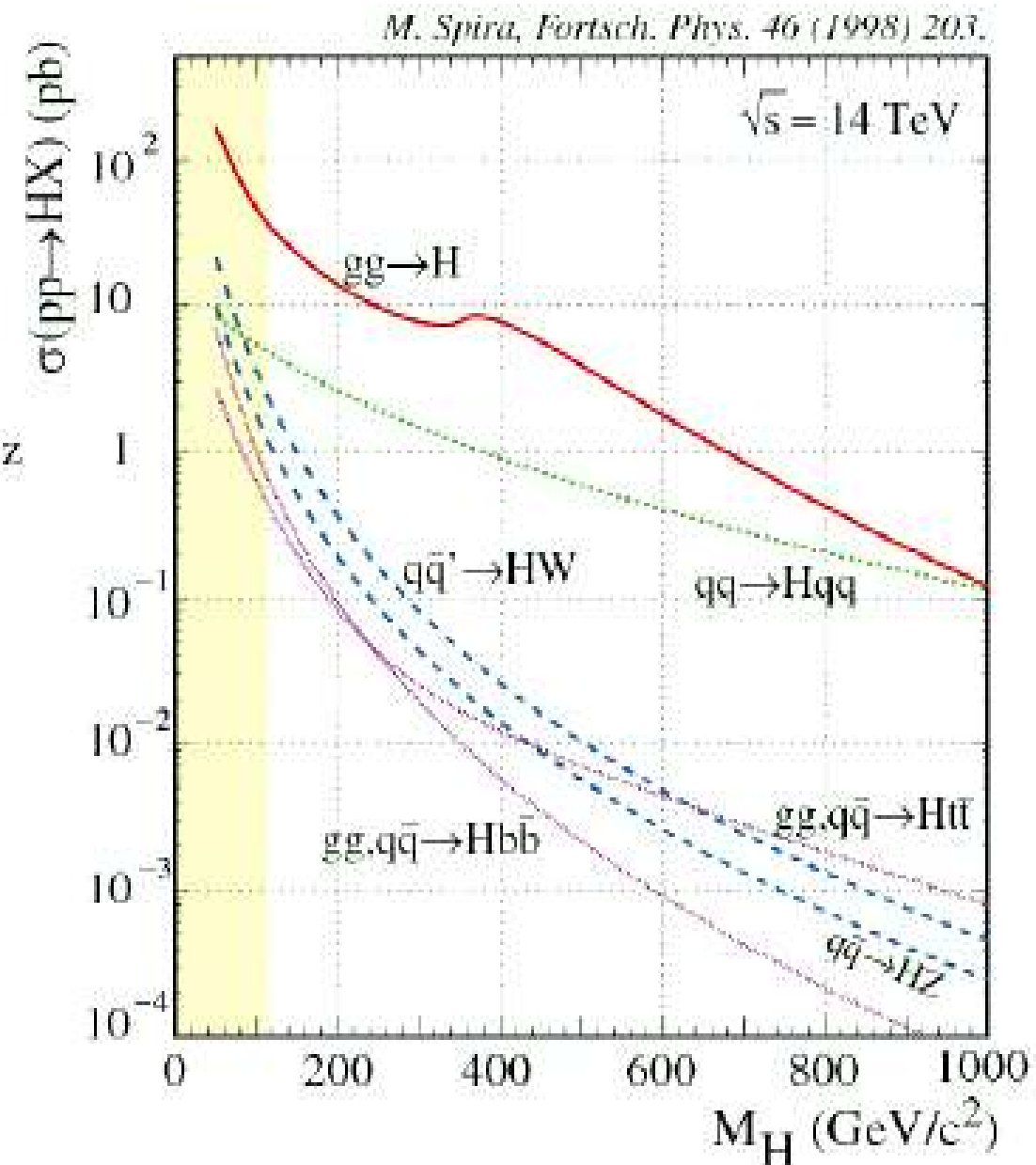
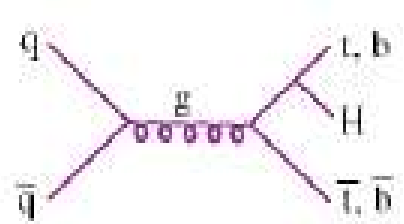
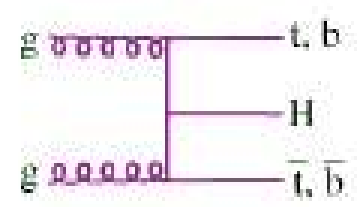
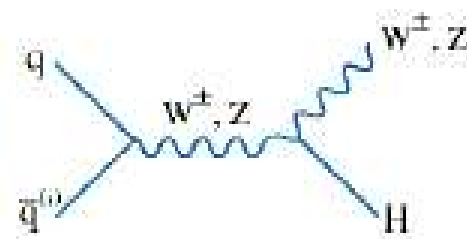
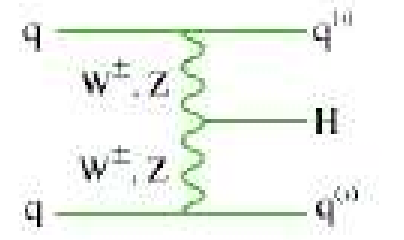
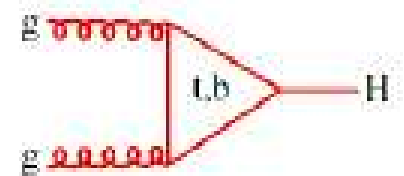
one of main mission of LHC: discover Higgs if mass is below 1 TeV

**Direct:**  
Gluon Fusion  
large bkg. close  
to LEP limit

**Vector Boson  
Fusion (VBF):**  
Distinct Final  
State

**Associated  
Production  
(W or Z):**  
Small  $\sigma$

**Associated  
Production  
(tt or bb):**  
Small  $\sigma$

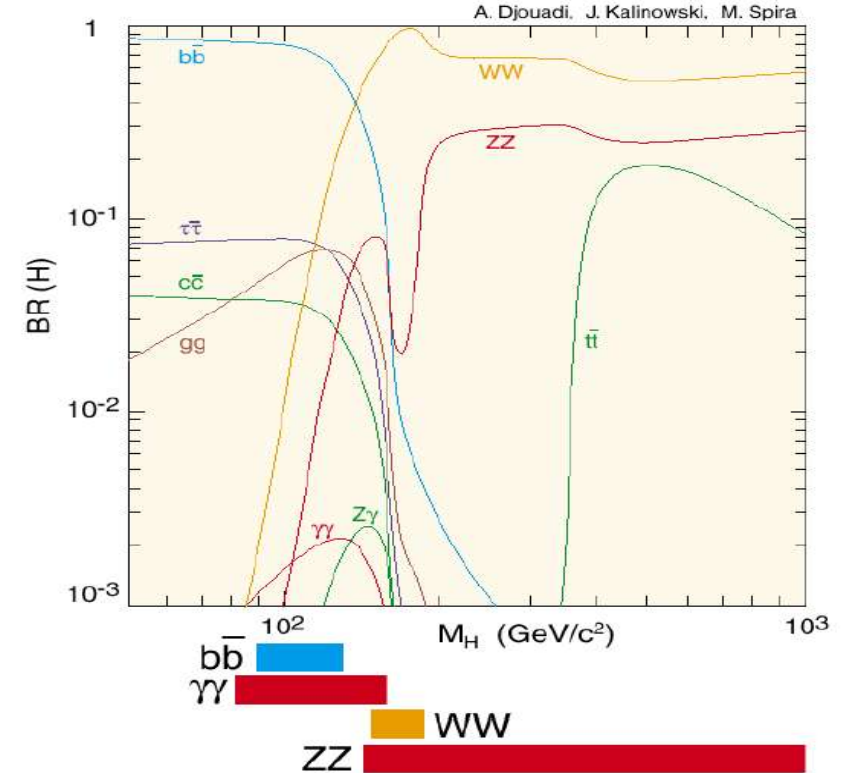


# SM Higgs Search Channels

Low mass  $M_H$  200 GeV

*M. Pieri*

Production	Inclusive	VBF	WH/ZH	ttH
<b>DECAY</b>				
$H \rightarrow \gamma\gamma$	YES	YES	YES	YES
$H \rightarrow bb$			YES	YES
$H \rightarrow \tau\tau$		YES		
$H \rightarrow WW^*$	YES	YES	YES	
$H \rightarrow ZZ^*, Z \rightarrow \ell^+\ell^-$	YES			
$H \rightarrow Z\gamma, Z \rightarrow \ell^+\ell^-$ $\ell = e, \mu$	very low $\sigma$			



Intermediate mass  
(200 GeV  $M_H$  700 GeV)

inclusive  $H \rightarrow WW$

inclusive  $H \rightarrow ZZ$

High mass ( $M_H$  700 GeV)

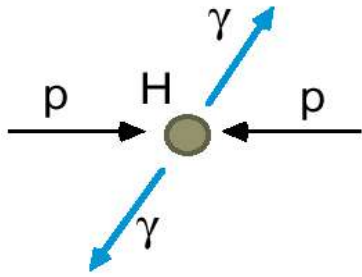
VBF  $qqH \rightarrow ZZ \rightarrow \ell\ell\nu\nu$

VBF  $qqH \rightarrow WW \rightarrow \ell\nu jj$

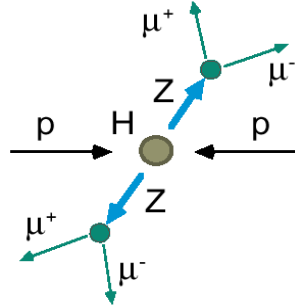
$H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^* \rightarrow 4\ell$  are the only channels with a very good mass resolution  $\sim 1\%$

# Higgs Searches Depending on Mass

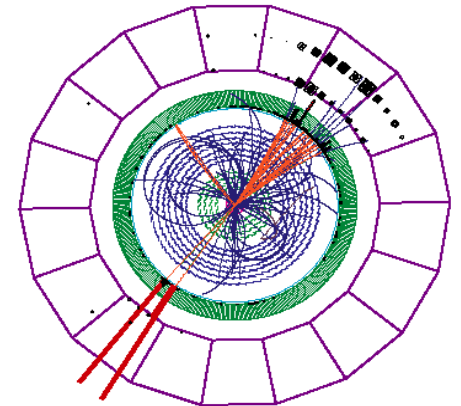
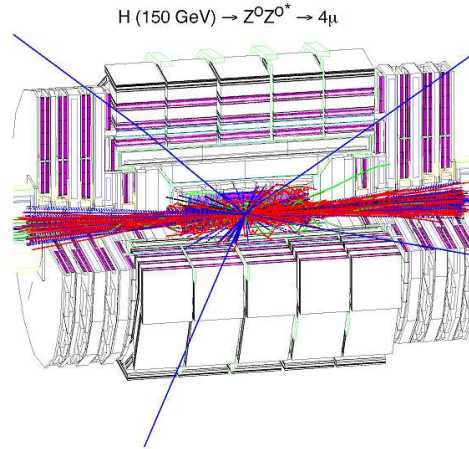
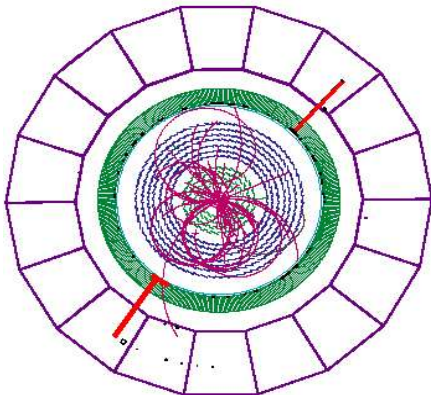
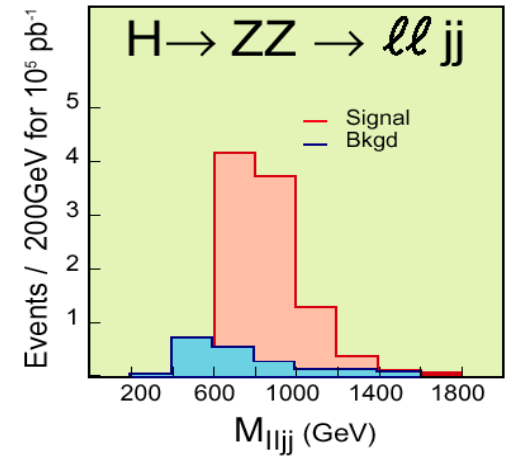
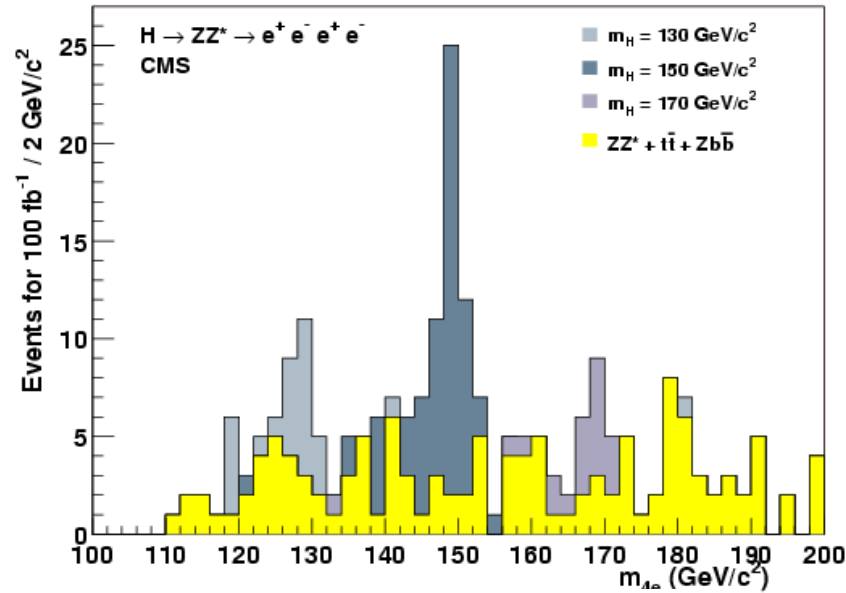
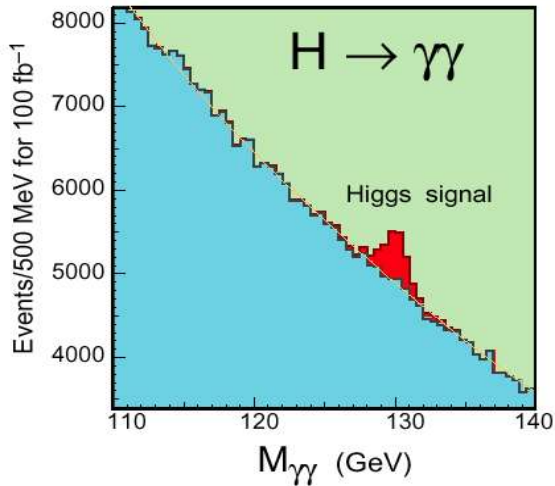
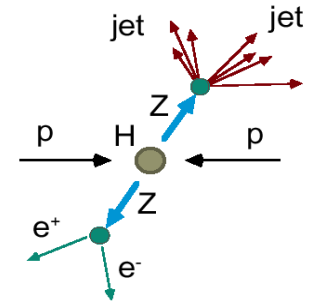
Low  $M_H < 140 \text{ GeV}/c^2$



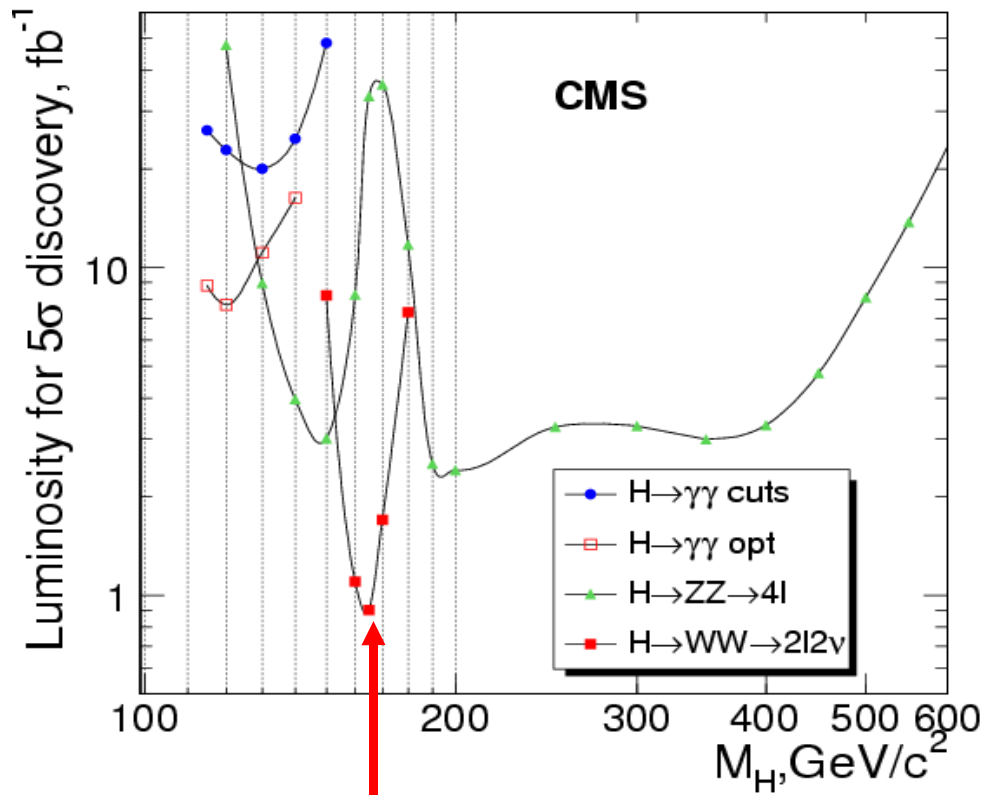
Medium  $130 < M_H < 500 \text{ GeV}/c^2$



High  $M_H > \sim 500 \text{ GeV}/c^2$

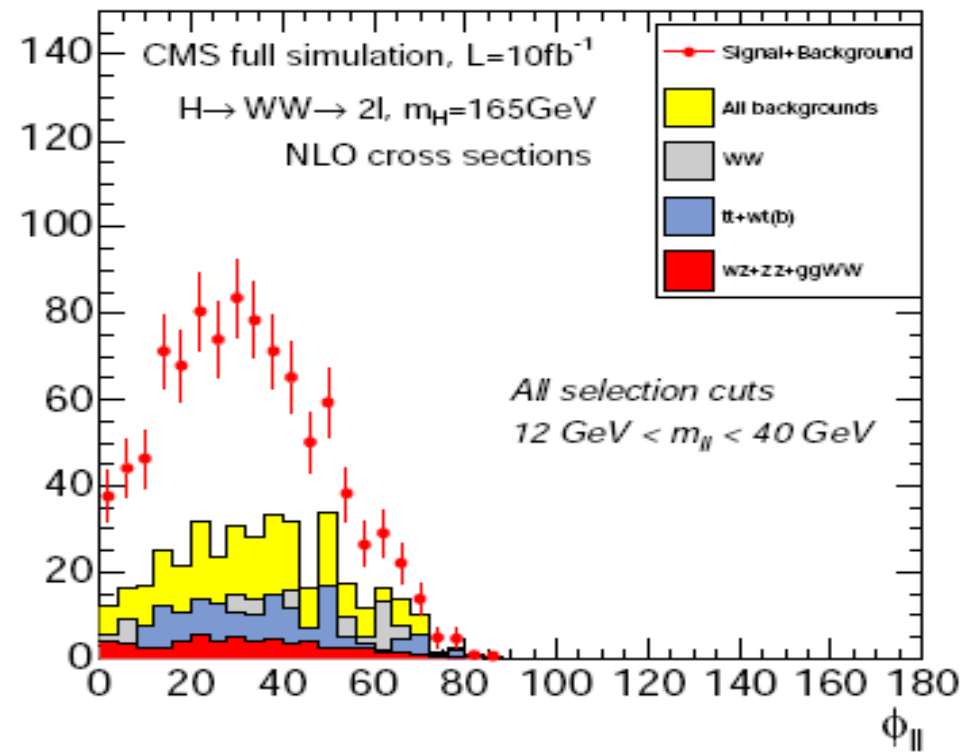
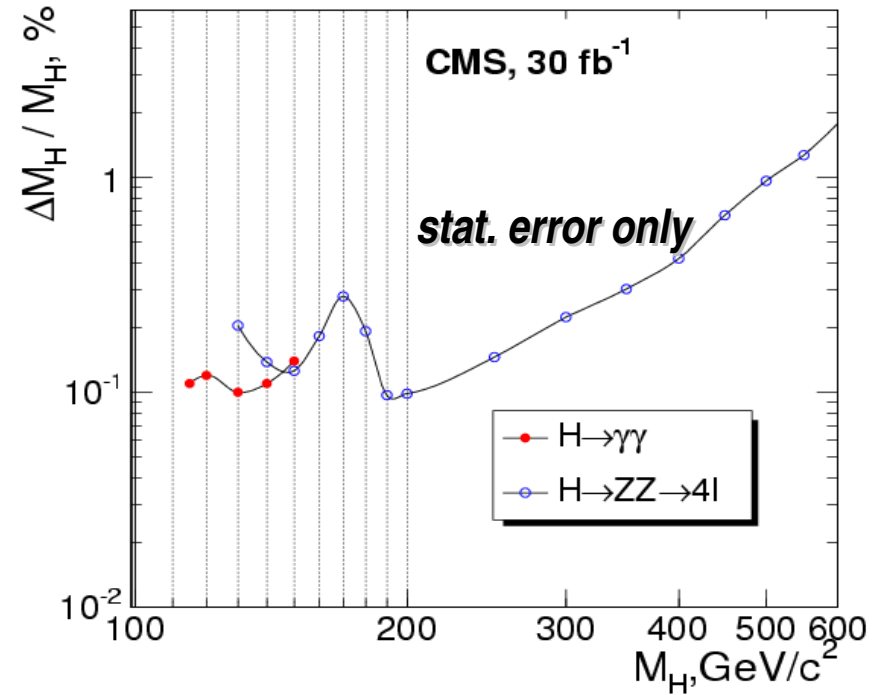


# SM Higgs boson discovery and mass measurement



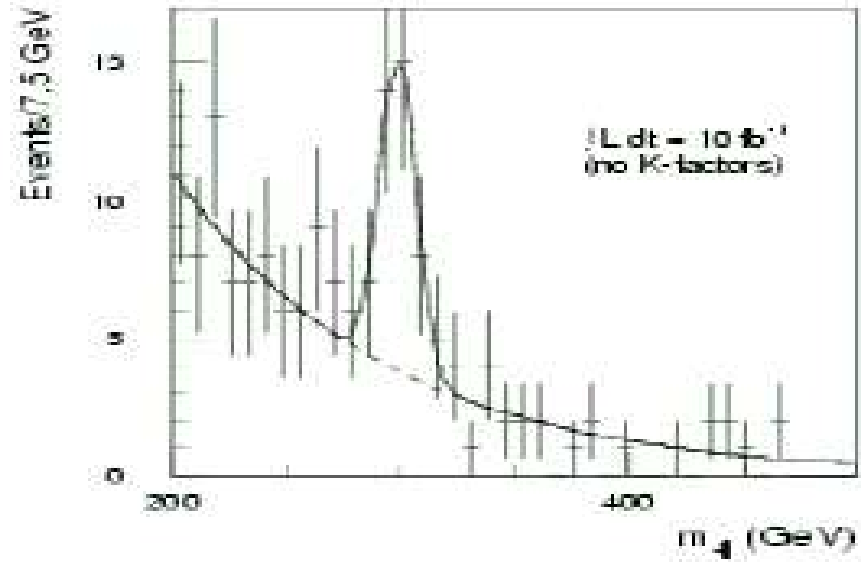
Discovery with  $\sim 1 \text{ fb}^{-1}$

Very detailed studies  
on SM backgrounds  
and related systematics



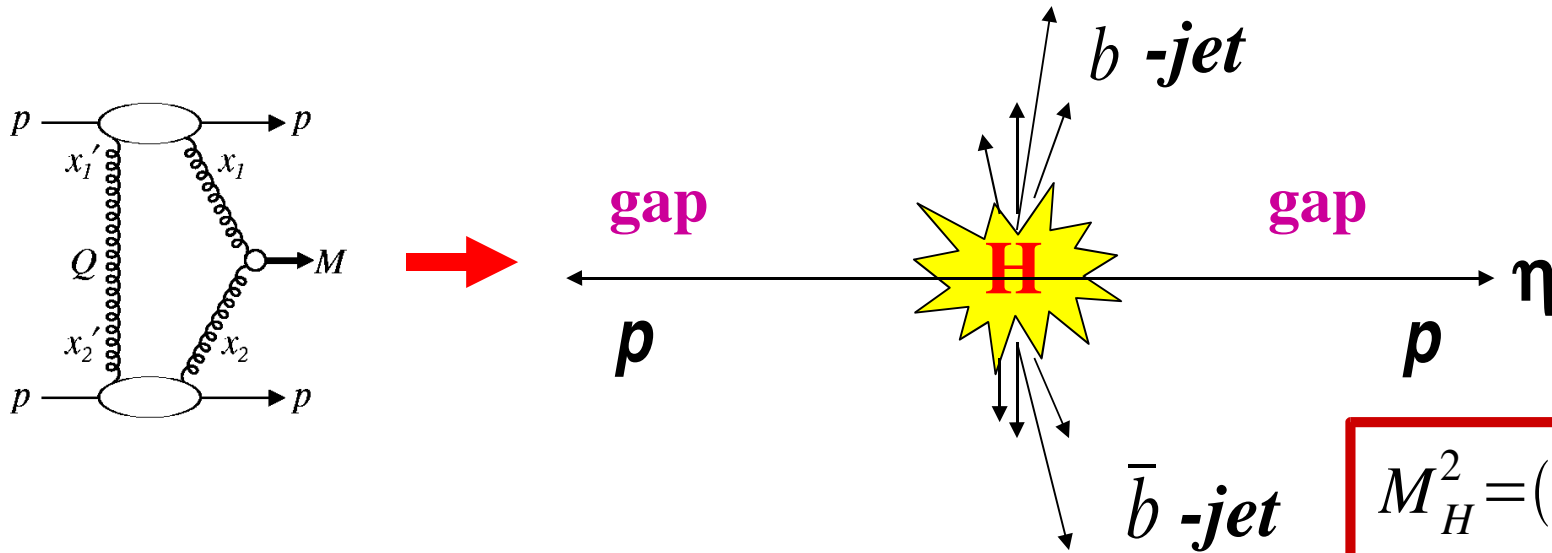
$H \rightarrow ZZ \rightarrow 4\mu$

erwartetes Higgs-Signal nach  
einem Jahr Messzeit von ATLAS



# Central Exclusive Higgs Production

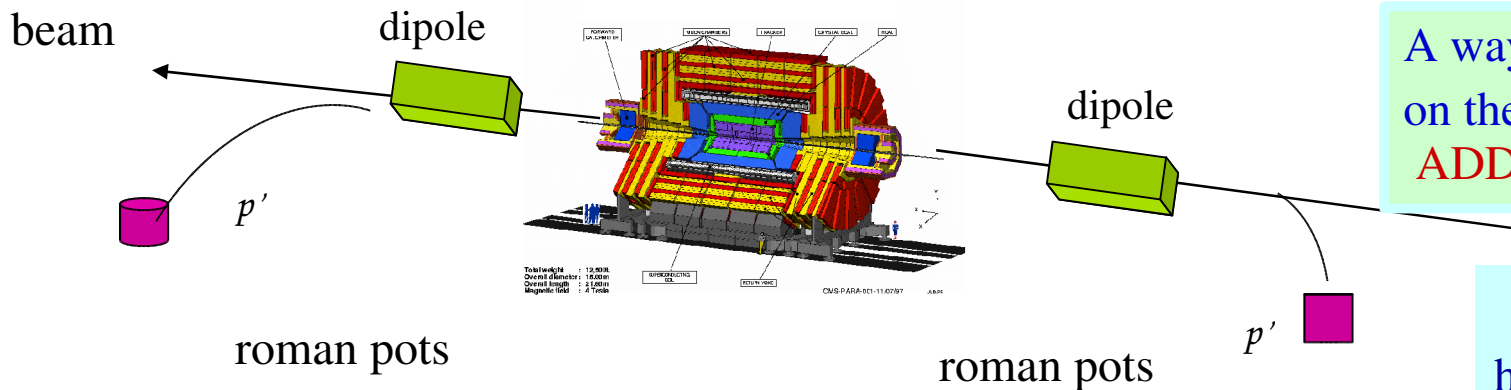
Central Exclusive Higgs production  $pp \rightarrow p H p$  : 3 fb (SM)  
~10-100 fb (MSSM)



E.g. V. Khoze et al  
 M. Boonekamp et al.  
 B. Cox et al.  
 V. Petrov et al...  
 Levin et al...

$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

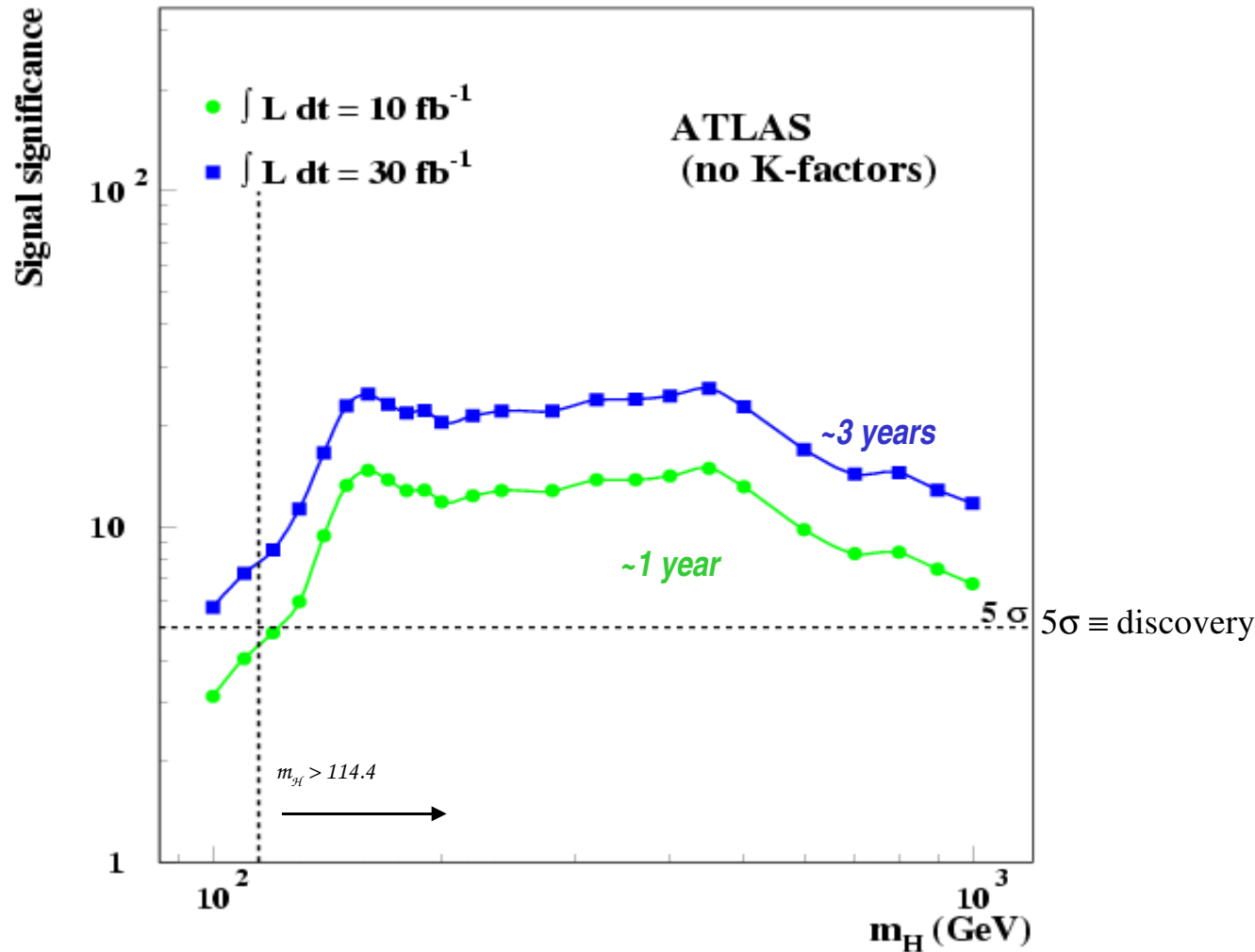
$\Delta M = O(1.0 - 2.0) \text{ GeV}$



A way to get information on the spin of the Higgs  
**ADDED VALUE TO LHC**

**FP420 R&D Project**  
<http://www.fp420.com>

# Higgs Reach



- Higgs can be discovered over full allowed mass range in 1 year of good LHC operation  
-> final word about SM Higgs mechanism by 2009 or so
- However: it will take time to understand and calibrate ATLAS and CMS ...
- In most difficult region  $m_H < 130 \text{ GeV}$   $\geq 3$  different channels observable -> robustness

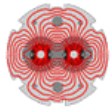
Important test for theories requiring a light Higgs (SUSY, Baryogenesis)

# The LHC Progress & Schedule

Crucial part: 1232 superconducting dipoles

Can follow progress on the LHC dashboard

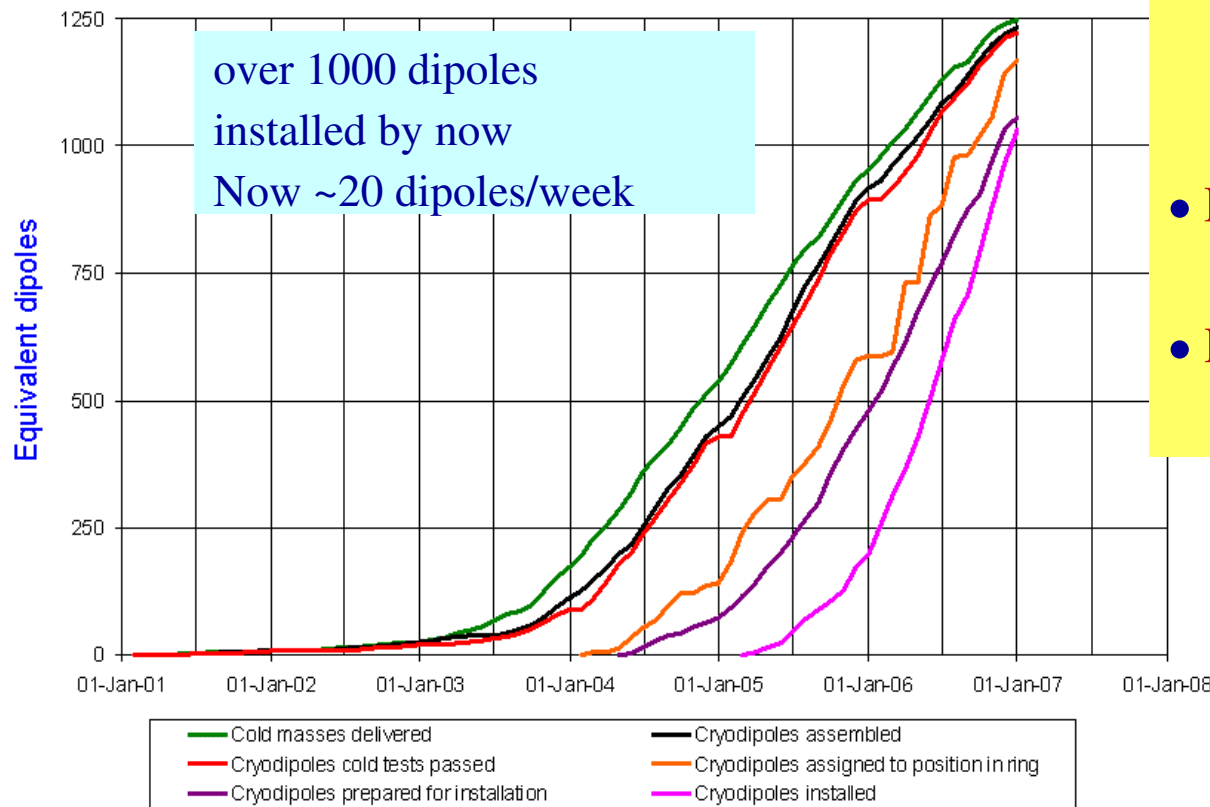
<http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/>



LHC Progress  
Dashboard



Cryodipole overview



## The LHC Schedule(\*)

- LHC will be closed and set up for beam on **1 September 2007**

LHC commissioning will take time!

- First collisions expected in **November/December 2007**

A short pilot run

Collisions will be at injection energy ie cms of 0.9 TeV

- **First physics run in 2008**

~ 1 fb<sup>-1</sup>? 14TeV!

- **Physics run in 2009 +...**

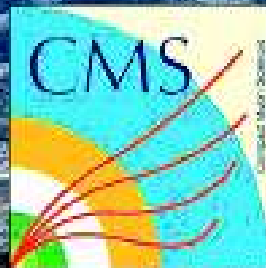
10-20 fb<sup>-1</sup>/year 100 fb<sup>-1</sup>/year

(\*) eg. M. Lamont et al, September 2006.  
Achtung! Lumi estimates are mine, not from the machine

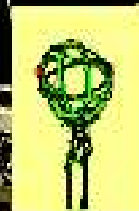
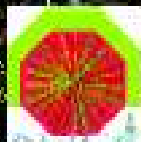
# LHC = Large Hadron Collider

7000 GeV Proton

+ 7000 GeV Proton



2007 - 2020



# Experiments searching for the Higgs at the LHC

**ATLAS** A Toroidal LHC ApparatuS

**CMS** Compact Muon Solenoid

