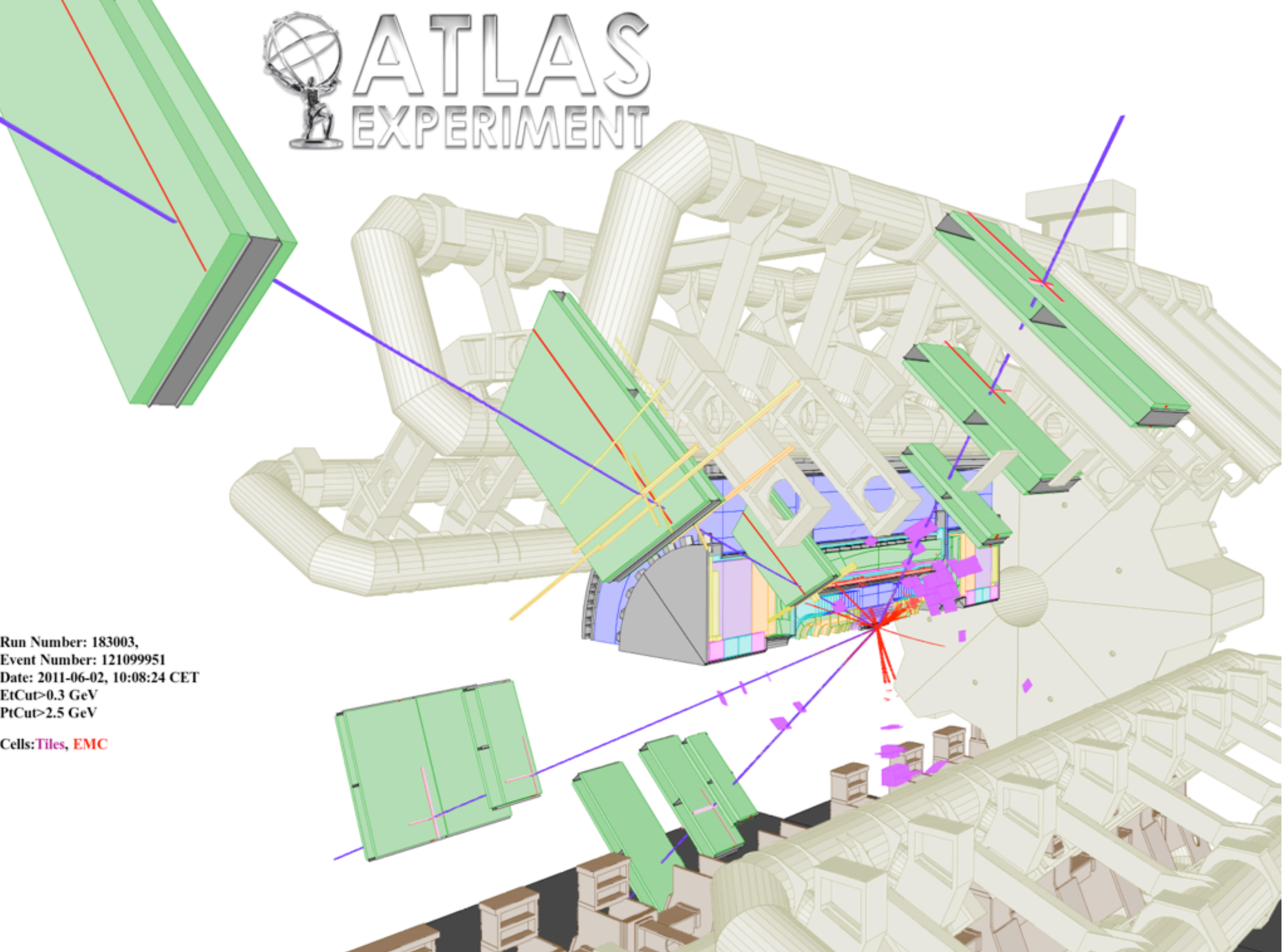

PP7 - Higgs Boson Physics

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MPAGS
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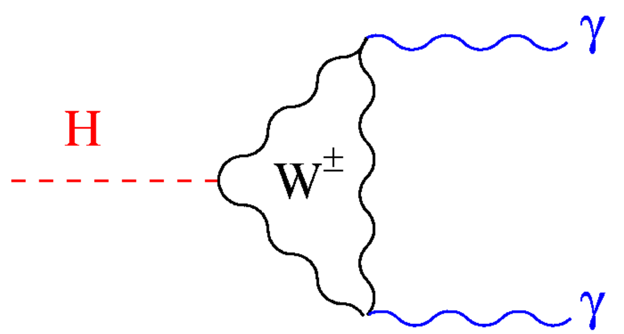
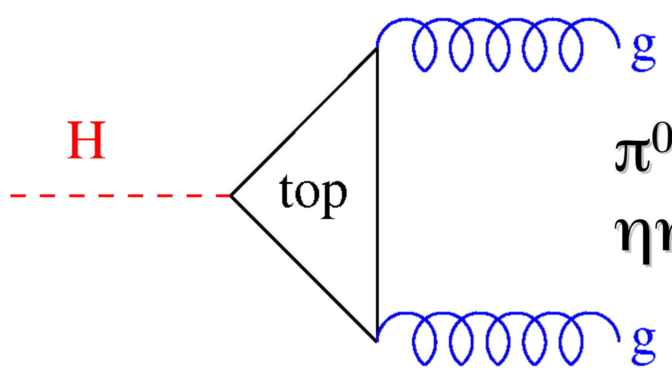
LEP Searches for the Standard Model Higgs boson

The decay branching ratios depend only on m_H:

- $m_H < 2m_e$: $H \rightarrow \gamma\gamma$ + large lifetime;



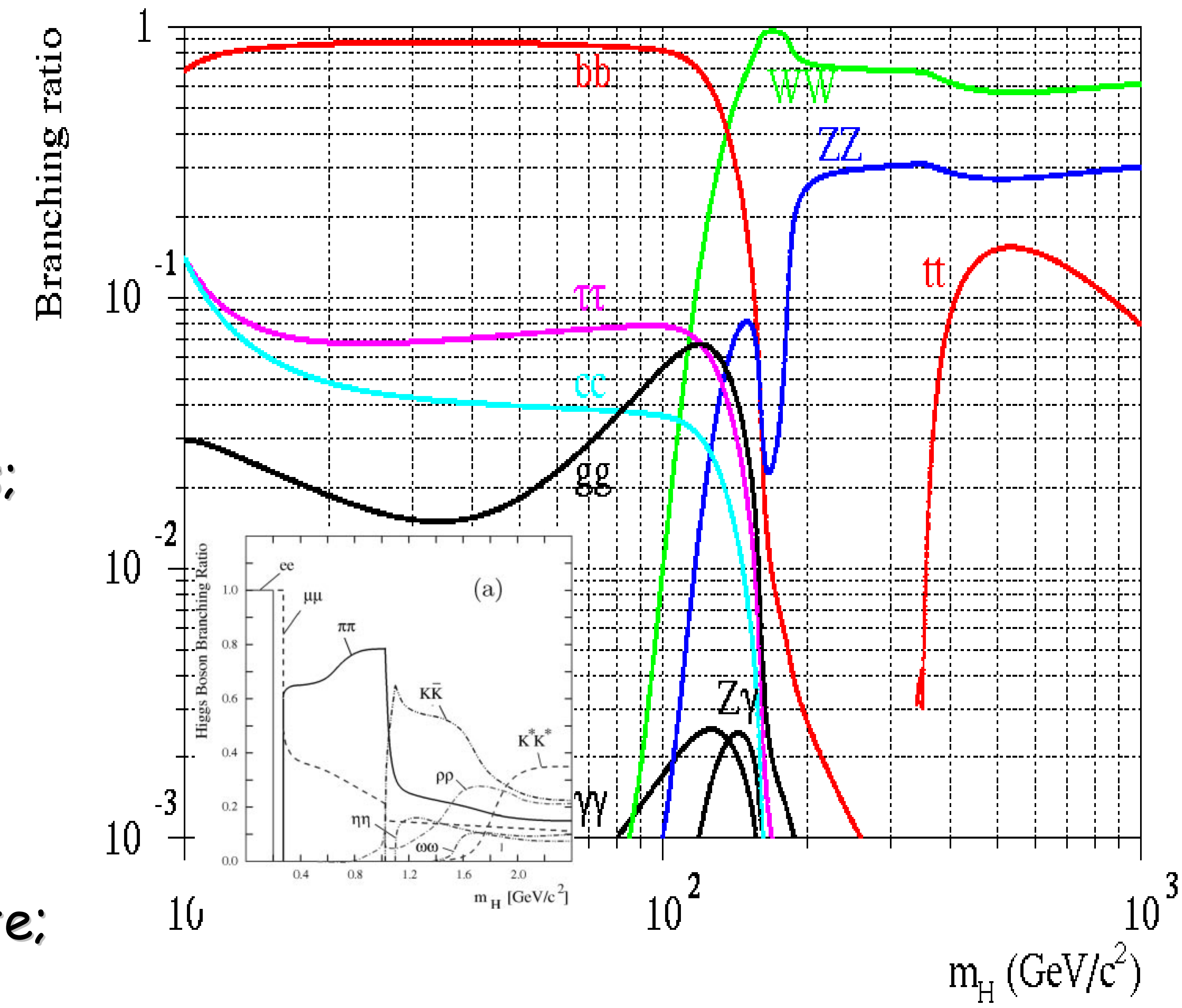
- $m_H < 2m_\mu$: $H \rightarrow e^+e^-$ dominates;
- $m_H < 2m_\pi$: $H \rightarrow \mu^+\mu^-$ dominates;
- $m_H <$ 3 - 4 GeV: $H \rightarrow gg$ dominates;



$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, … etc

- $m_H < 2m_b$: $H \rightarrow \tau^+\tau^-$ and $c\bar{c}$ dominate;

- $m_H > 2m_b$ up to 1000 GeV/c²:



LEP

The LEP collider housed in a 26.7 km tunnel [8 × 2.9-km-long arcs and 8 × 420-m-long straight sections]
4 experiments: ALEPH, DELPHI, L3 and OPAL.
>5000 magnets (3400 dipoles, 800 quadrupoles, 500 sextupoles, and over 600 beam orbit correctors)
LEP1 from the summer of 1989 until 1995 → LEP operated at energies close to the Z resonance.
LEP2 from 1995 to 2000 → LEP operated above the WW threshold and up to 209 GeV.

LEP produced its first collisions on August 13th 1989,
less than six years after ground was broken on September 13th 1983.

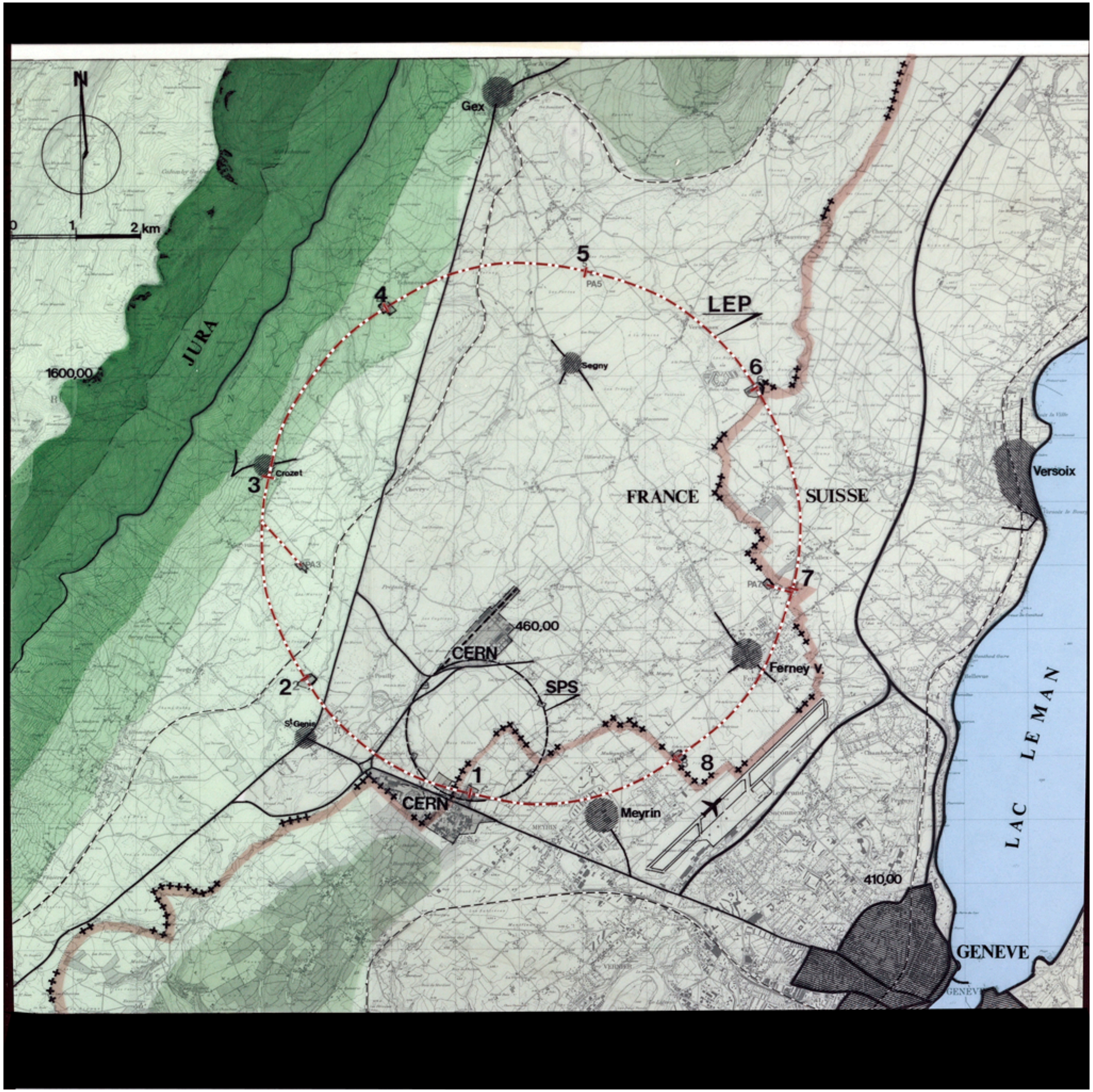
Geometric parameters of LEP.

Parameter	Symbol	Value
Effective bending radius	ρ	3026.42 m
Revolution frequency	$f_{\rm rev}$	11245.5 Hz
Length of circumference, $L = c/f_{\rm rev}$	L	26658.9 m
Geometric radius $(L/2\pi)$	R	4242.9 m
Radio frequency harmonic number	h	31320
Radio frequency of the RF-system, $f_{\rm RF} = h\, f_{\rm rev}$	$f_{\rm RF}$	352 209 188 Hz

LEP: design and reality.

Parameter	Design (55/95 GeV)	Achieved (46/98 GeV)
Bunch Current	0.75 mA	1.00 mA
Total Beam Current	6.0 mA	8.4 mA/6.2 mA
Vertical Beam-beam parameter	0.03	0.045/0.083
Emittance ratio	4.0%	0.4%
Maximum Luminosity	$16/27\ 10^{30} cm^{-2} s^{-1}$	$34/100\ 10^{30} cm^{-2} s^{-1}$
Horizontal beta function at IP	1.75 m.	1.25 m.
Vertical beta function at IP	7.0 cm.	4.0 cm.

LEP



N
0
1
2 km
Gex
JURA
1600,00
5
PA5
4
LEP
Segny
6
3
Crozet
FRANCE
SUISSE
Versoix
PA3
7
460,00
CERN
Ferney V.
SPS
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St Genis
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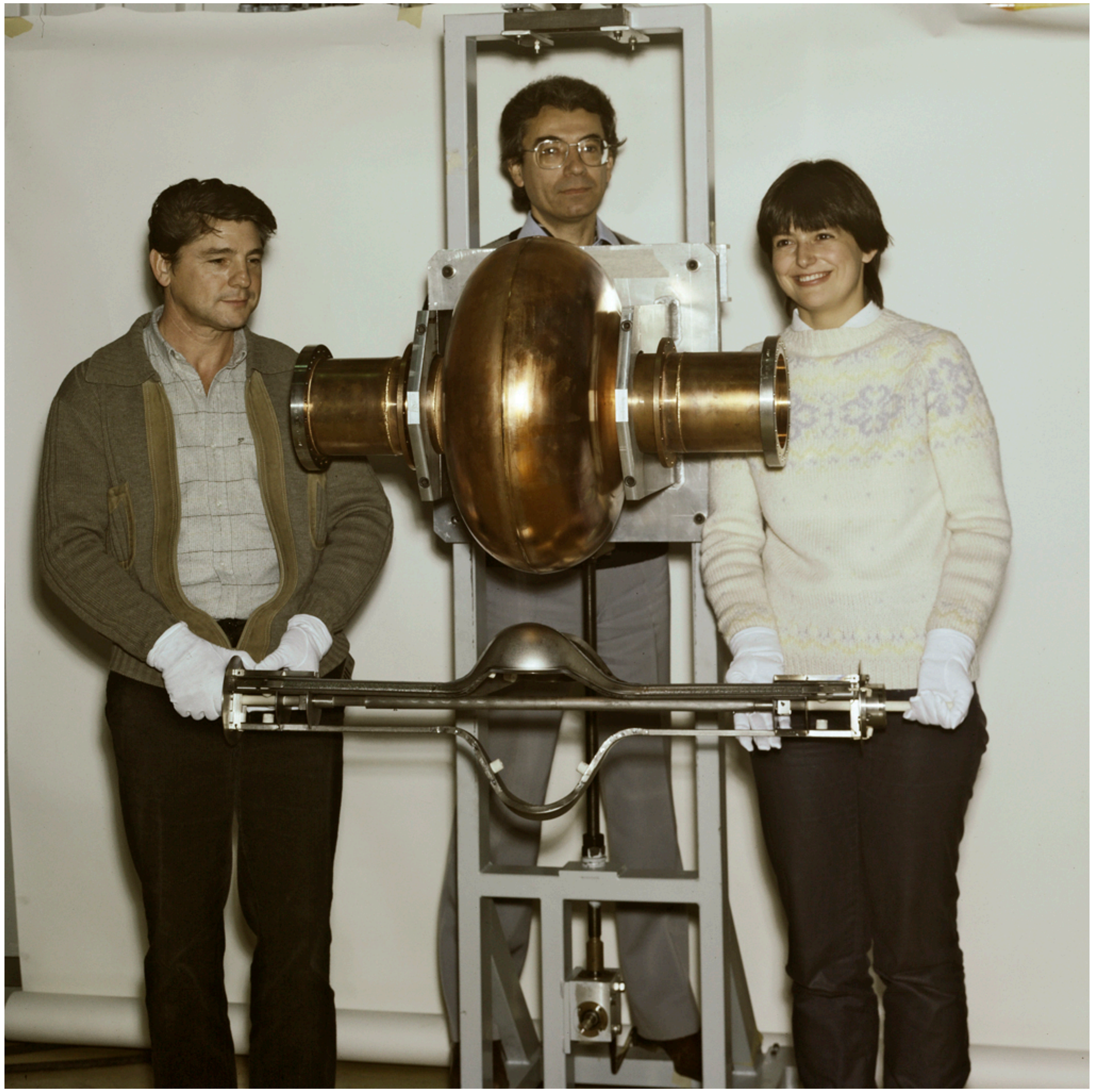
8
CERN
Meyrin
LAC LEMAN
410,00
GENEVE

LEP

LEP



This is the first RF superconducting cavity made of copper with a very thin layer of pure niobium deposited on the inner wall by sputtering.

LEP

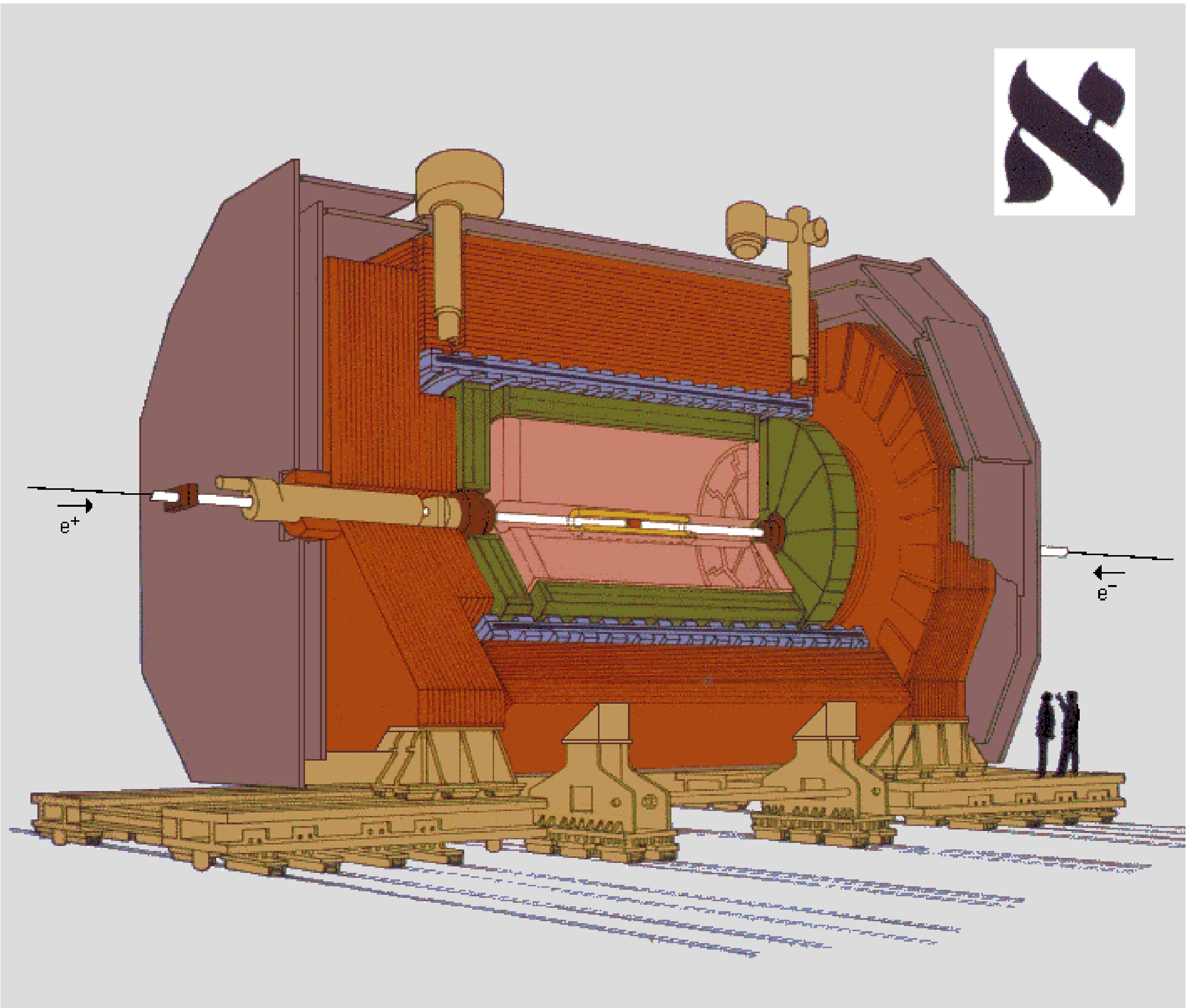
Overview of LEP performance from 1989 to 2000. $\int \mathcal{L}dt$ is the luminosity integrated per experiment over each year and I_{tot} is the total beam current $2k_\mathrm{b}I_\mathrm{b}$. The luminosity $\mathcal{L}$ is given in units of $10^{30}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

Year	$\int \mathcal{L}dt$ (pb^{-1})	E_b ($\mathrm{GeV/c^2}$)	k_b	I_{tot} (mA)	$\mathcal{L}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60

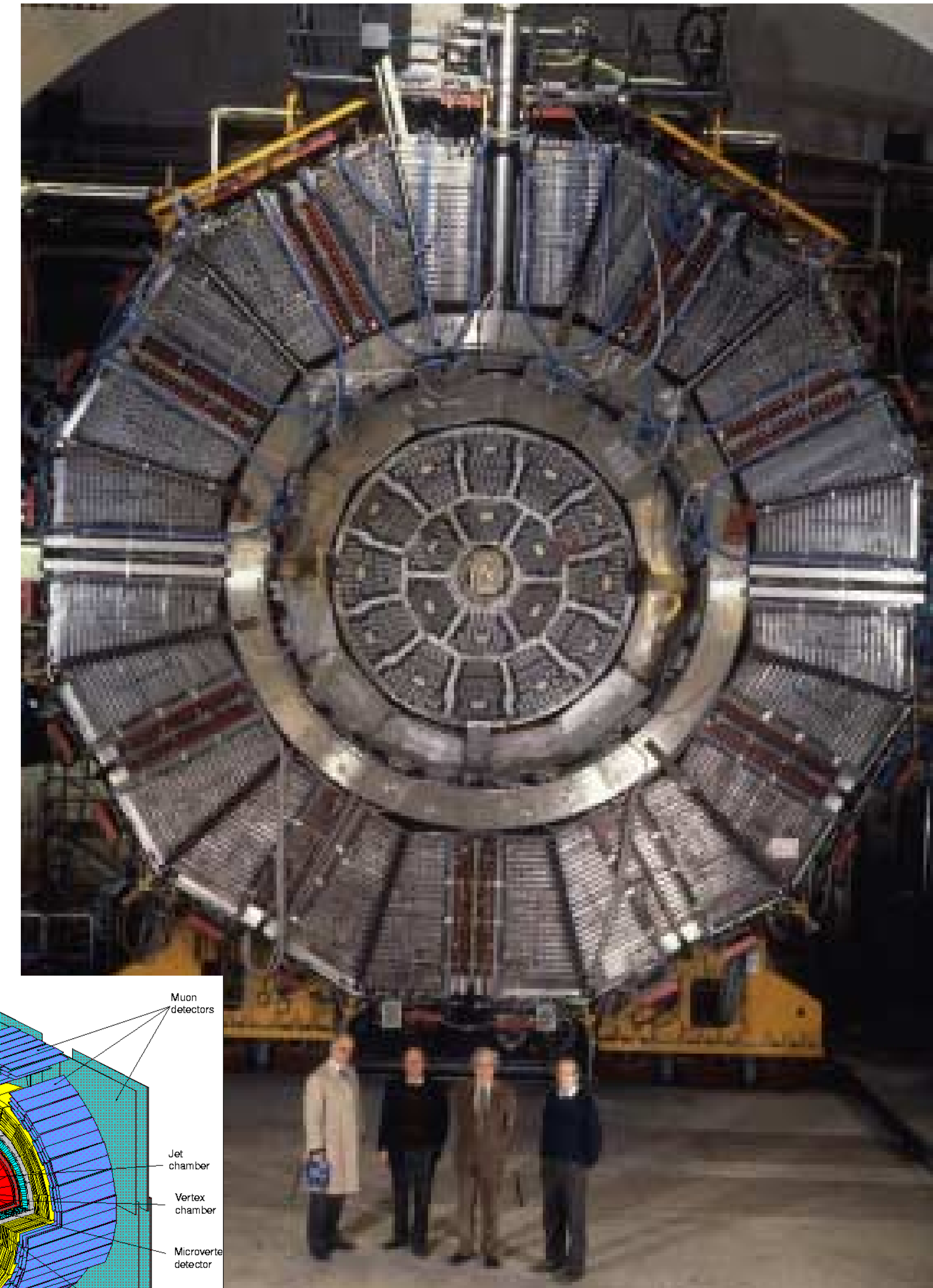
LEP 1

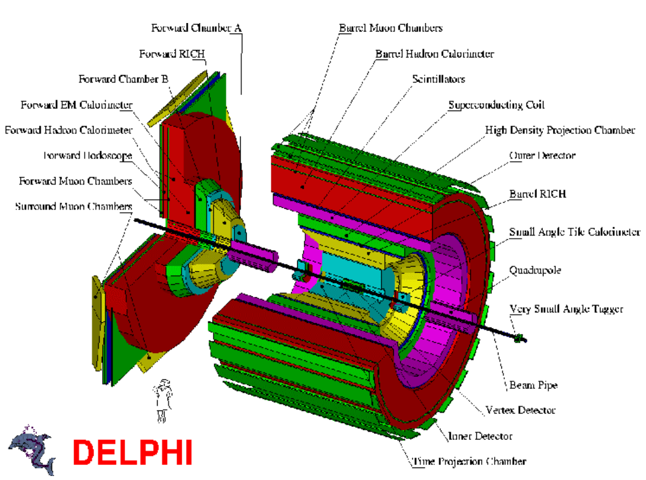
LEP 2

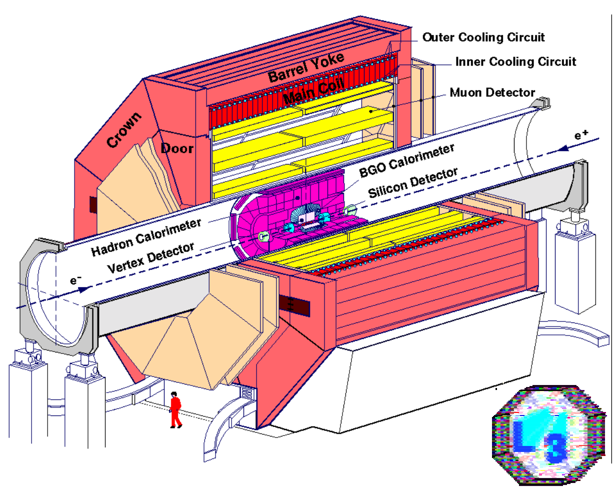
The LEP experiments

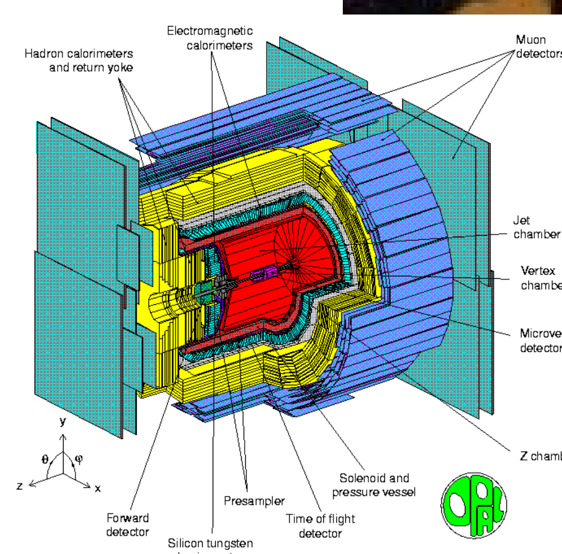


The ALEPH Detector

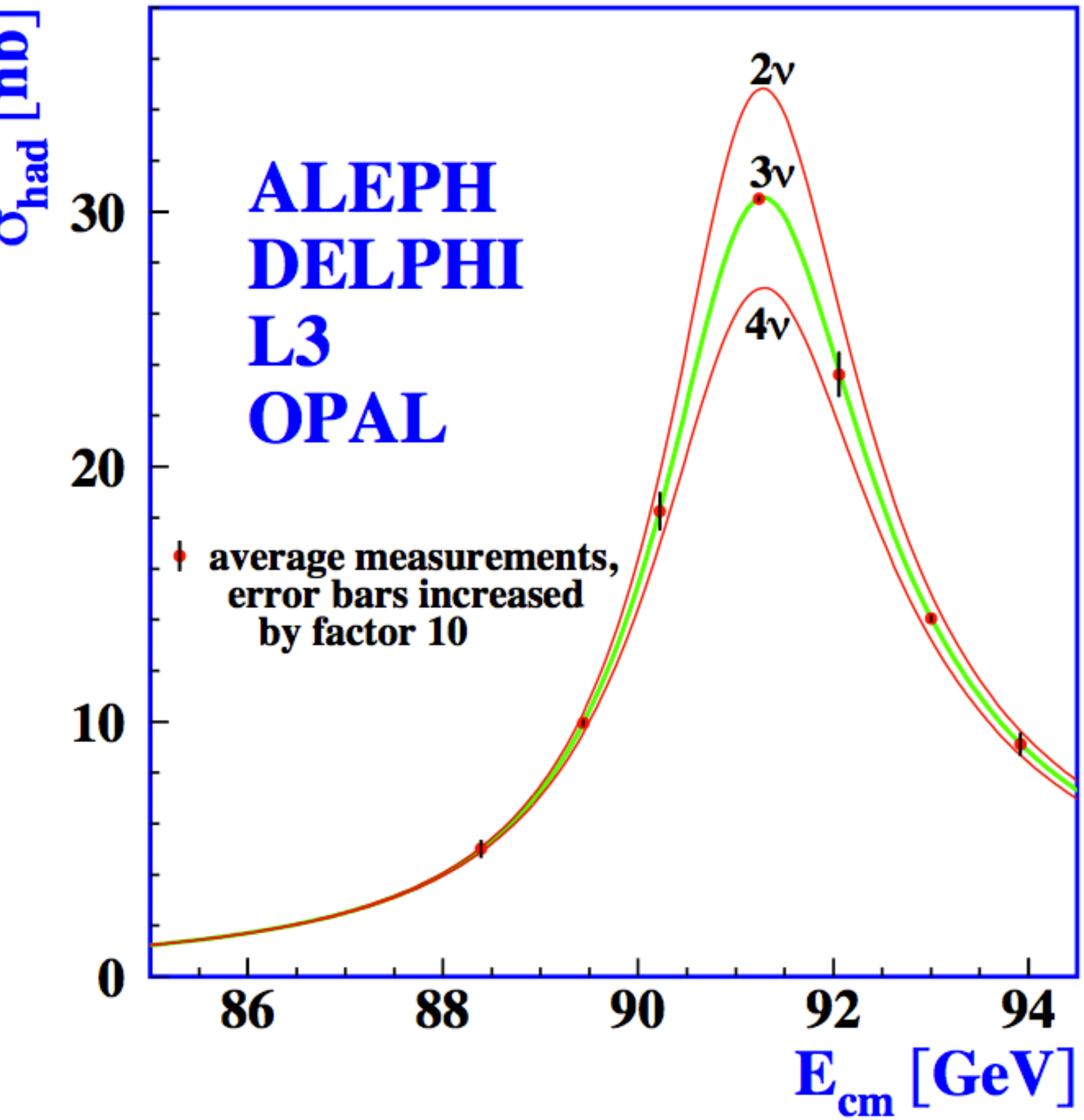


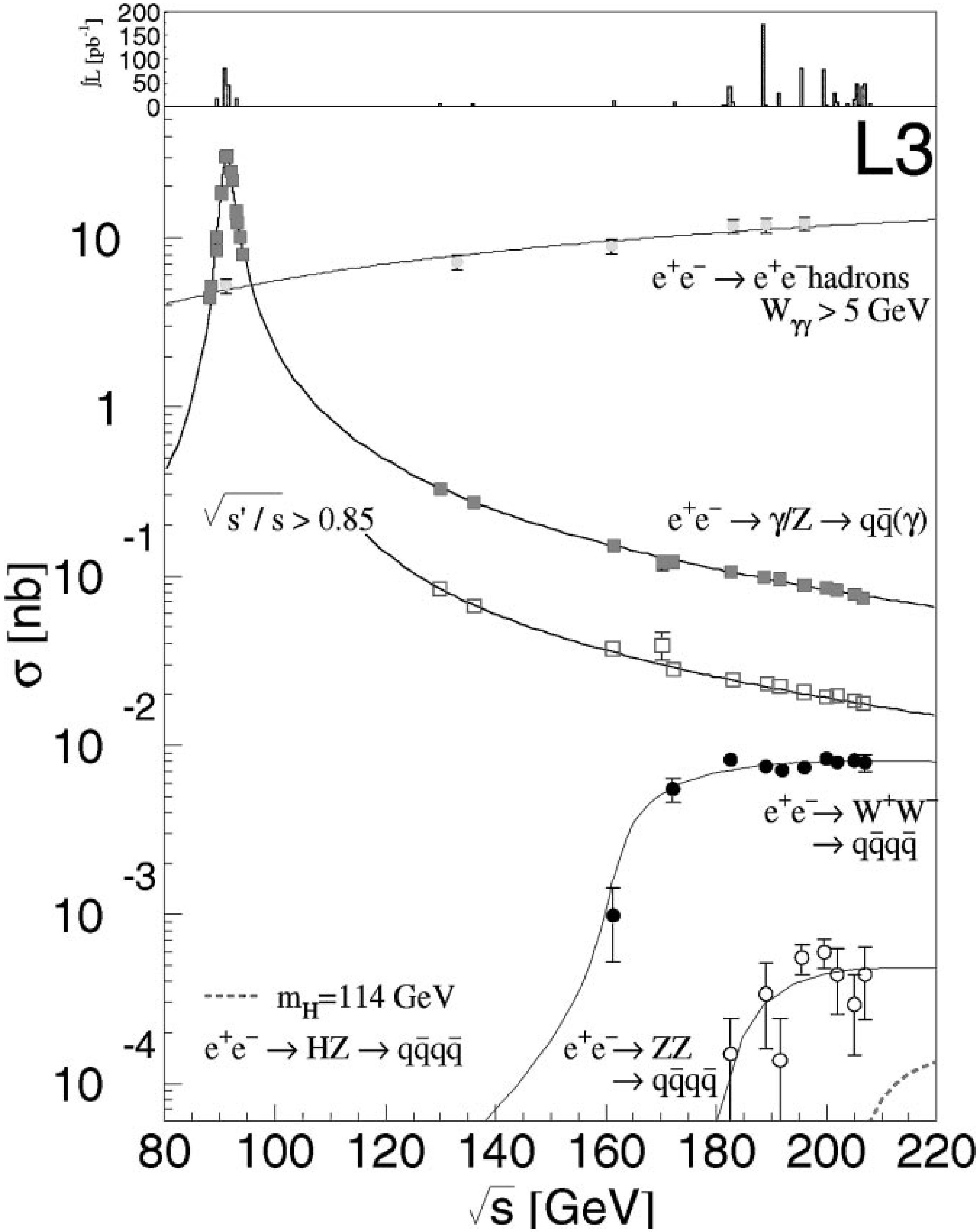






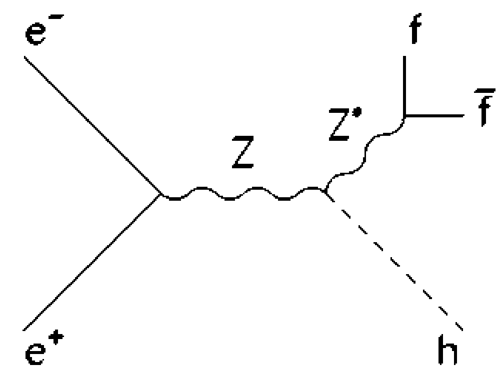
Physics at LEP

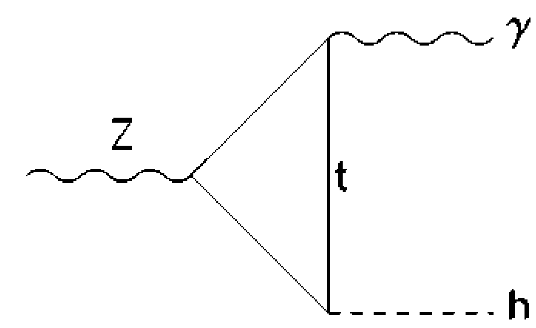




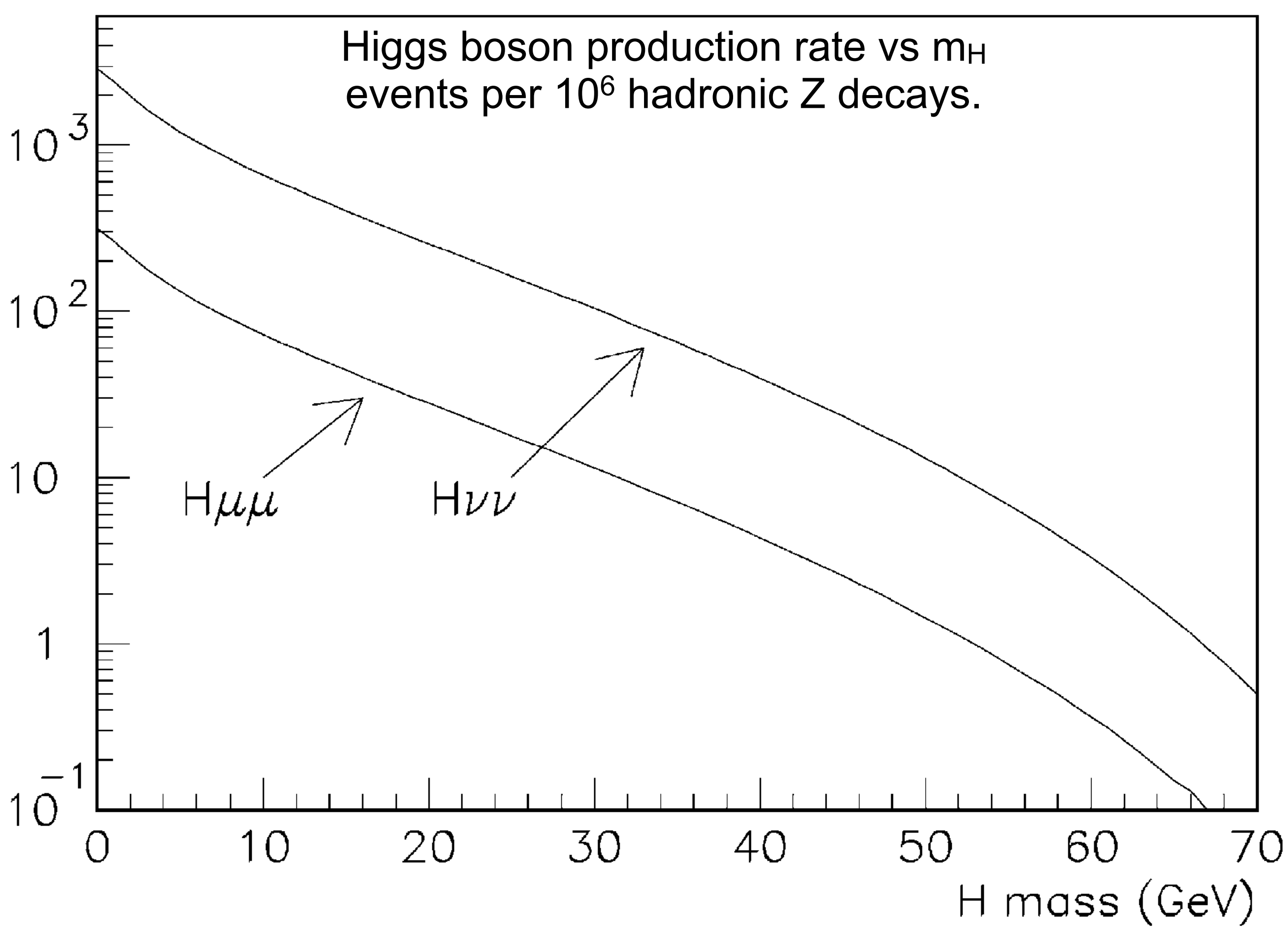
LEP 1: Higgs boson Production

- The Bjorken process, usually called Higgs-strahlung, $e^+e^- \to HZ^* \to Hff$, is the dominant production mechanism
- The Wilczek process, $e^+e^- \to H\gamma$, had much lower rate, but also important backgrounds:
    - $e^+e^- \to qq\gamma$
    - $e^+e^- \to qqg$, with a jet hadronizing to an energetic π^0





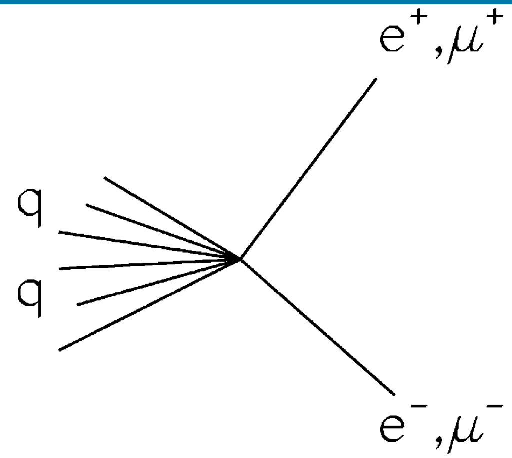
Only the Higgs-strahlung process with Z→ee/μμ/νν has been extensively explored and searches were divided in two regions:
- "Low" mass (m_H<20 GeV)
- "High" mass (m_H>20 GeV)

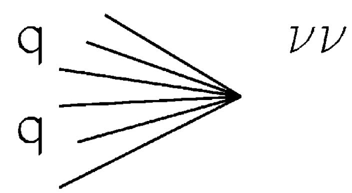


$$\frac{1}{\Gamma(Z \to \mu^+\mu^-)} \frac{d\Gamma(Z \to Hf\bar{f})}{dx} = \frac{\alpha}{4\pi \sin^2\theta_W \cos^2\theta_W} \times \frac{(1 - x + x^2/12 + 2r^2/3)(x^2 - 4r^2)^{1/2}}{(x - r^2)^2 + (\Gamma_Z/m_Z)^2}$$

where α is the fine structure constant, θ_W the Weinberg angle, $x = 2E_H/m_Z$, E_H the energy of the Higgs boson and $r \equiv m_H/m_Z$. The total production rate is obtained by integration over the kinematic range $2r \leqslant x \leqslant 1 + r^2$.

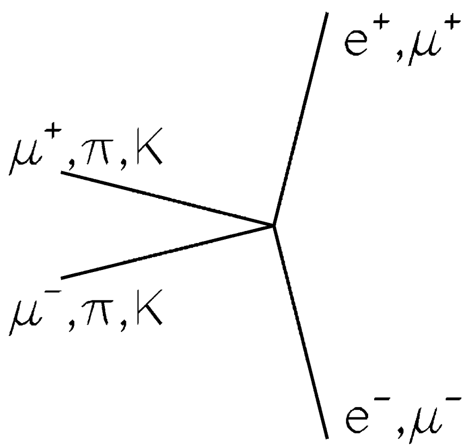
LEP 1: Low mass searches





Mono-jets

- Monojets are expected for m_H between ~4 and 20 GeV.
- The mono-jet results from a small invariant mass between two quarks of the decay of a light Higgs boson.
- Such mono-jets have not been observed and the mass region is excluded at 99% CL for the SM Higgs boson

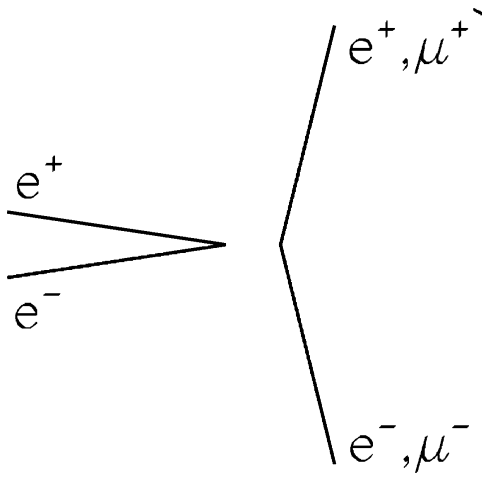


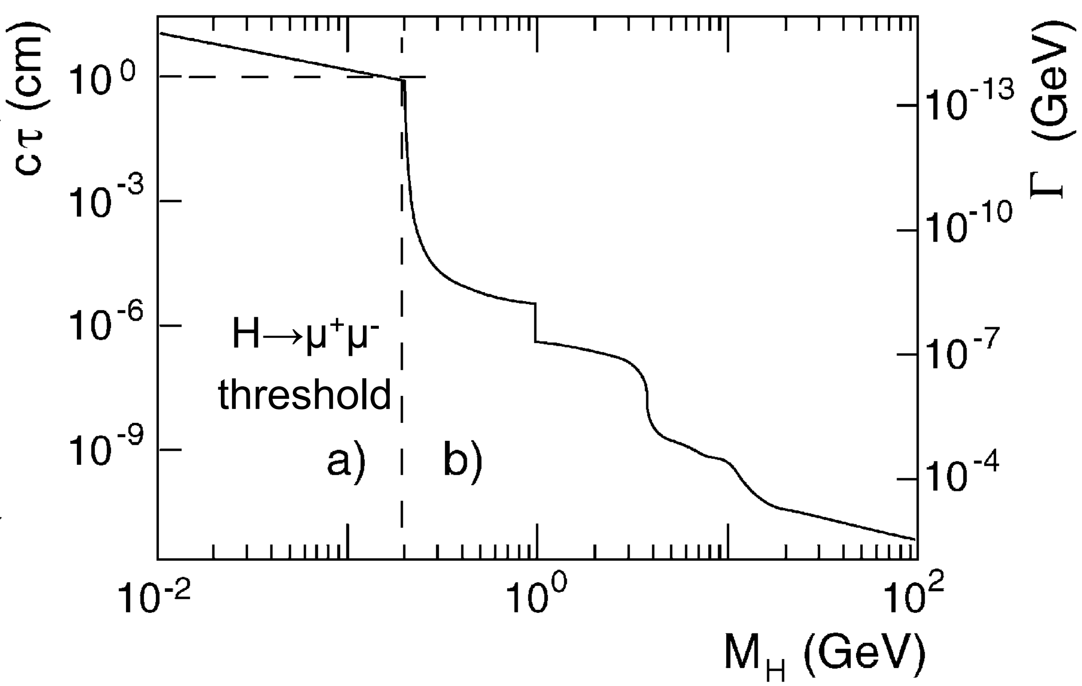
Various final states

For m_H< 4 GeV many possibilities for Higgs boson decays. No signal has been observed and the mass region below 4 GeV is excluded at 99% CL

L3 selection efficiencies (in %) for a low-mass Higgs boson in the He^+e^- channel, for the Higgs decaying into charged particles

m_H (GeV)	0.01	0.1	0.22	0.3	1.0	3.6
$H \to e^+e^-$	8.2	7.4	—	—	13.6	—
$H \to \mu\mu$	—	—	22.0	—	28.0	24.0
$H \to \pi^+\pi^-$	—	—	—	9.4	17.0	15.0
$H \to K^+K^-$	—	—	—	—	13.0	16.0

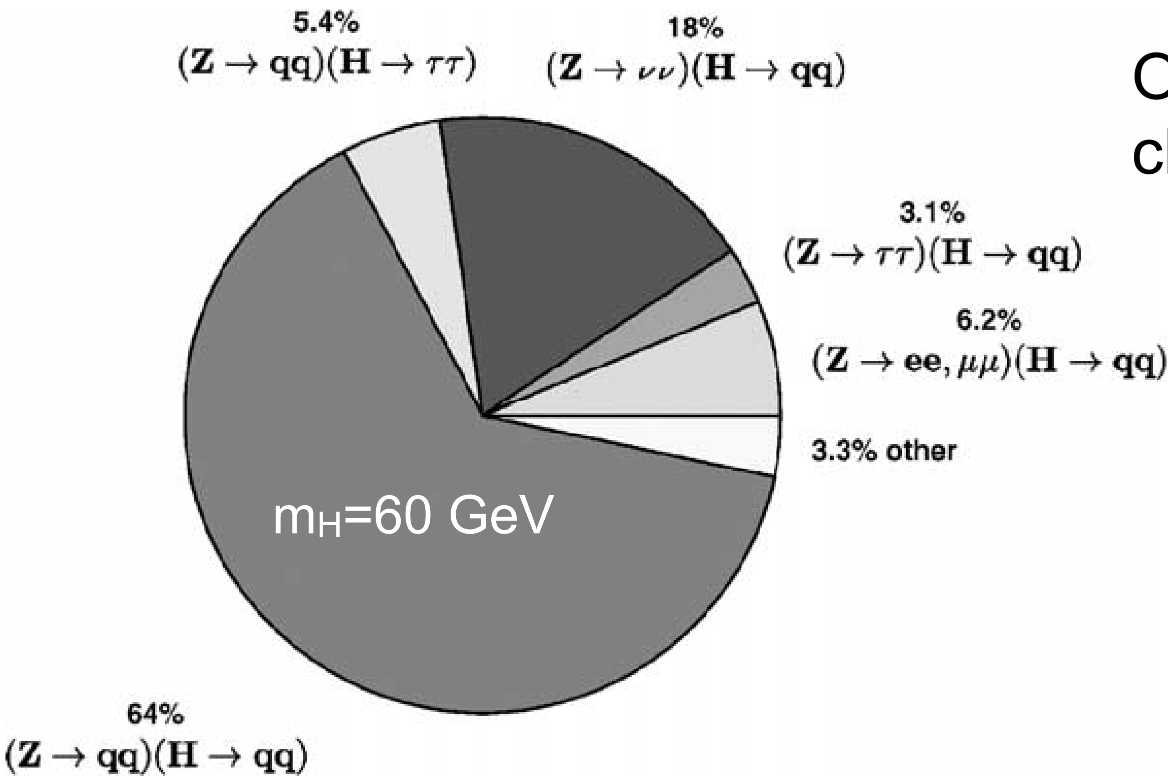




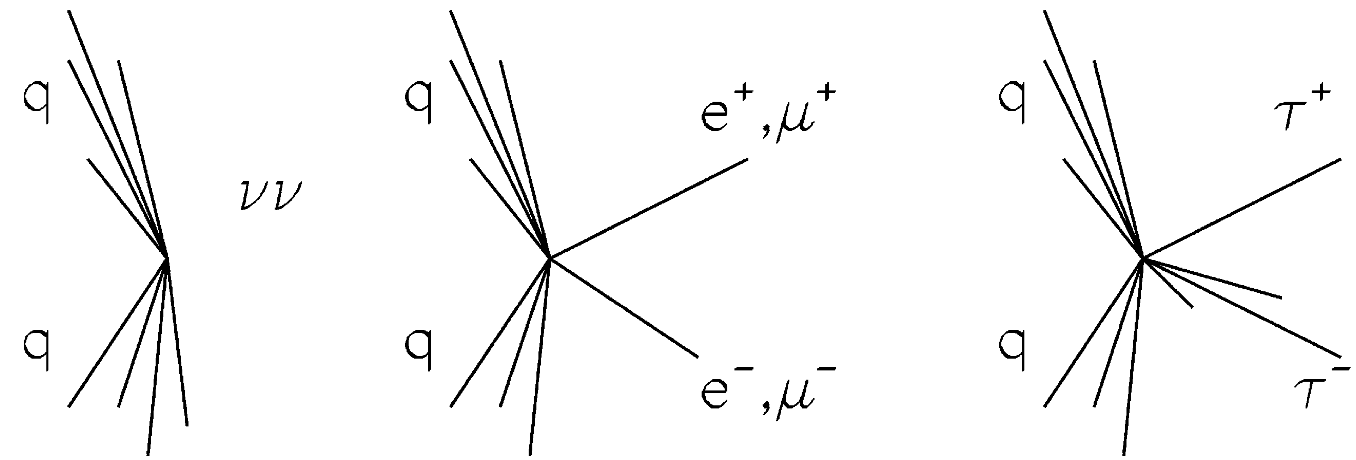
Secondary vertices

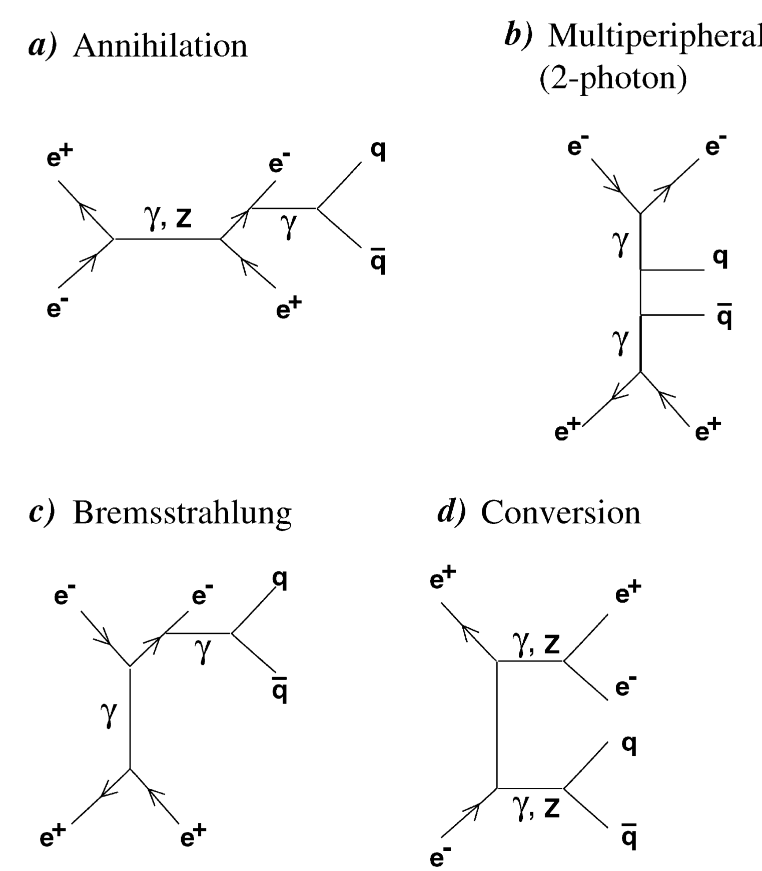
For m_H<$2m_\mu$ the Higgs boson does not decay at the primary interaction point. Two signatures can be distinguished, where the Higgs boson:
(a) decays outside the detector,
(b) decays in the detector material ('V' signature)
No signal has been observed either...

LEP 1: High mass searches



Only the Hvv and the Hll channels considered, the Hqq channel suffers from large hadronic background





Hvv
- Higgs boson decay leads to jets not back-to-back in Δφ and missing energy from Z→vv
- dominant background arises from hadronic events with spurious missing energy

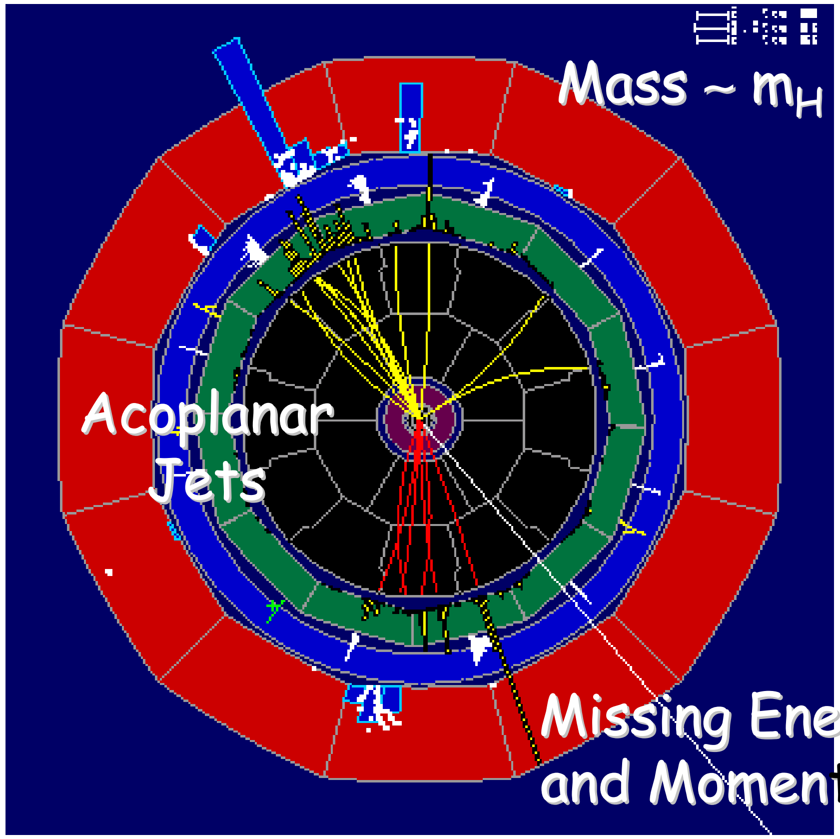
Hll
- Higgs boson decay leads to two jets and a lepton pair
- dominant background arises from semileptonic decays Z→bb→eeX and four fermion process ee→eeqq

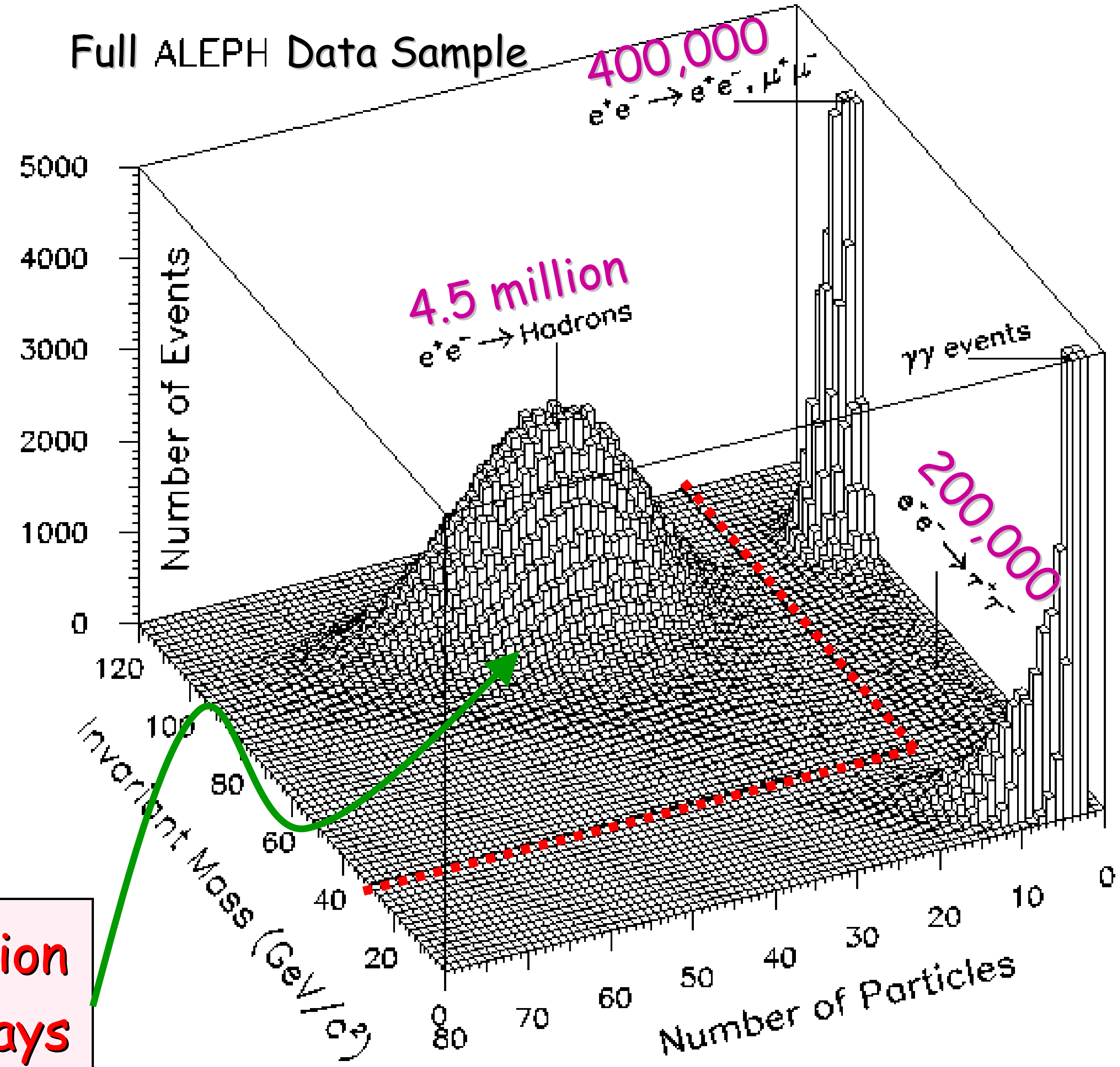
Example LEP1 Analysis: ALEPH $e^+e^- \to H\nu\nu$

Search for acoplanar jets ($e^+e^- \to H\nu\bar{\nu}$)

P. Janot

20 $H\nu\bar{\nu}$ events to be looked for
(4 expts, if m_H = 65 GeV/c^2)





Within more than 20 million other events from Z decays (or from other processes)

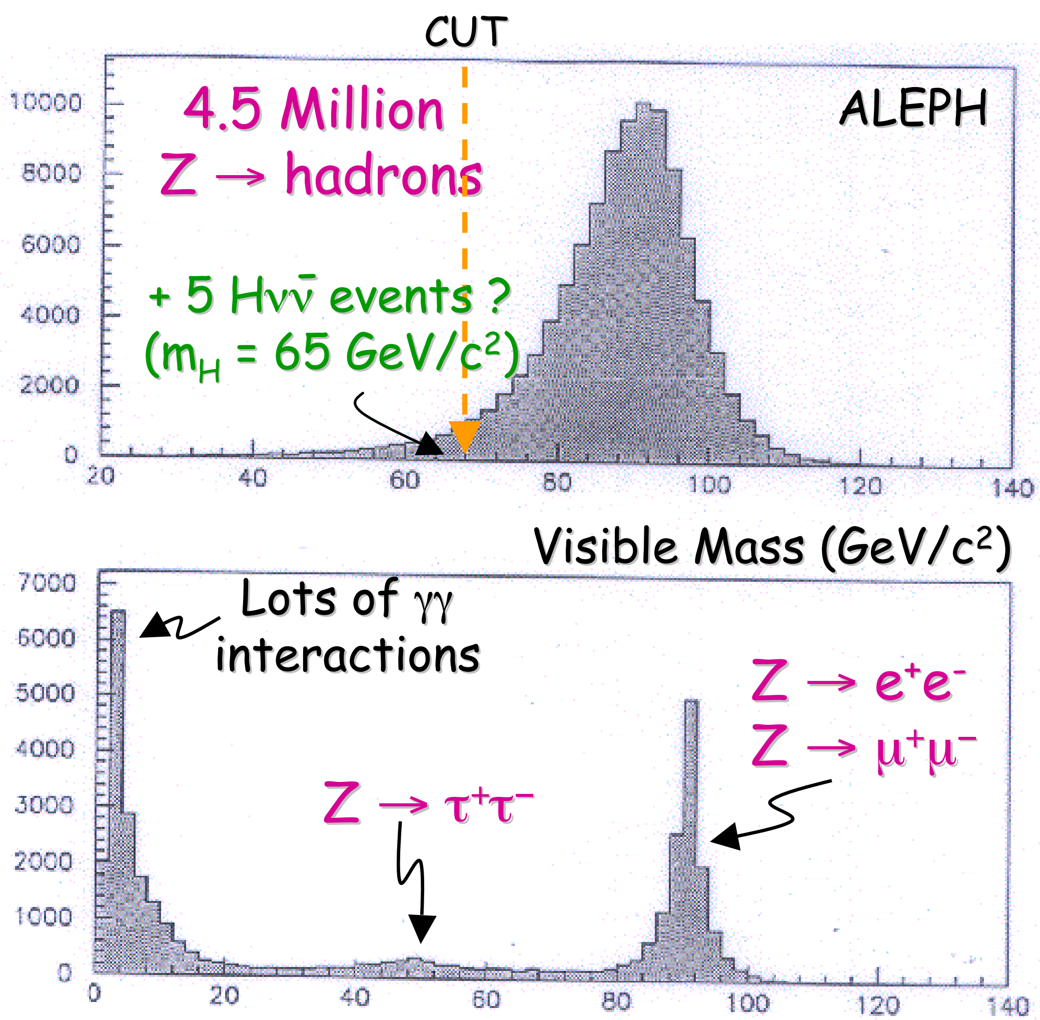
Example LEP1 Analysis: ALEPH $e^+e^- \to H\nu\nu$

P. Janot

Search for acoplanar jets ($e^+e^- \to H\nu\bar{\nu}$)

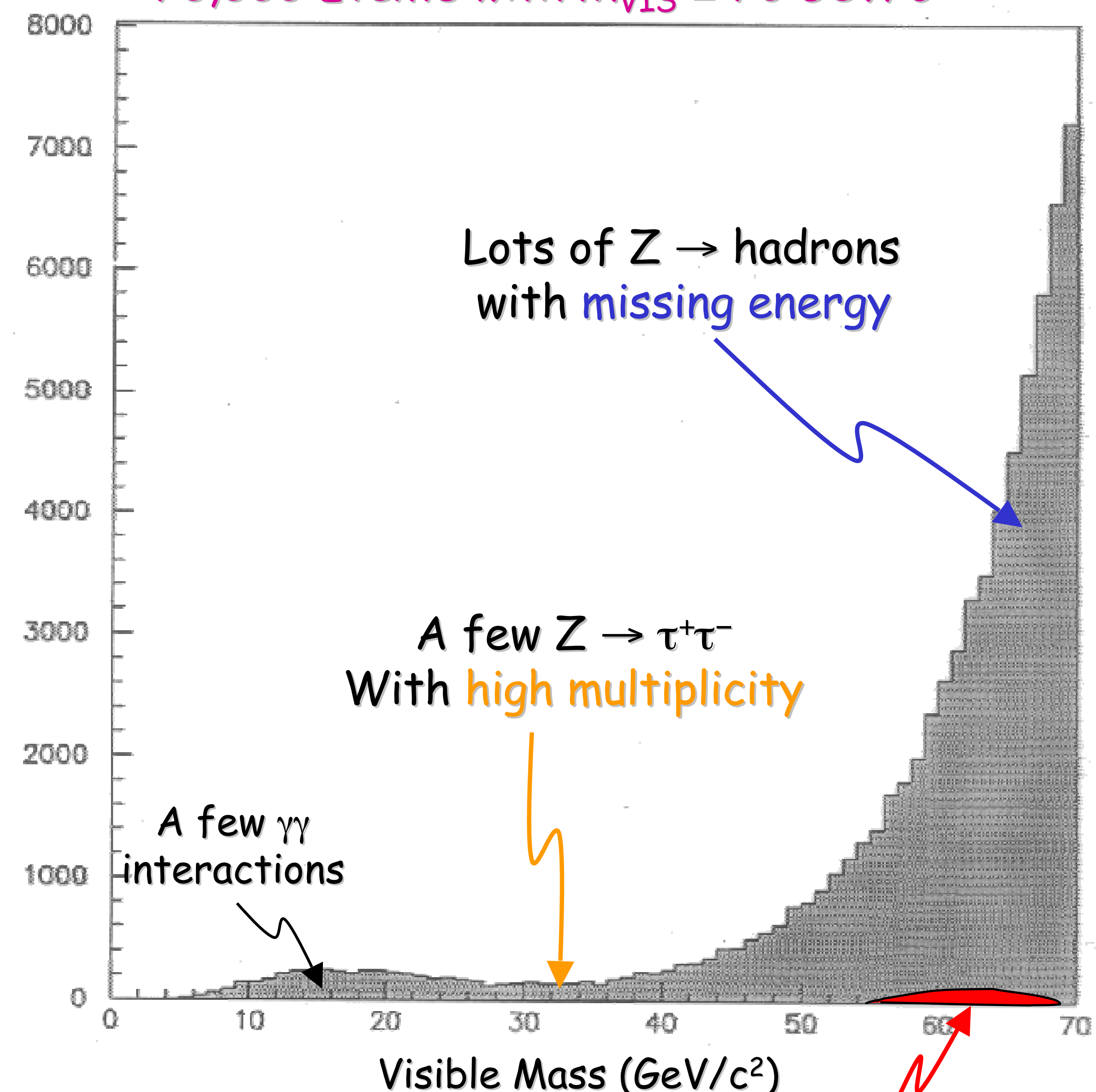
Two main subsamples:

1) High Multiplicity (Selected)



2) Low Multiplicity (Rejected)

70,000 Events with $M_{VIS} \le 70$ GeV/c^2 :



- Visible invariant mass < 70 GeV
- ≥8 charged tracks with |cosθ|<0.9
- Tracks from collision point (20 cm in z and 2 cm coaxial).

Origin of missing energy in Z → hadrons ?

Example LEP1 Analysis: ALEPH $e^+e^- \to H\nu\nu$

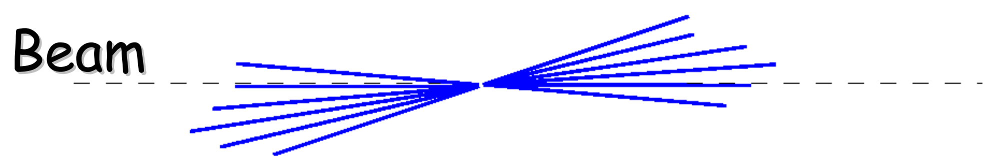
Energy Losses in the Beam Pipe

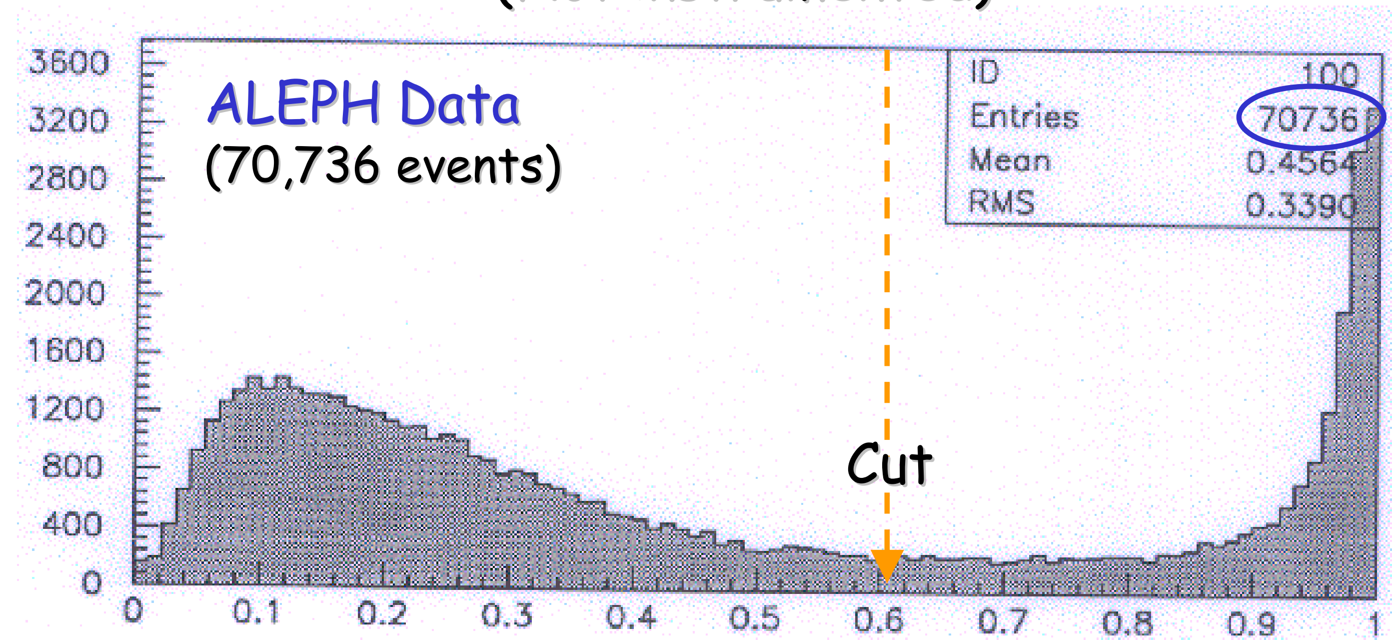
P. Janot

(Not instrumented)

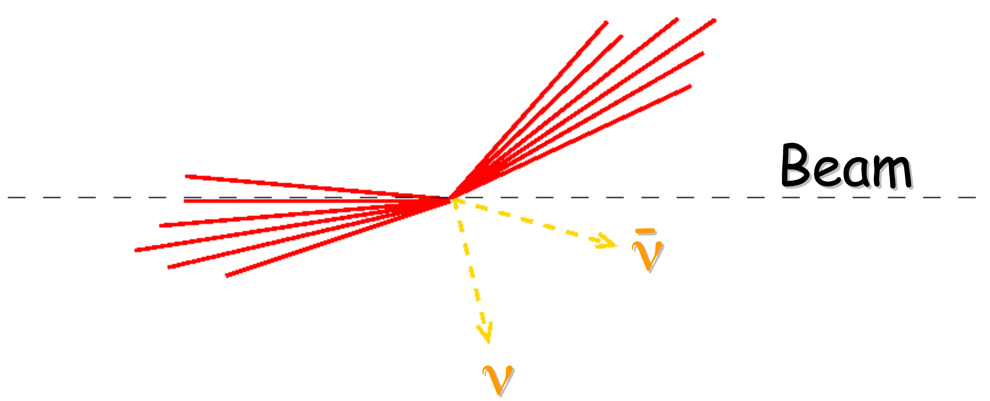
Fraction of energy beyond 30° is >60%
energy within 12°< 3 GeV

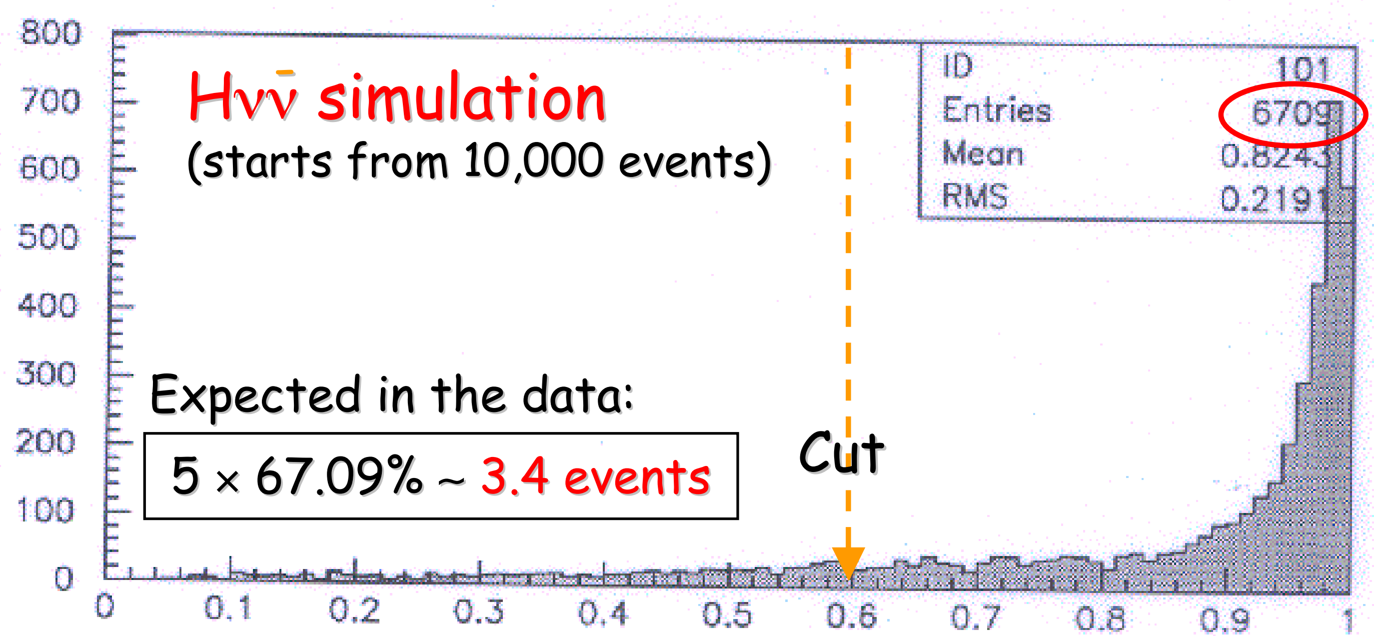
$Z \to q\bar{q}$ events:
Two back-to-back jets





$H\nu\bar{\nu}$ signal





$X_{30} \geq 60\%$

X_{30} = Fraction of measured energy above 30 degrees from the beam axis

Example LEP1 Analysis: ALEPH $e^+e^- \to H\nu\nu$

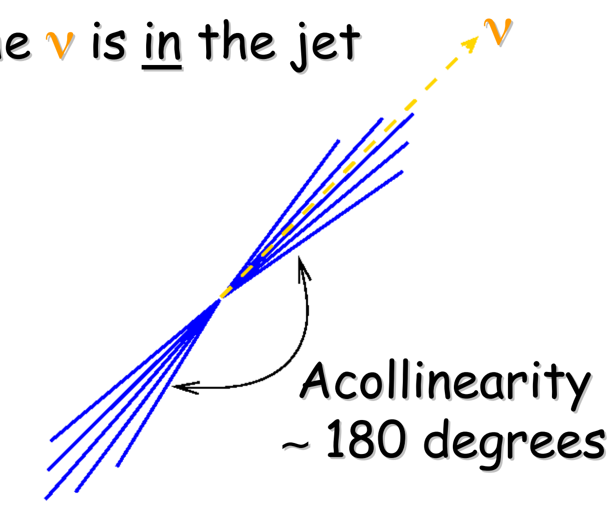
P. Janot

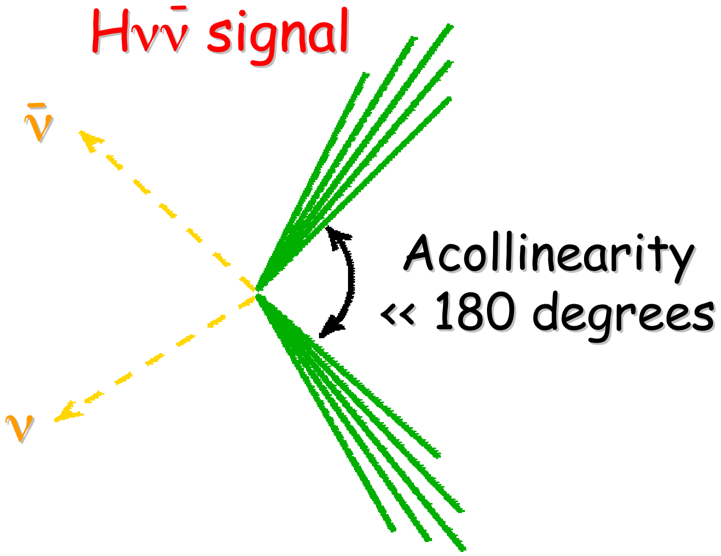
Energy Losses in Semi-Leptonic b decays

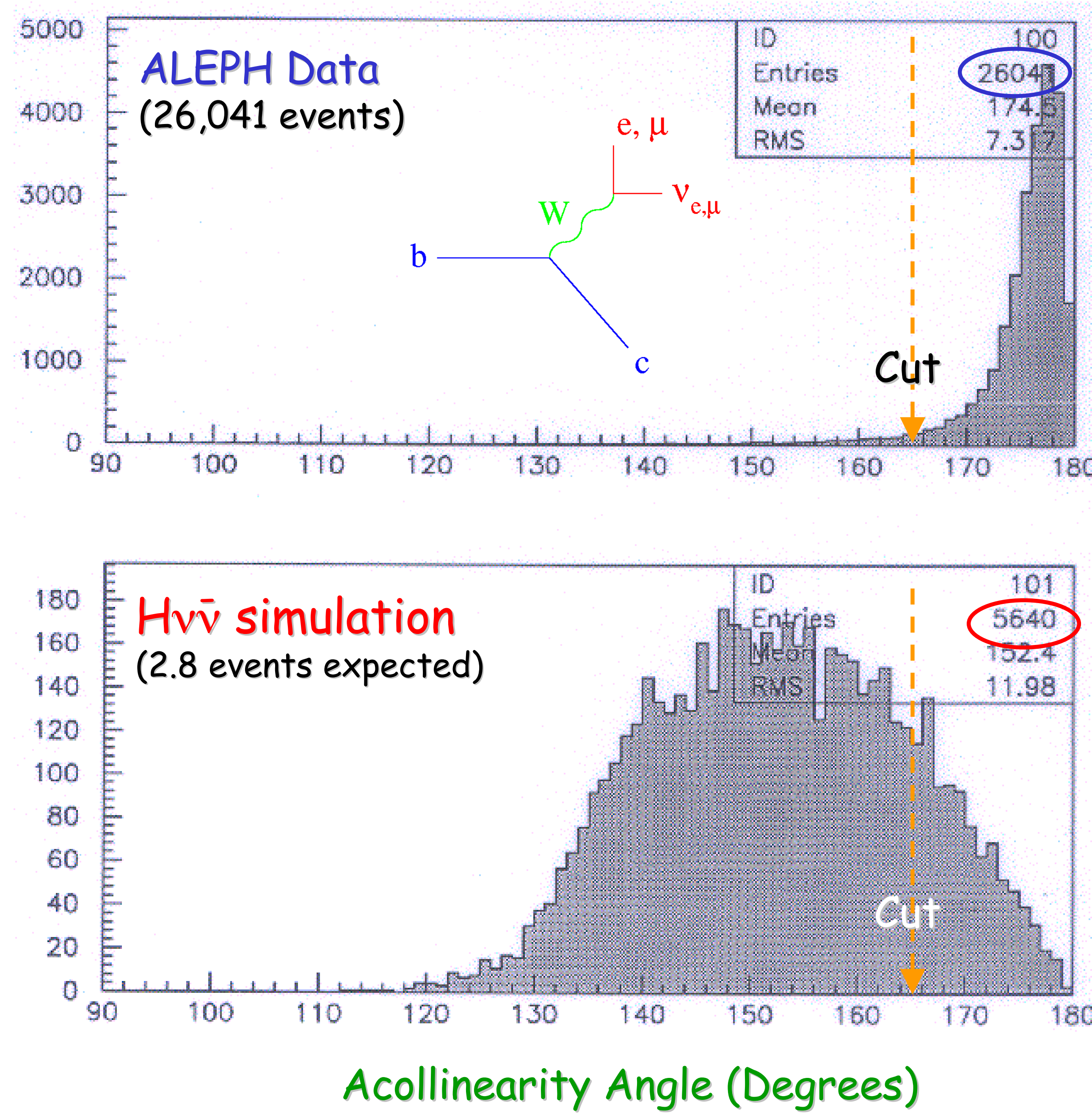
To reject events with back-to-back jets from Z decays, events are divided into two hemispheres by a plane perpendicular to the thrust axis. The angle of the total momenta measured in the two hemispheres defines the acollinearity angle.

$Z \to b\bar{b}$ events:

The ν is in the jet







Acoll. ≤ 165 deg.

Example LEP1 Analysis: ALEPH $e^+e^- \to H\nu\nu$

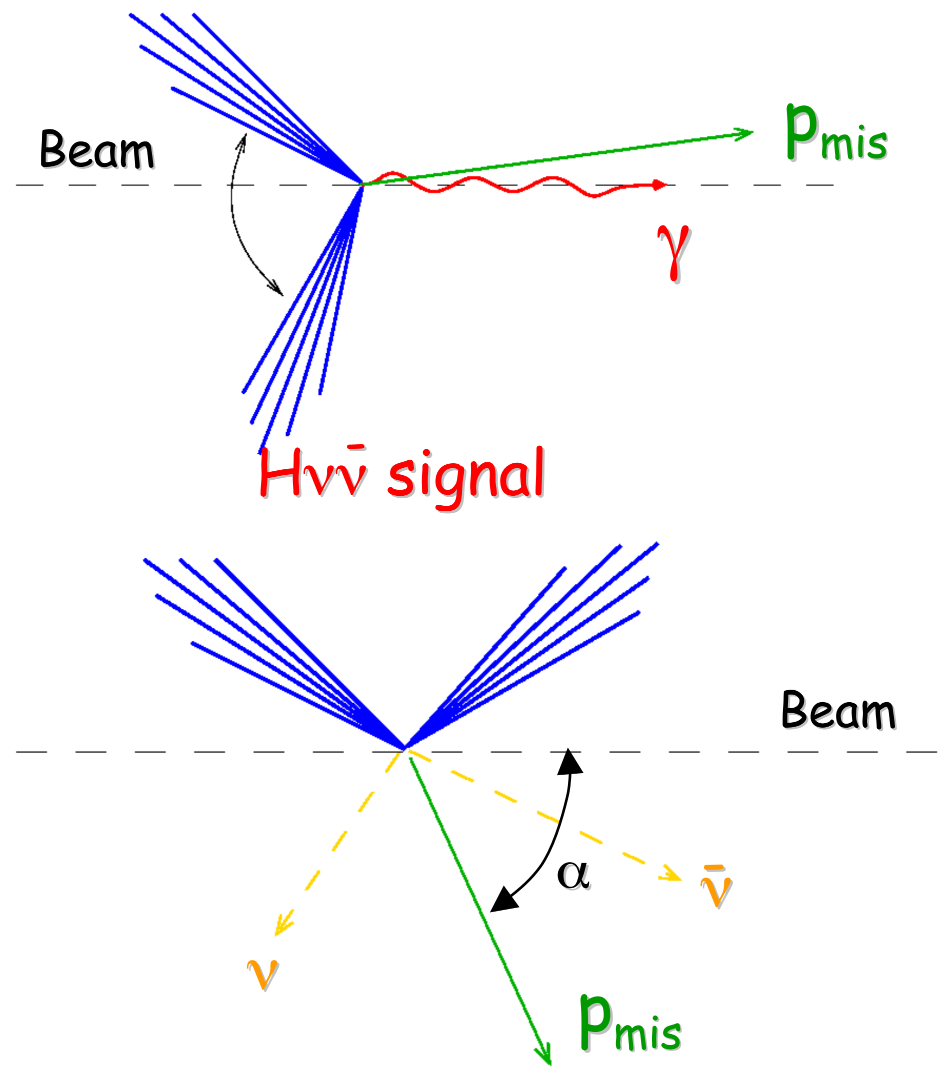
Energy Losses due to I.S.R.

P. Janot

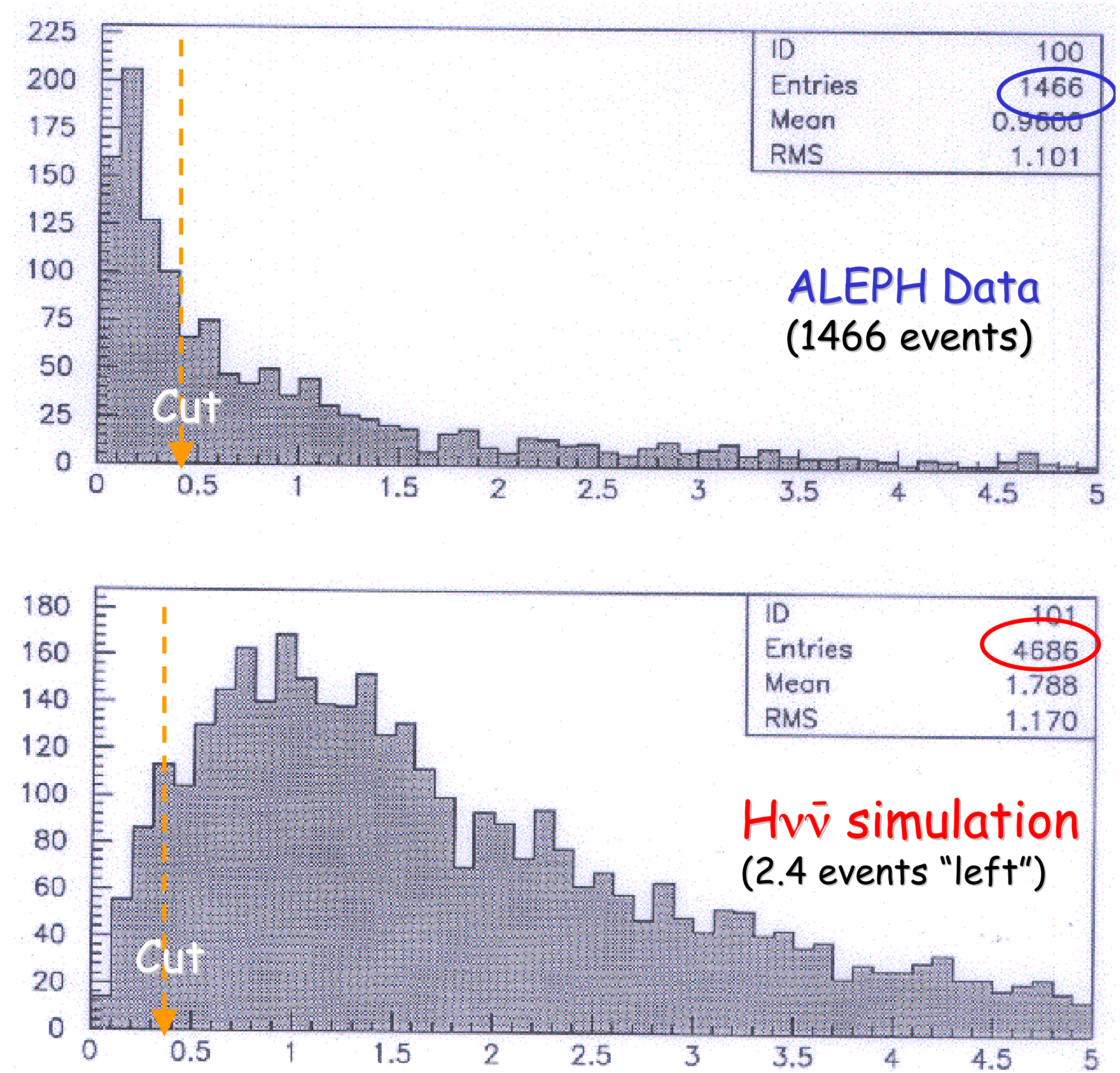
(Initial State Radiation)

$e^+e^- \to q\bar{q}\gamma$ events:

The p_{mis} is along the beam



tan α ≥ 0.4



Example LEP1 Analysis: ALEPH $e^+e^- \rightarrow H\nu\nu$

Energy Losses due to I.S.R. + Semi-Leptonic b decay

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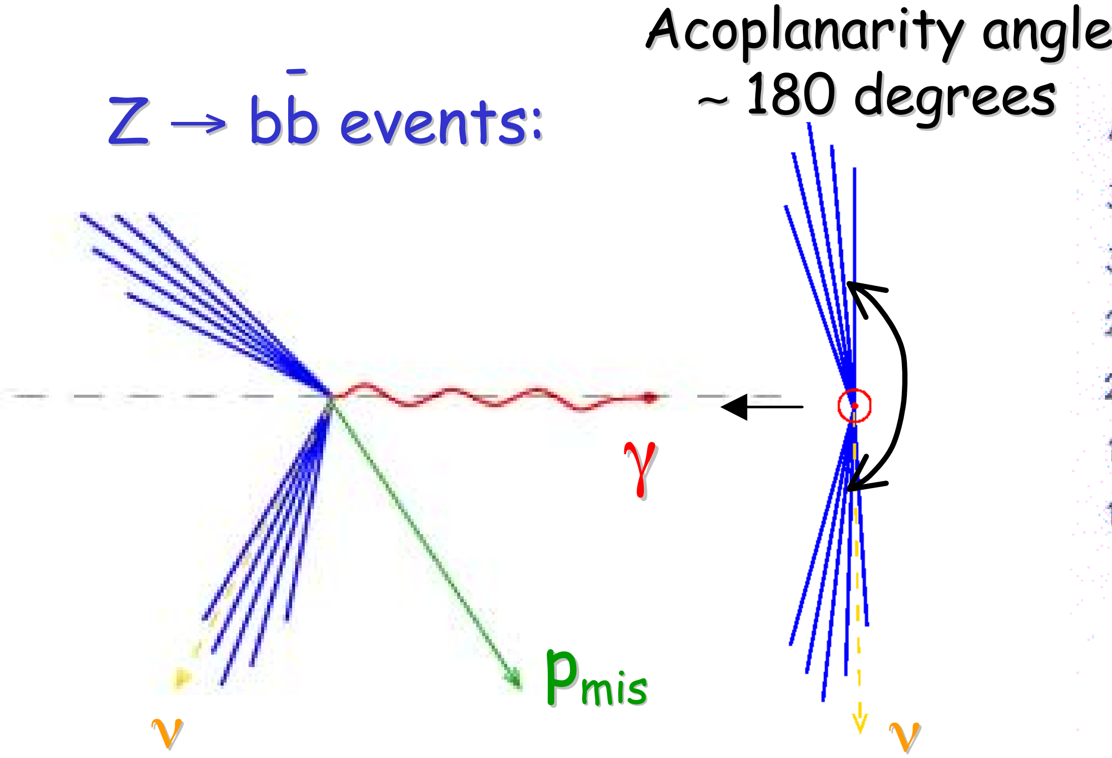
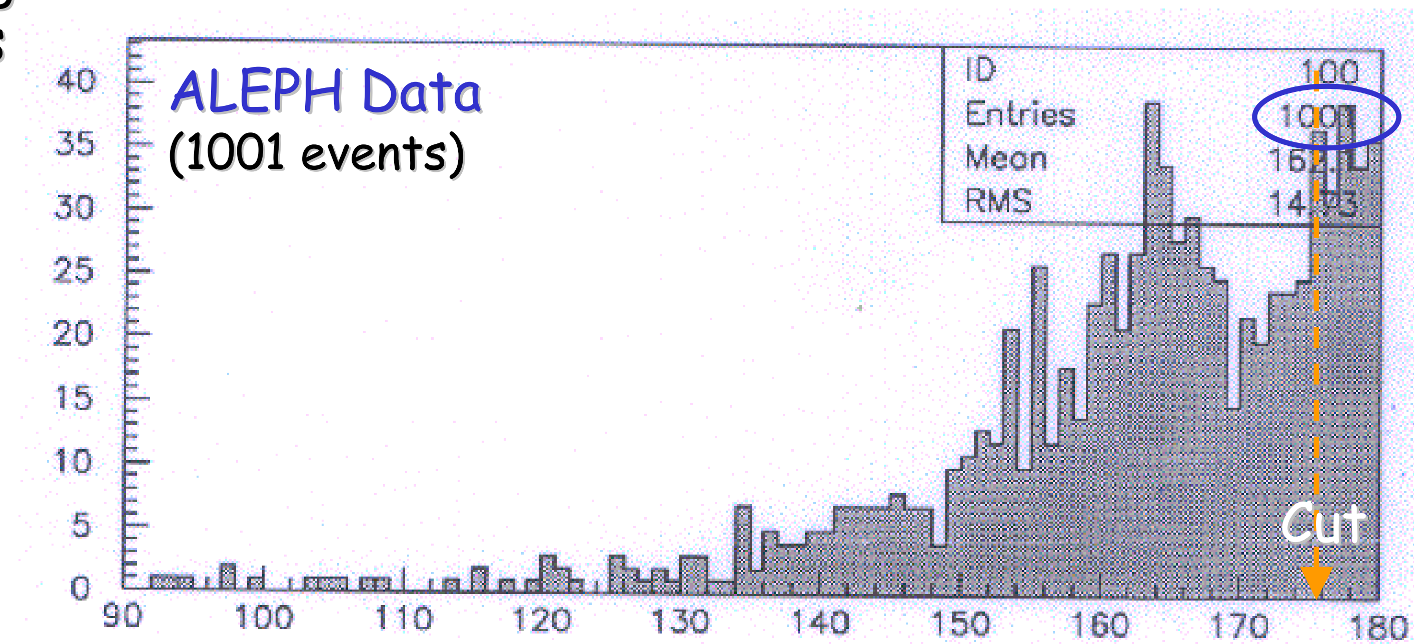
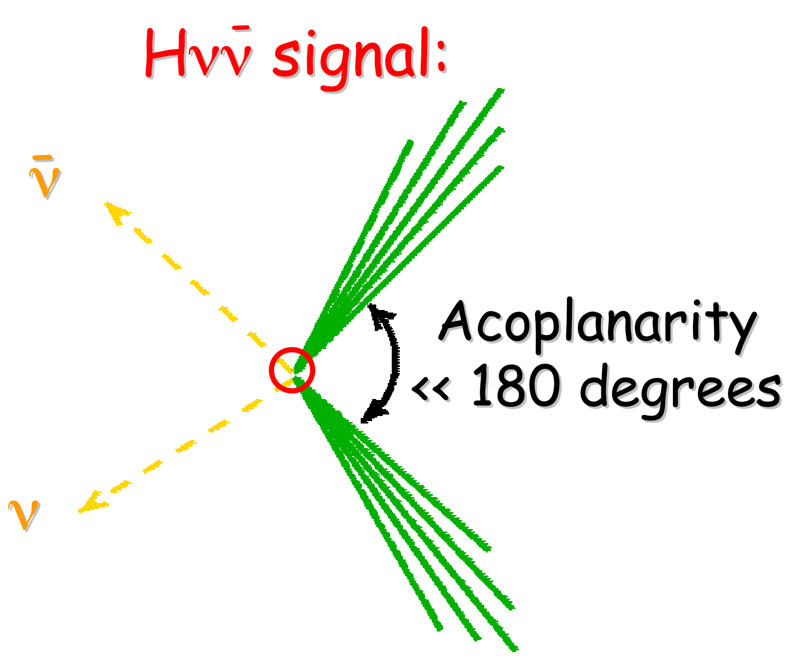
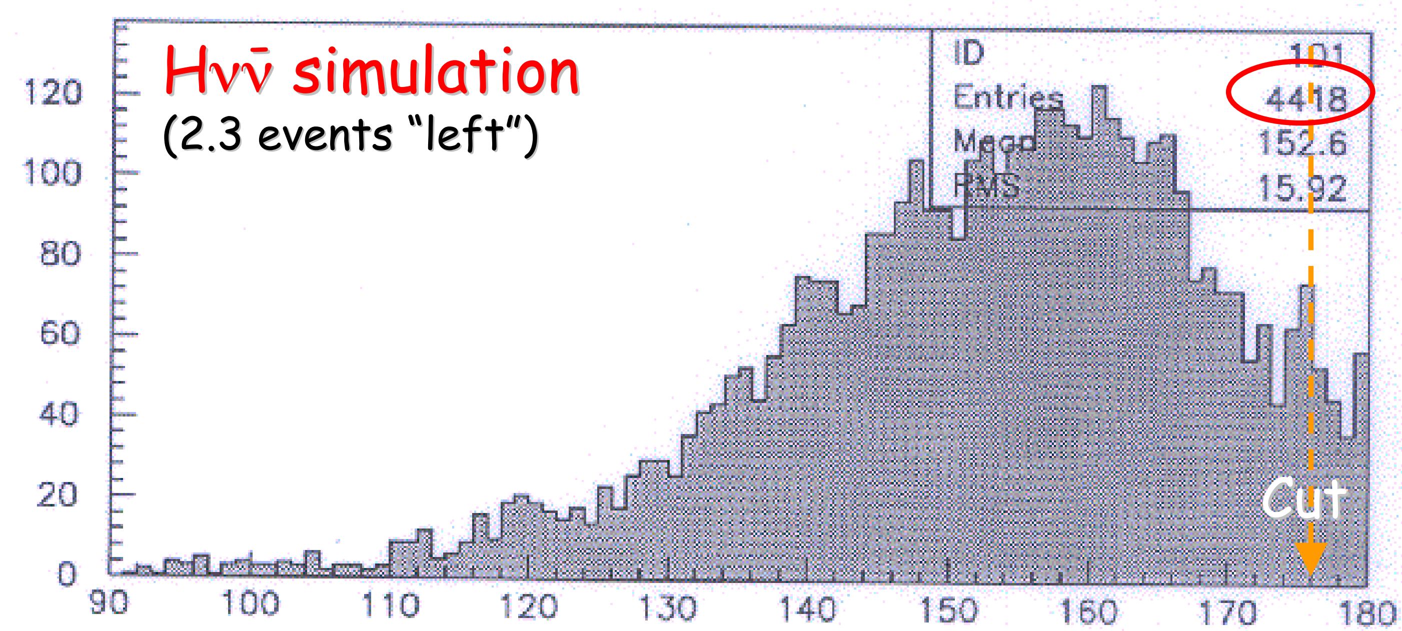








Acoplanarity Angle (Degrees)

Acop. ≤ 175 deg.

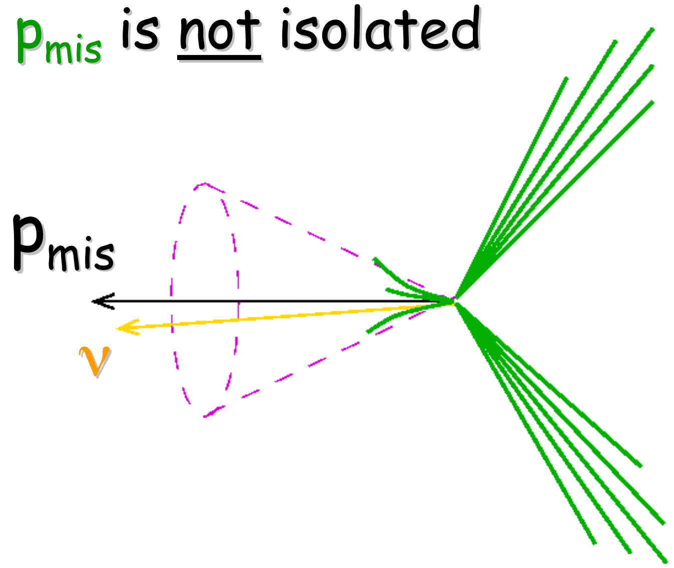
Example LEP1 Analysis: ALEPH $e^+e^- \to H\nu\nu$

A Semi-Leptonic decay in $b\bar{b}g$ (3-jet) events

P. Janot

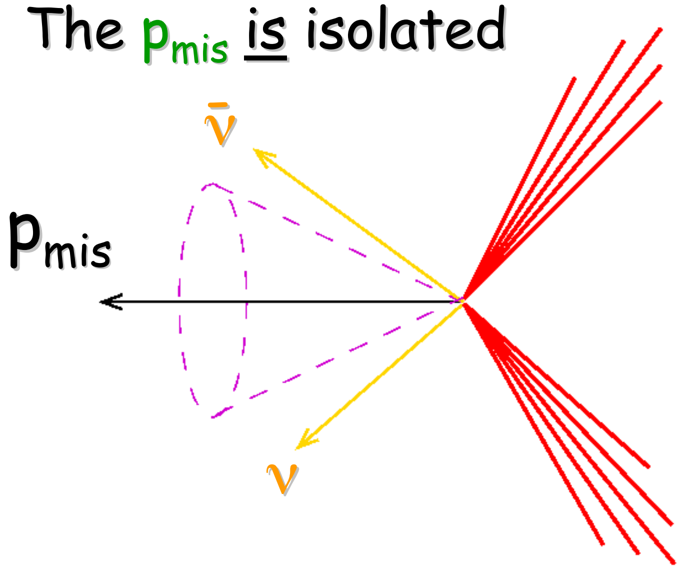
$Z \to b\bar{b}g$ events:

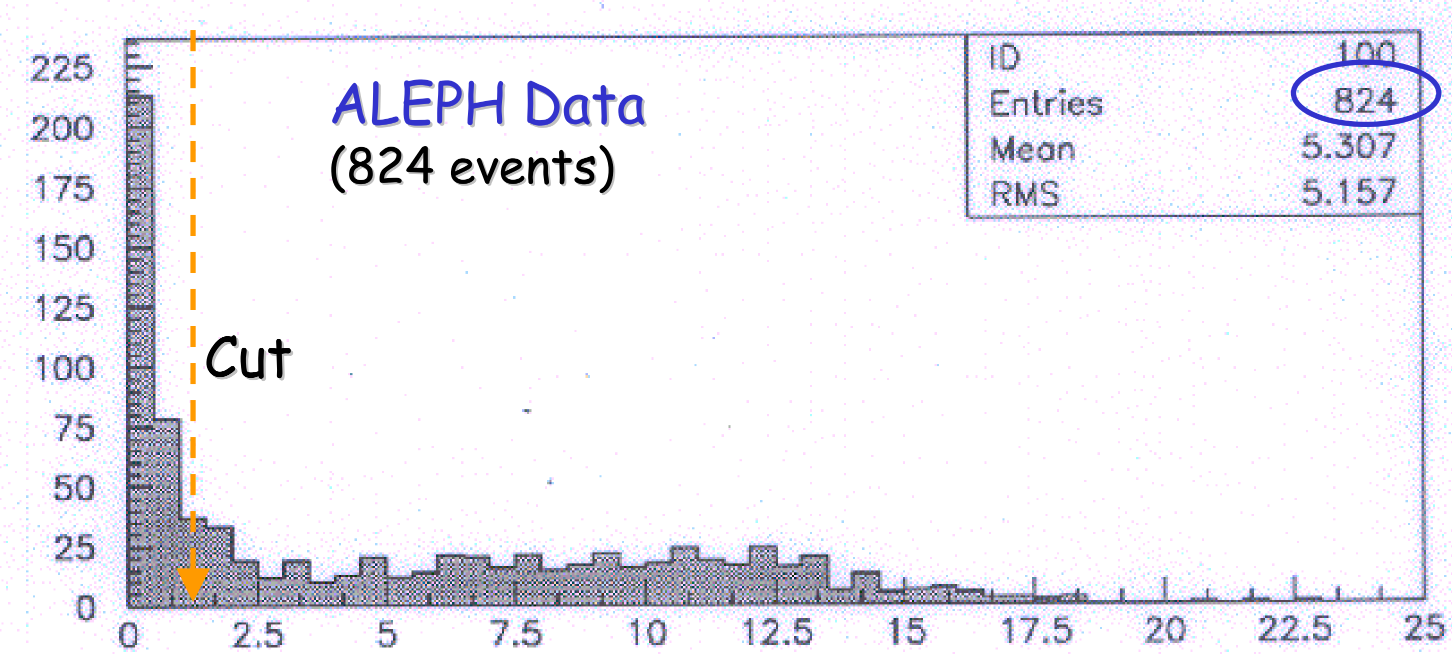
The p_{mis} is not isolated

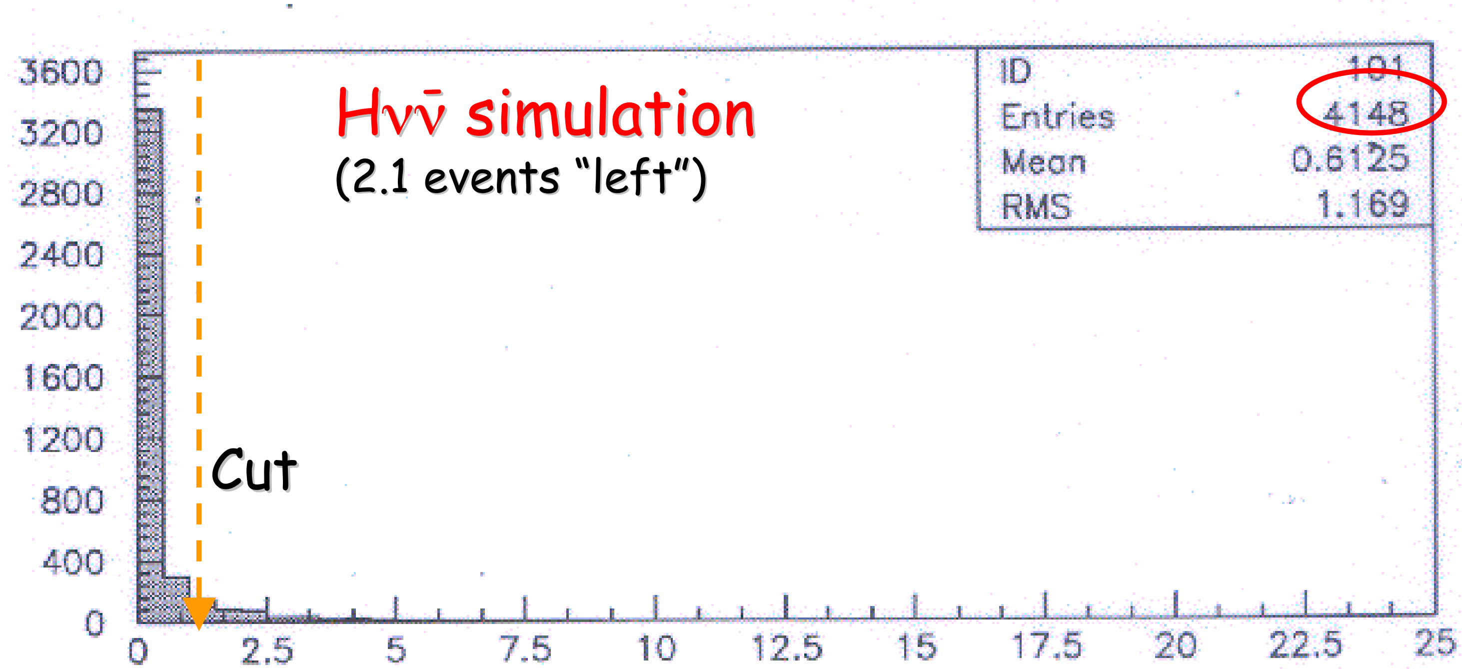


$H\nu\bar{\nu}$ signal:

The p_{mis} is isolated







$E_{CONE} \leq 1$ GeV

E_{CONE} (GeV) = Energy contained in a cone of half-angle 30 degrees around p_{mis}

Example LEP1 Analysis: ALEPH $e^+e^- \rightarrow H\nu\nu$

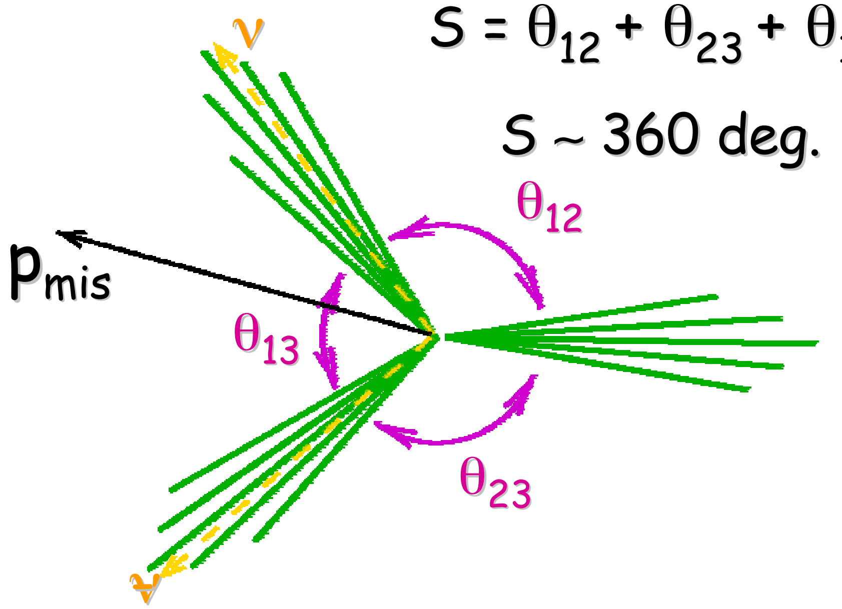
Two Semi-Leptonic decays in $b\bar{b}g$ (3-jet) events

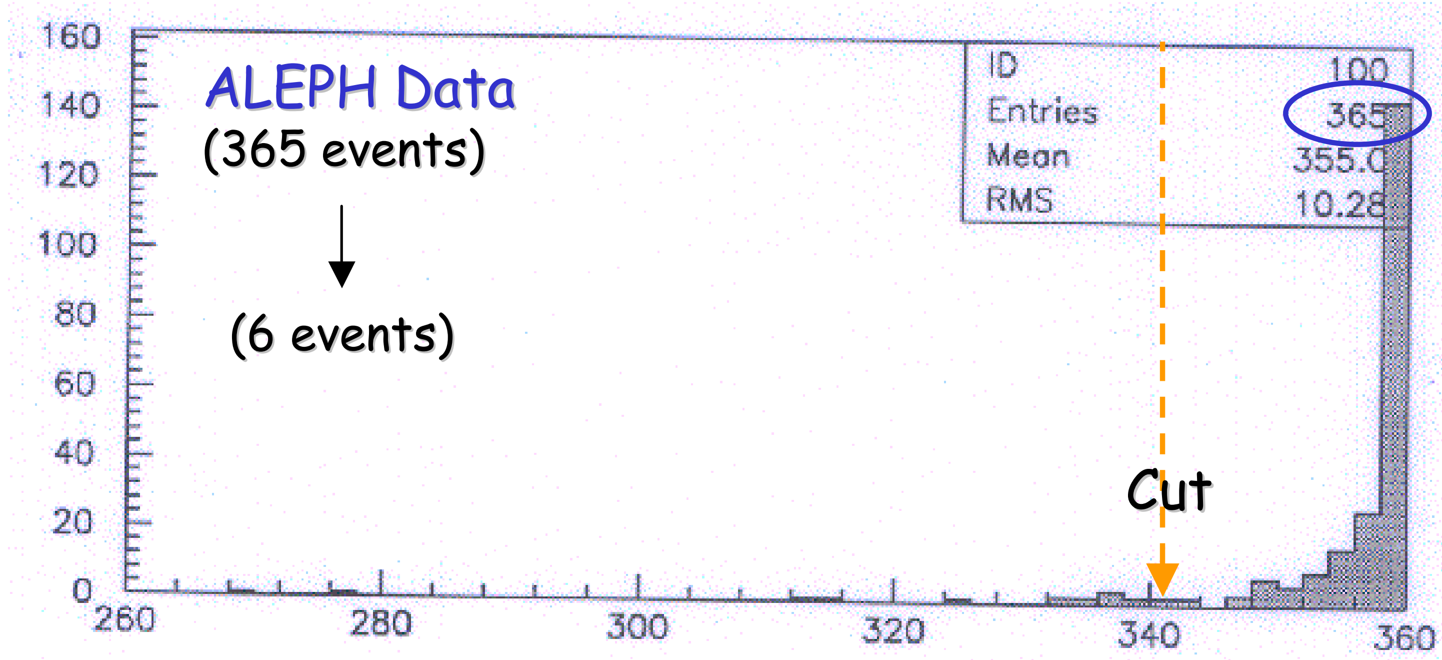
P. Janot

$Z \rightarrow b\bar{b}g$ events:

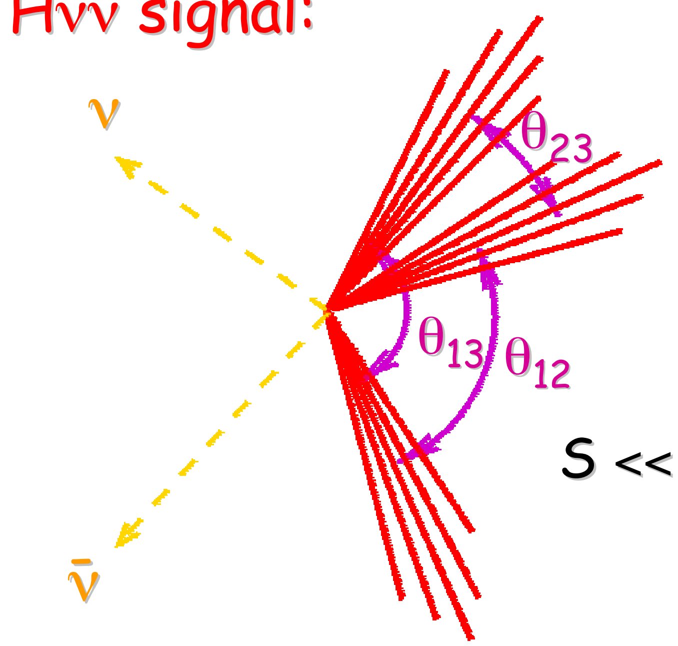
$S = \theta_{12} + \theta_{23} + \theta_{13}$

$S \sim 360$ deg.

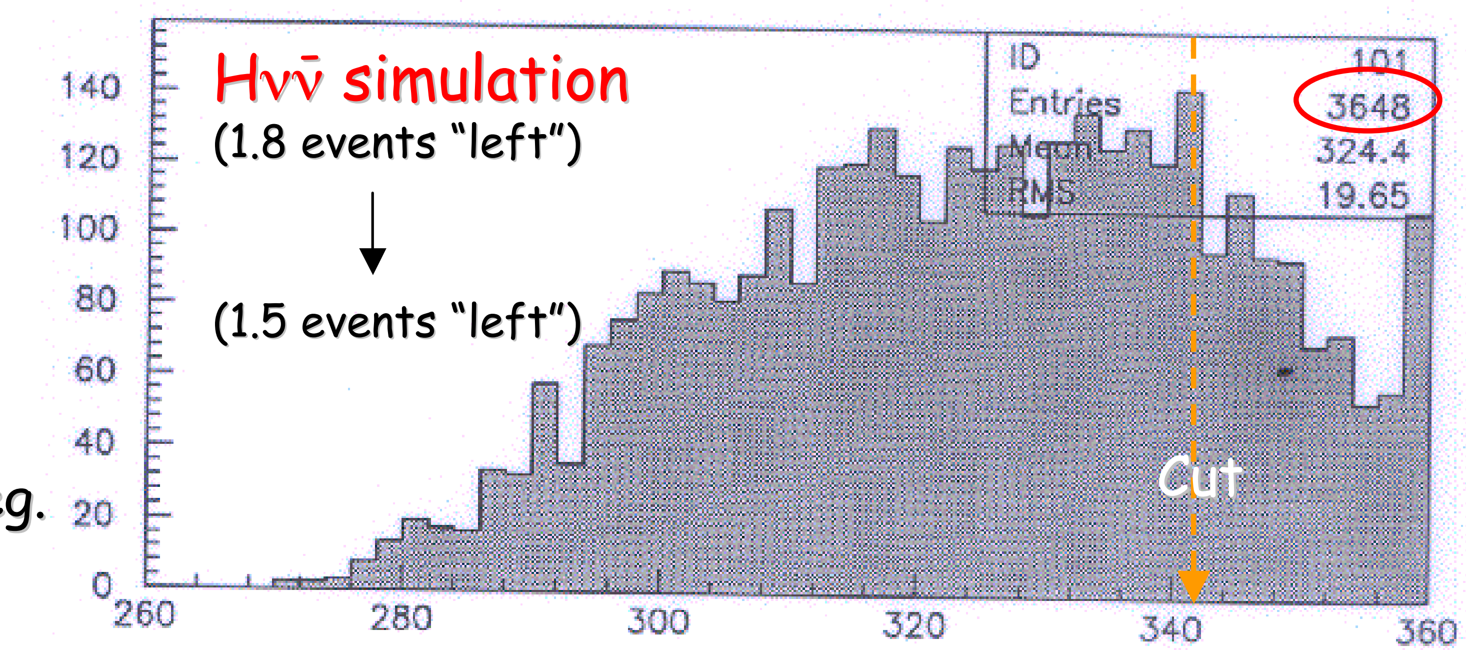




$H\nu\bar{\nu}$ signal:



$S \ll 360$ deg.



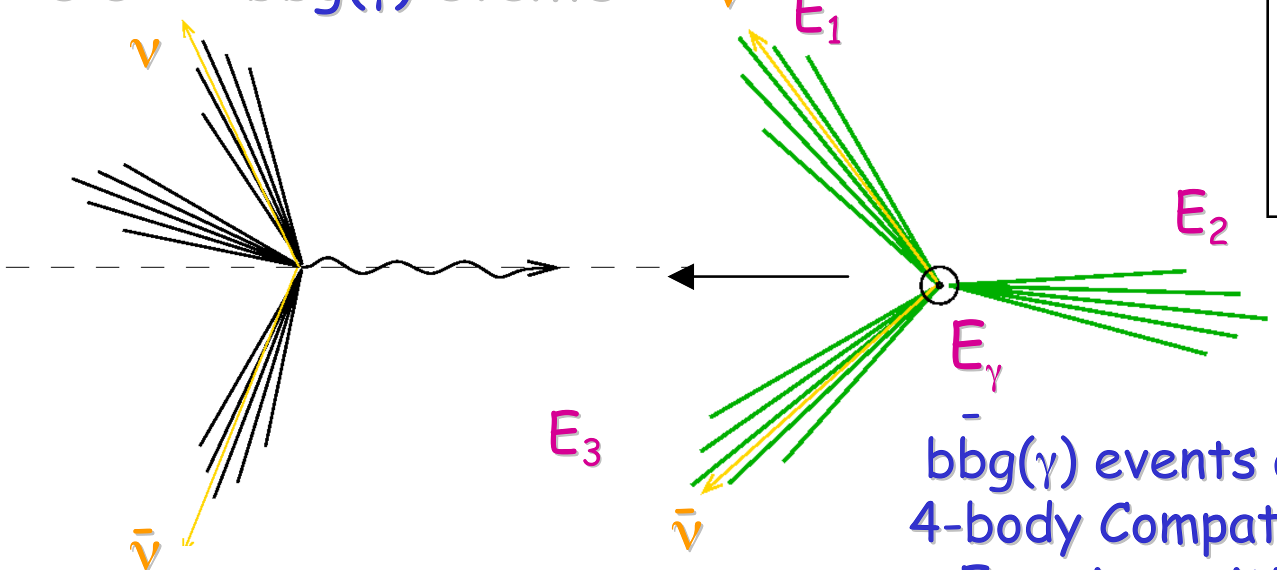
$S \leq 342$ degrees

$S = \theta_{12} + \theta_{23} + \theta_{13}$

Example LEP1 Analysis: ALEPH $e^+e^-\to H\nu\nu$

Two Semi-Leptonic decays + Three Jets + I.S.R. (!!) R Janot

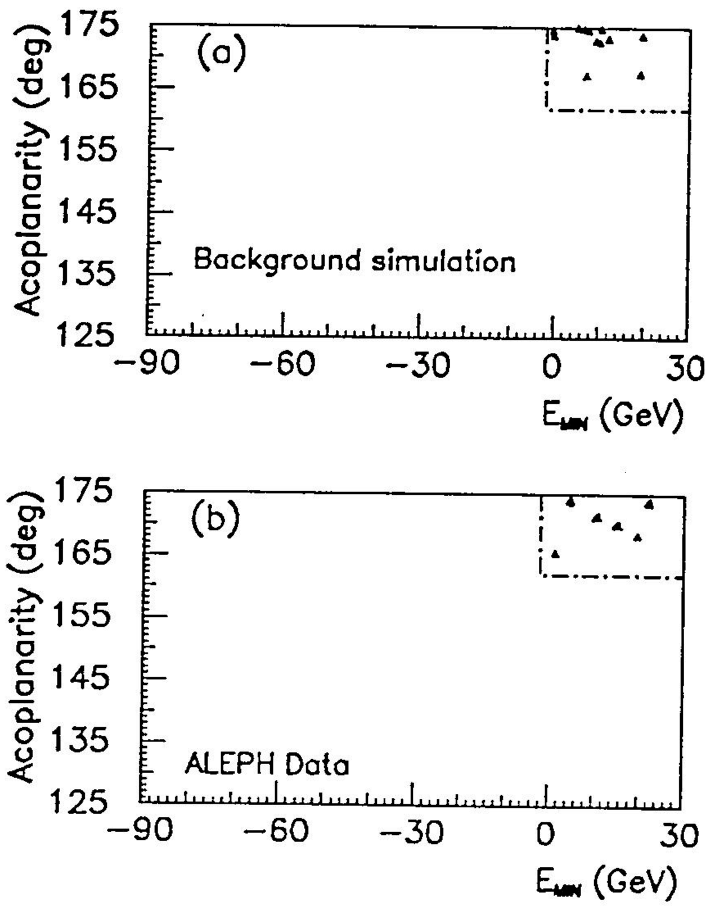
$e^+e^- \to b\bar{b}g(\gamma)$ events:

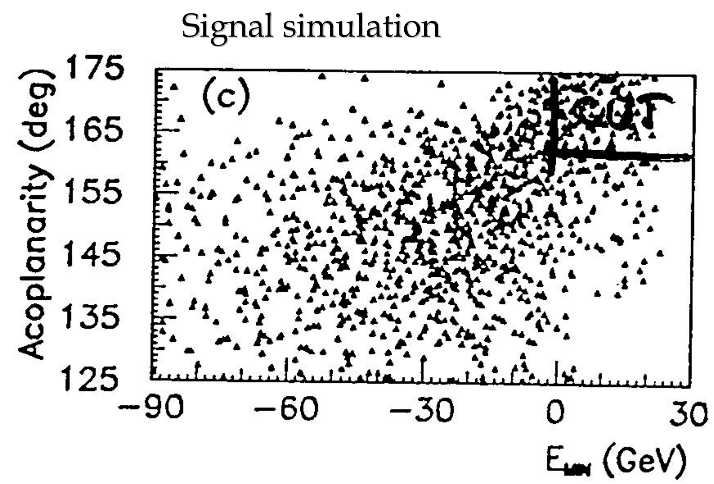


E_1, E_2, E_3, E_γ = Energies Recomputed with energy-momentum conservation constraint

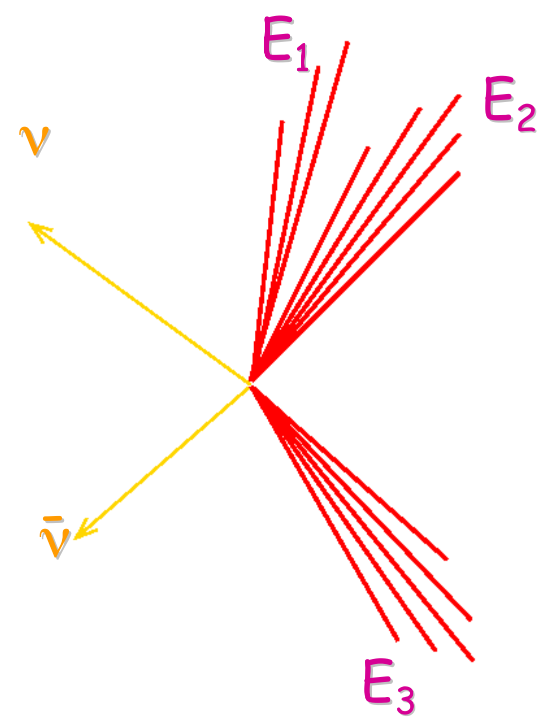
$E_{MIN} = MIN(E_1, E_2, E_3)$

$b\bar{b}g(\gamma)$ events are 4-body Compatible: E_{MIN} is positive





$H\nu\bar{\nu}$ signal:



$H\nu\bar{\nu}$: The three jets are in the same hemisphere. One of the E_i tend to be negative

No events left in the data;
Still 1.3 event expected from $H\nu\bar{\nu}$

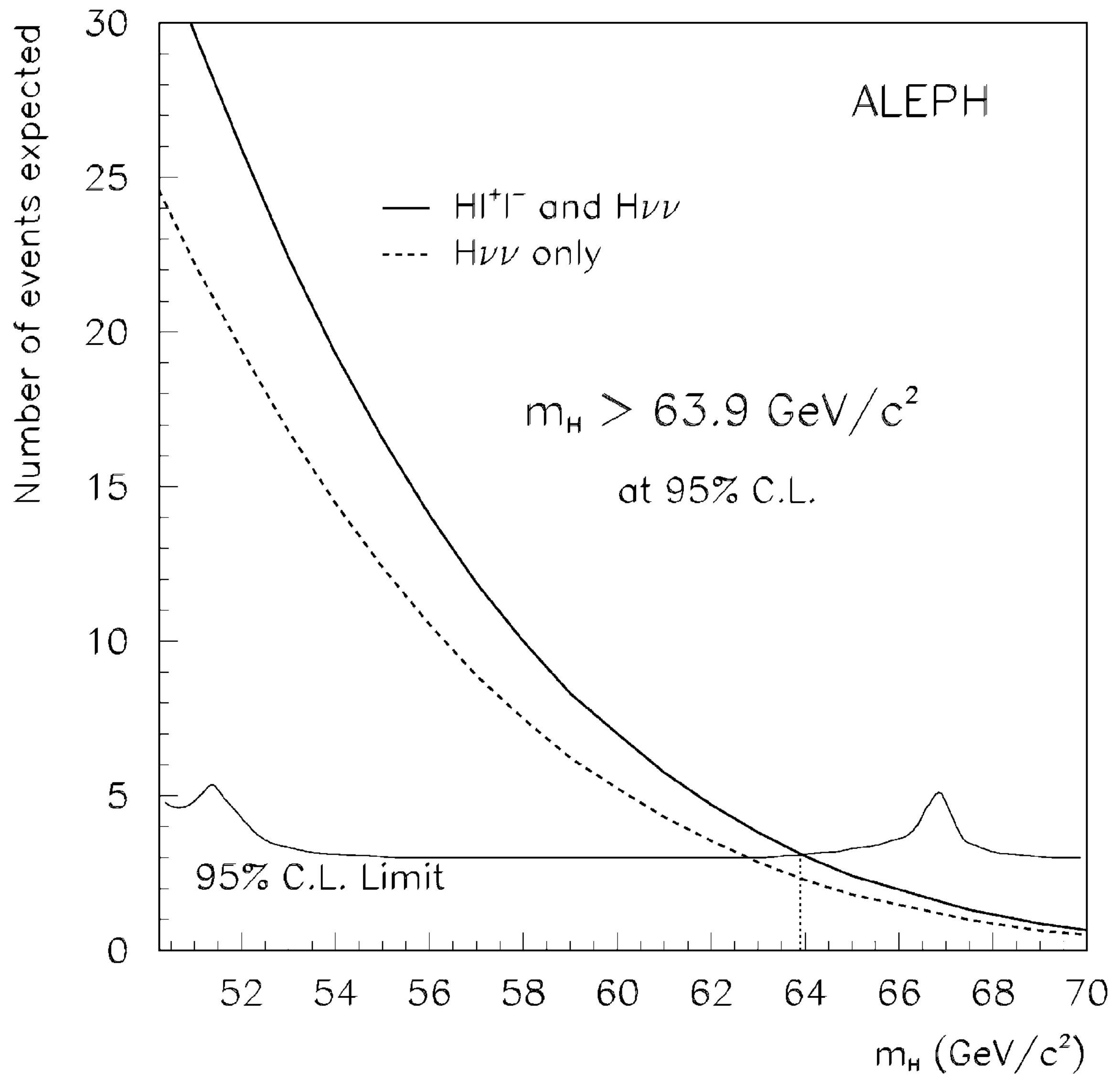


Fig. 2.23. ALEPH number of expected $e^+e^- \rightarrow HZ$ events. The intersection of the line of expected events with the line of 95% CL marks the observed mass limit. Two candidate events increase the 95% CL line according to the measured mass resolution.

LEP1 Combined Limits: DELPHI

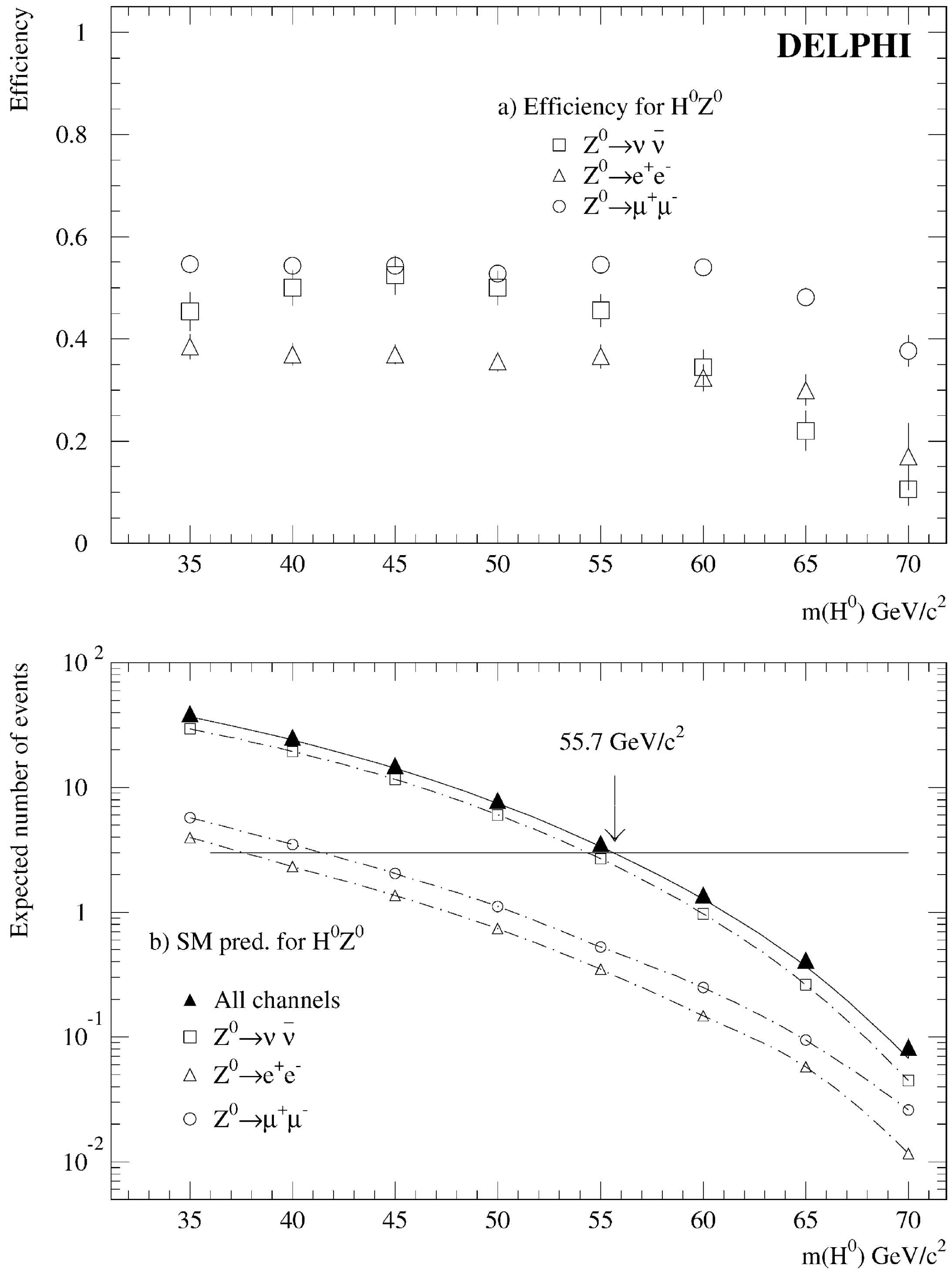


Fig. 2.24. DELPHI efficiency and number of expected $e^+e^- \to HZ$ events based on the event sample of 1.0 million hadron Z decays. The individual results from the neutrino, electron and muon channels are shown as well. In the absence of high mass candidate events the 95% CL line is at 3.0 and the intersection with the number of expected events gives the mass limit of 55.7 GeV.

LEP1 Combined Limits: L3

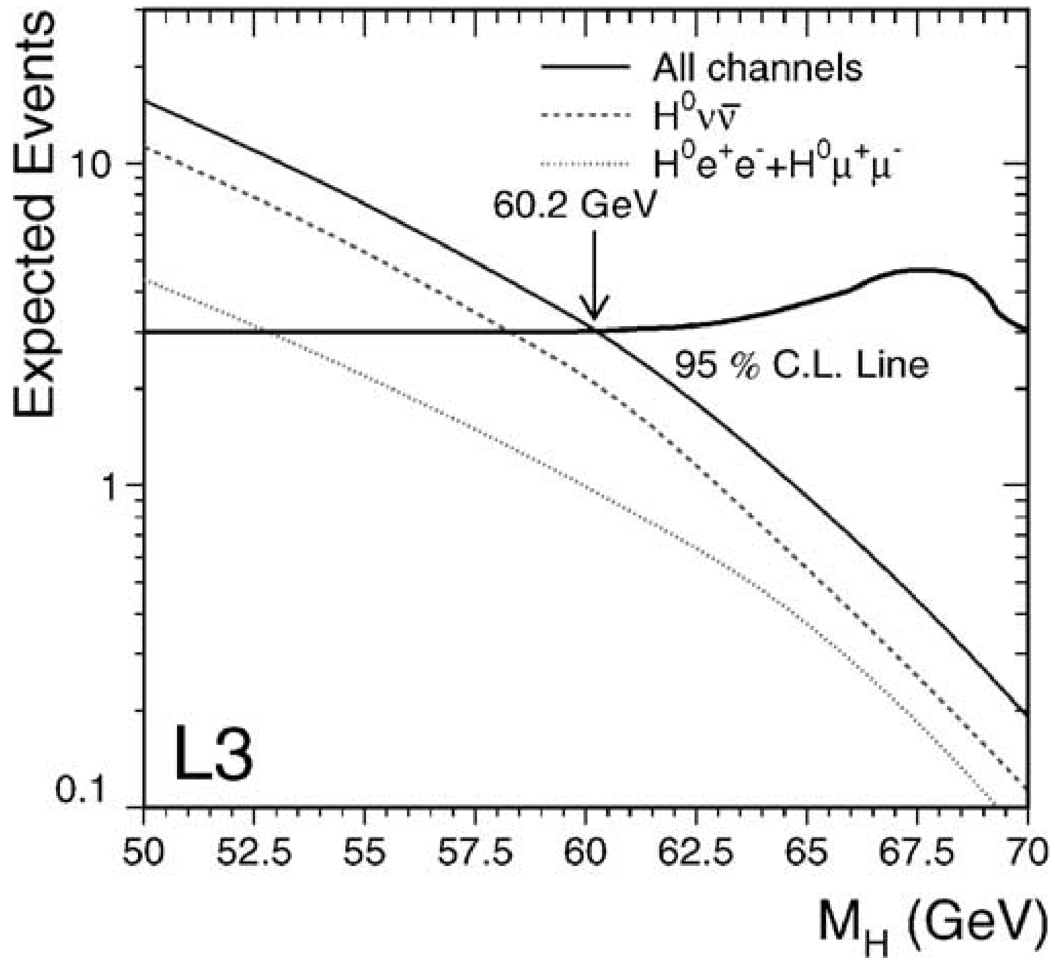


Fig. 2.25. L3 number of expected $e^+e^- \to HZ$ events. The mass limit of 60.2 GeV is set where the line of expected events intersects the 95% CL line. The candidate at 67.6 ± 0.7 GeV increases the 95% CL line from 3.0 to 4.7 with the given mass resolution.

LEP1 Combined Limits: OPAL

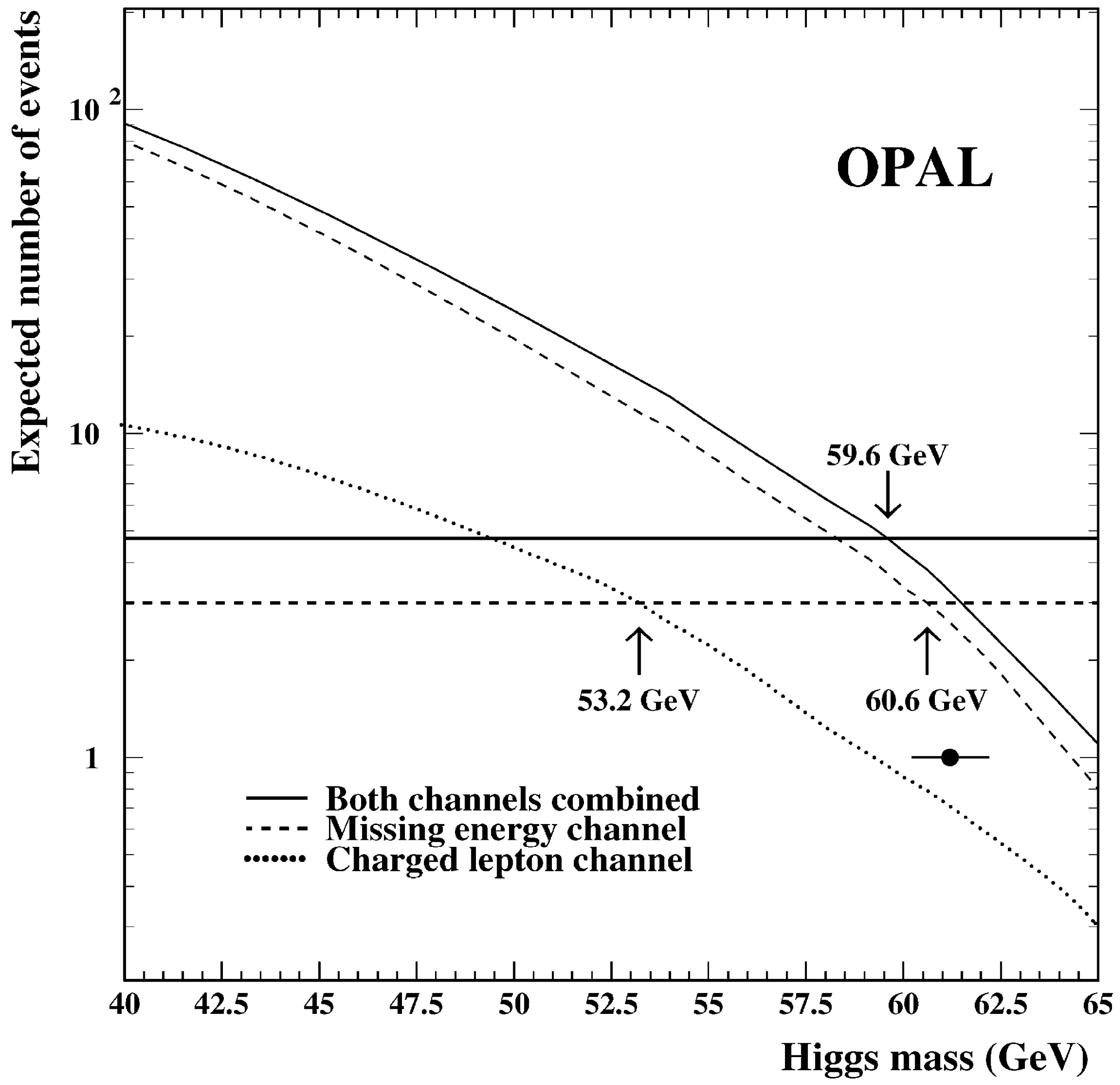


Fig. 2.26. OPAL number of expected $e^+e^- \to HZ$ events. The mass limit from the $H\ell^+\ell^-$ alone is 60.6 GeV. This limit is reduced to 59.6 GeV when combined with the $H\nu\nu$ channel because of a candidate event in the region where the limit is set.

Example Event

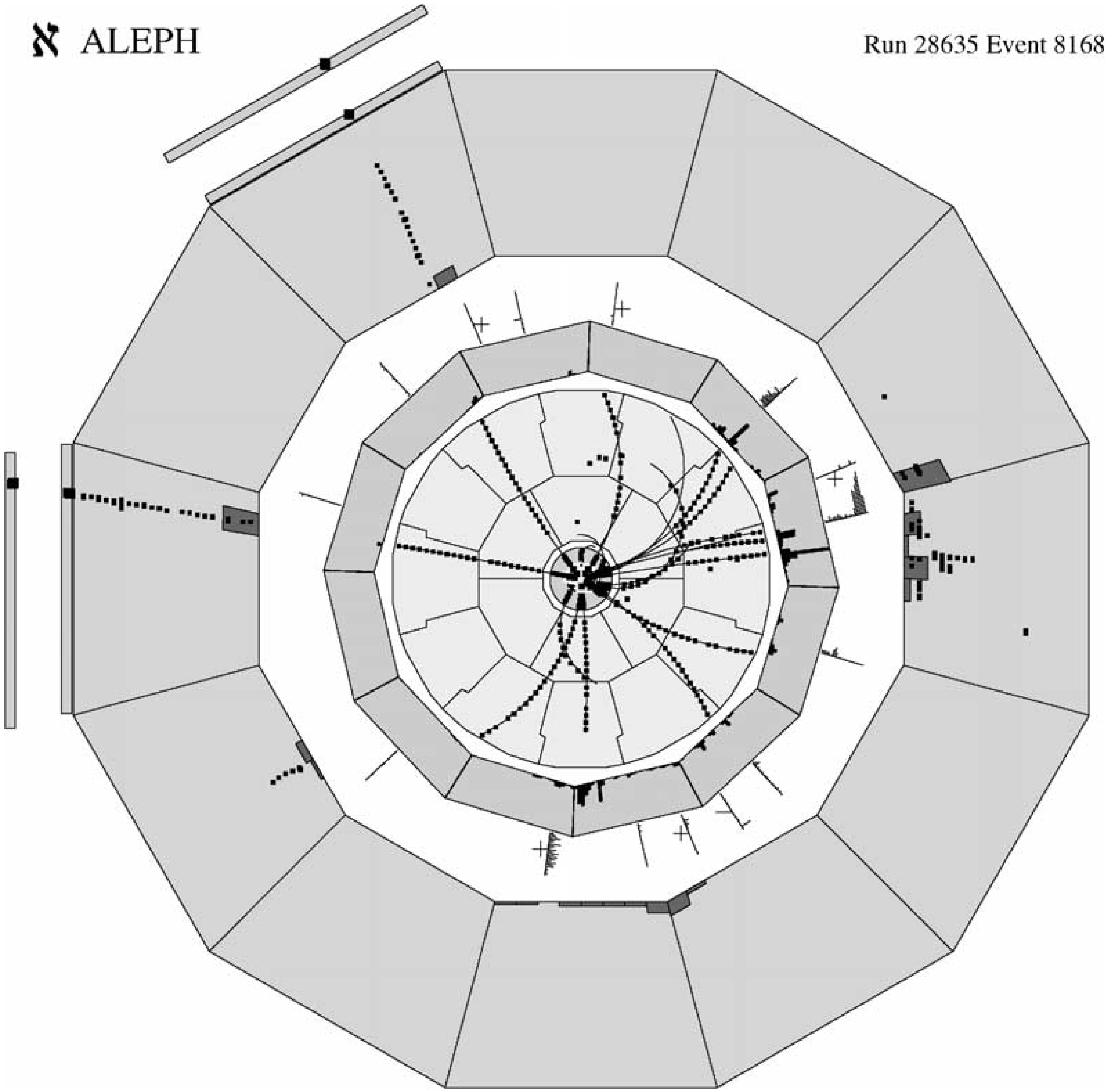


Fig. 2.27. ALEPH 49.7 GeV $H\mu^+\mu^-$ candidate. The muons are pointing to the upper left corner, opposite the hadronic activity.

Example Event

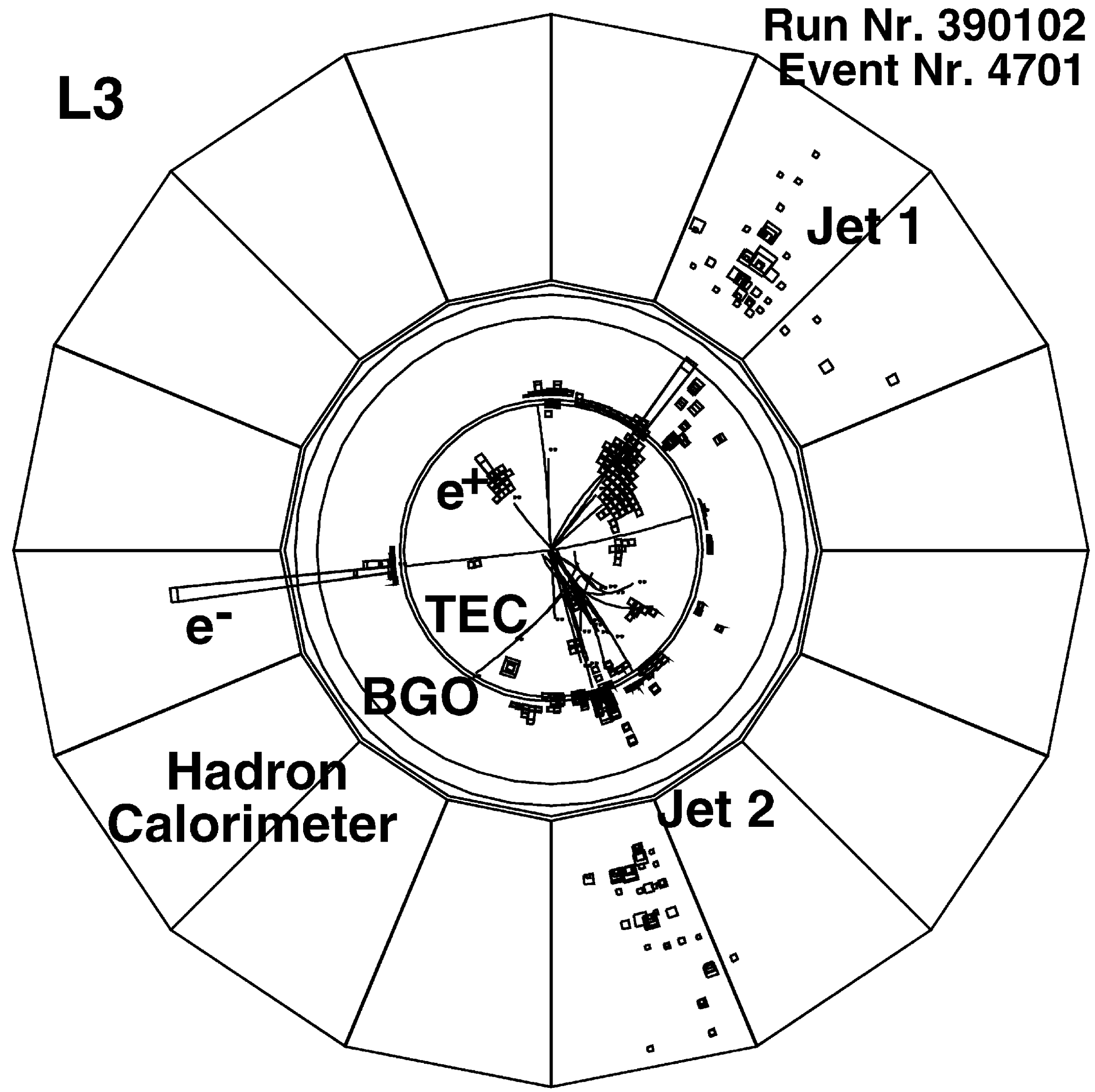


Fig. 2.28. L3 67.6 GeV He^+e^- Higgs boson candidate shown in the plane perpendicular to the beam line. The lines in the TEC represent the reconstructed charged tracks. The size of the symbols indicating individual calorimetric hits (towers in the BGO electromagnetic calorimeter and boxes in the hadron calorimeter) corresponds to the energy deposition in that hit. The towers which appear in the TEC region in this projection belong to the BGO endcaps.

LEP1 Efficiency/Expectation Comparison

Overview of detection efficiencies for a 50– 70 GeV Higgs boson. The efficiencies in brackets are determined by interpolation from the nearest Higgs boson masses used in the publication

Experiment	Efficiency (%)			Expected events			
	$H\nu\bar{\nu}$	He^+e^-	$H\mu^+\mu^-$	$H\nu\bar{\nu}$	He^+e^-	$H\mu^+\mu^-$	Sum
$m_H = 50$ GeV							
ALEPH	(46.2)	(46.1)	(46.1)	25.2	8.45		33.6
DELPHI	50.0	35.6	52.8	8.0	0.96	1.8	10.8
L3	34.8	46.6	36.1	11.3	2.5	1.88	15.7
OPAL	(38.6)	(24.2)	(30.8)	20.4	(2.0)	(2.8)	25.2
$m_H = 55$ GeV							
ALEPH	(41.7)	(51.2)	(51.2)	12.2	4.2		16.5
DELPHI	45.6	36.6	54.5	4.0	0.56	0.67	5.3
L3	(30.1)	(54.3)	(38.4)	5.3	1.3	0.92	7.5
OPAL	(31.7)	(24.9)	(29.7)	8.7	(1.0)	(1.0)	10.7
$m_H = 60$ GeV							
ALEPH	38.3	39.4	48.1	5.12	1.27	0.92	7.0
DELPHI	34.5	32.4	54.0	1.6	0.26	0.38	2.3
L3	28.6	42.2	32.3	2.17	0.57	0.42	3.2
OPAL	25.7	21.5	30.8	3.4	0.45	0.65	4.5
$m_H = 65$ GeV							
ALEPH	29.8	(34.7)	(34.7)	1.73	0.69		2.42
DELPHI	22.0	29.8	48.2	0.40	0.07	0.16	0.63
L3	16.0	39.9	26.2	0.55	0.23	0.16	0.93
OPAL	15.1	(18.0)	(22.1)	0.8	(0.15)	(0.15)	1.1
$m_H = 70$ GeV							
ALEPH	(26.7)	(27.7)	(27.7)	(0.52)	(0.16)		(0.68)
DELPHI	10.6	17.1	37.7	0.06	0.02	0.04	0.12
L3	9.2	35.8	3.3	0.11	0.07	0.01	0.19
OPAL	13.0	17.1	21.6	(0.24)	(0.58)	(0.007)	(0.31)

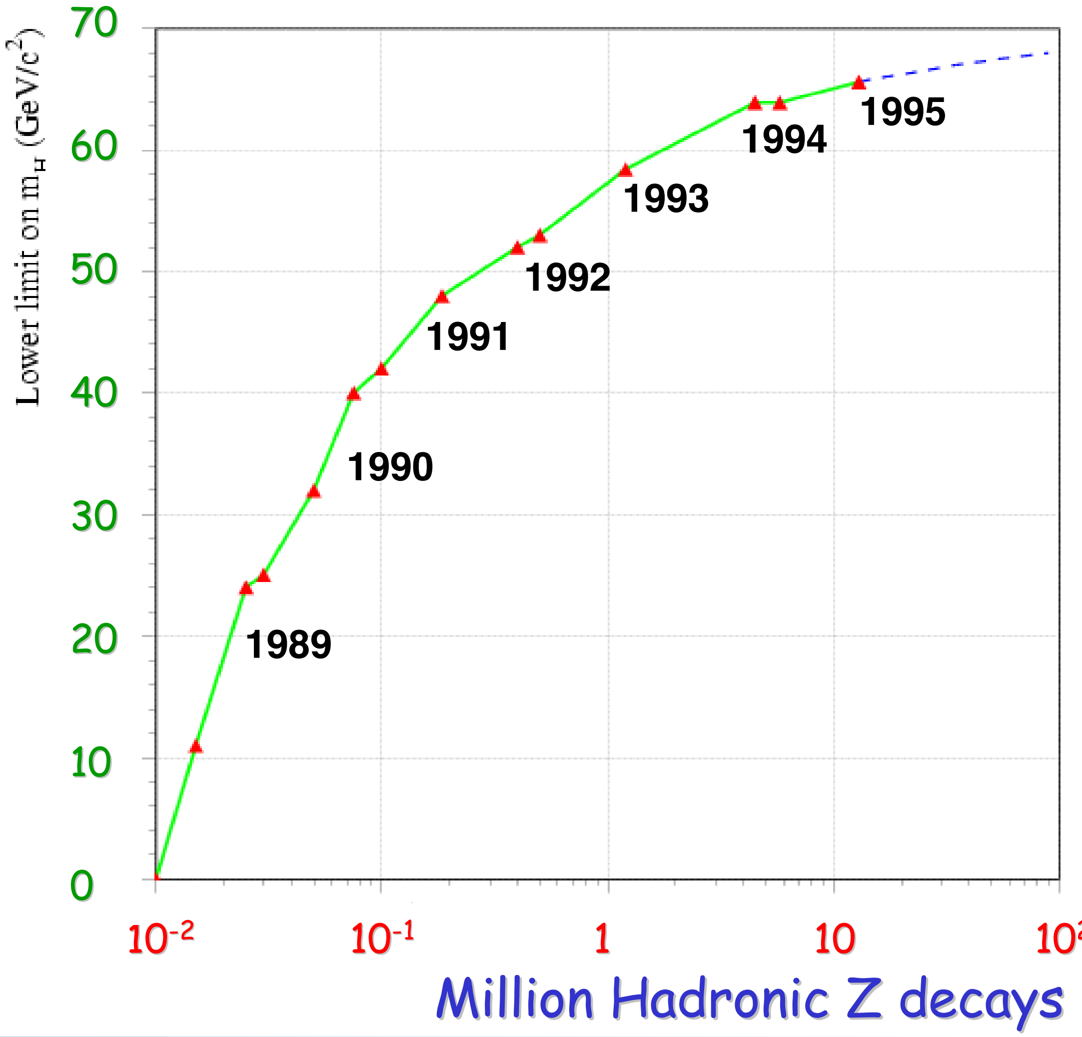
LEP1: Combination

Overview of individual Higgs boson mass limits at 95% CL from the LEP-1 results. Similar mass limits are observed by all LEP experiments, although the size of the analyzed data sample varies between them, since the Higgs boson production cross section decreases quickly for heavy Higgs bosons

	ALEPH	DELPHI	L3	OPAL
Data sample	1989–1995	1990–1993	1990–1994	1990–1995
Hadronic Z decays (10^6)	4.5	1.6	3.1	4.4
Mass limit (GeV)	63.9	58.3	60.1	59.6

Evolution of LEP-1 Higgs boson lower mass limits at 95% CL. The combined mass limits can be compared directly since the same method of combination was used as described in the text. The final LEP-1 mass limit was almost reached with the inclusion of the 1994 data. Significantly higher mass sensitivity required an increase of the center-of-mass energy beyond the scope of LEP-1

Including data of year	1991	1993	1994	1995
Hadronic Z decays (10^6)	2.0	6.0	12	14
Combined limit (GeV)	59.3 [83]	63.5 [84]	65.1 [85]	65.6 [86]



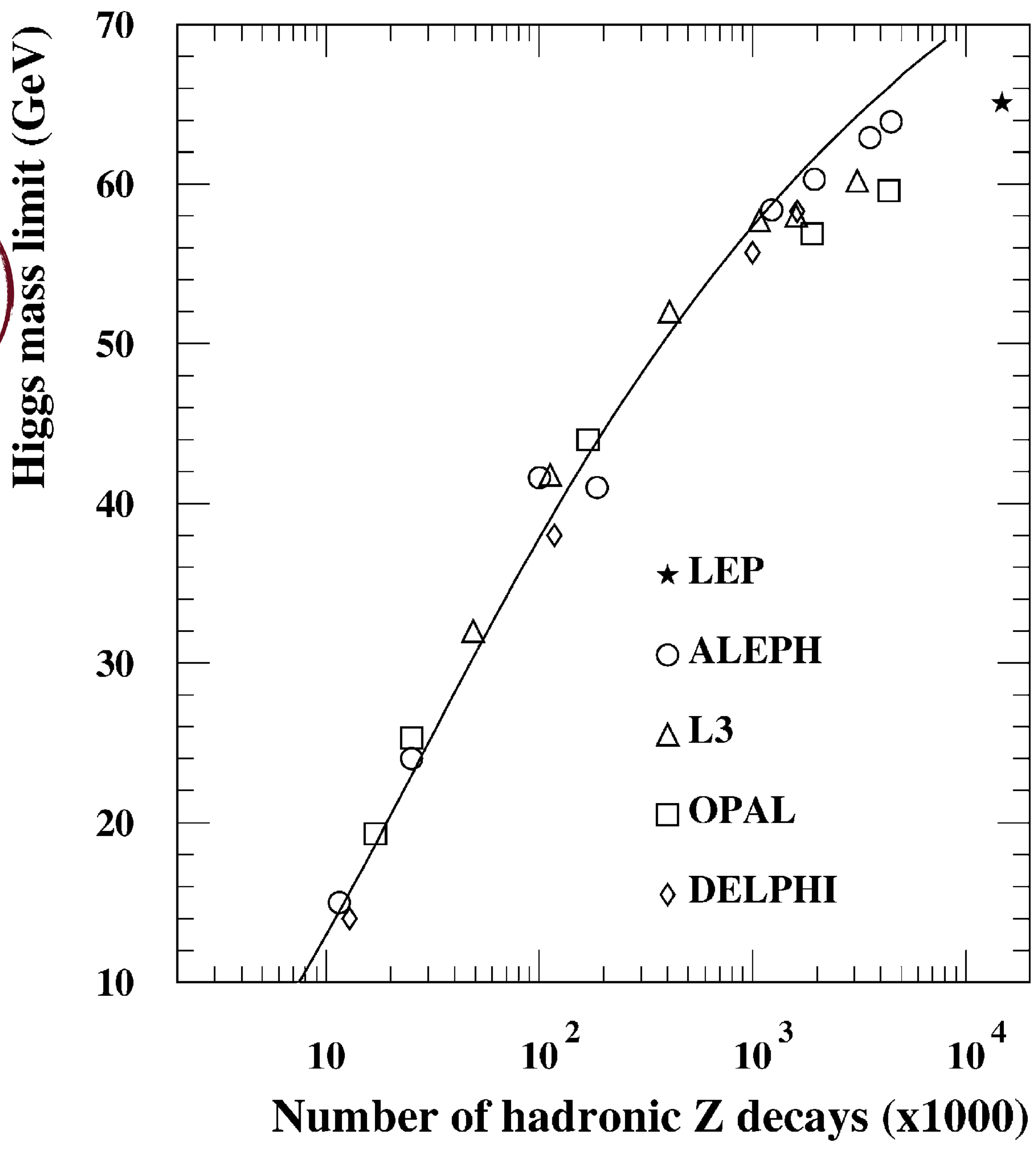


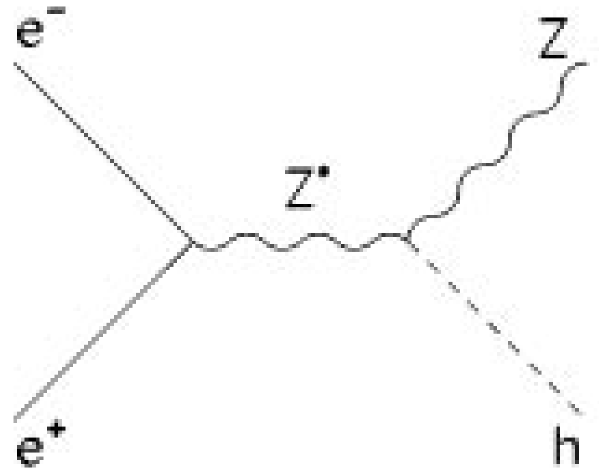
Fig. 2.30. Evolution of Higgs boson mass limits. The solid line shows the expected sensitivity taking 50% detection efficiency in the search channels. With increasing luminosity the mass limit lies below this line since the selection cuts have to be tightened to cope with the increasing background in order to obtain roughly zero background.

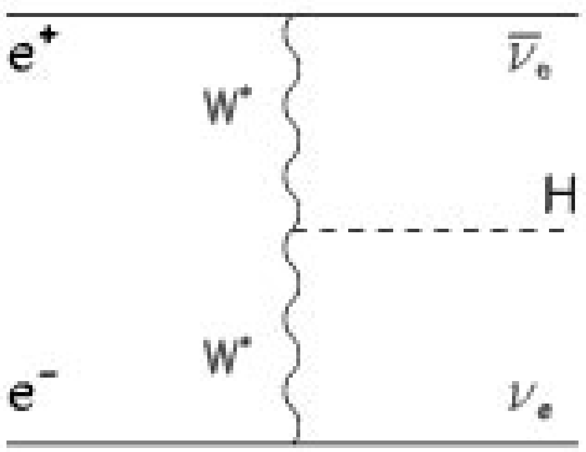
LEP 2: Higgs boson Production

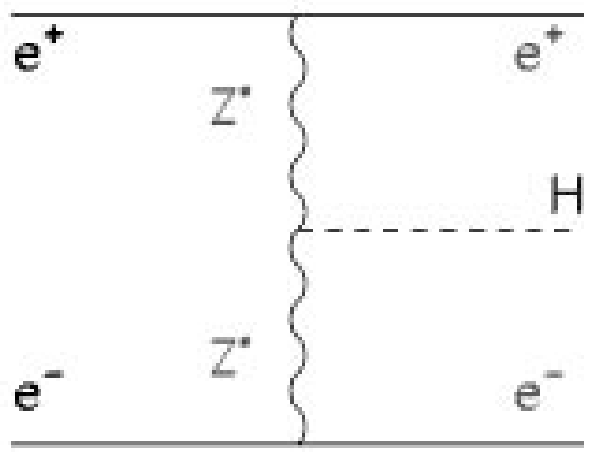
LEP2 was initially scheduled to run up to √s=200 GeV

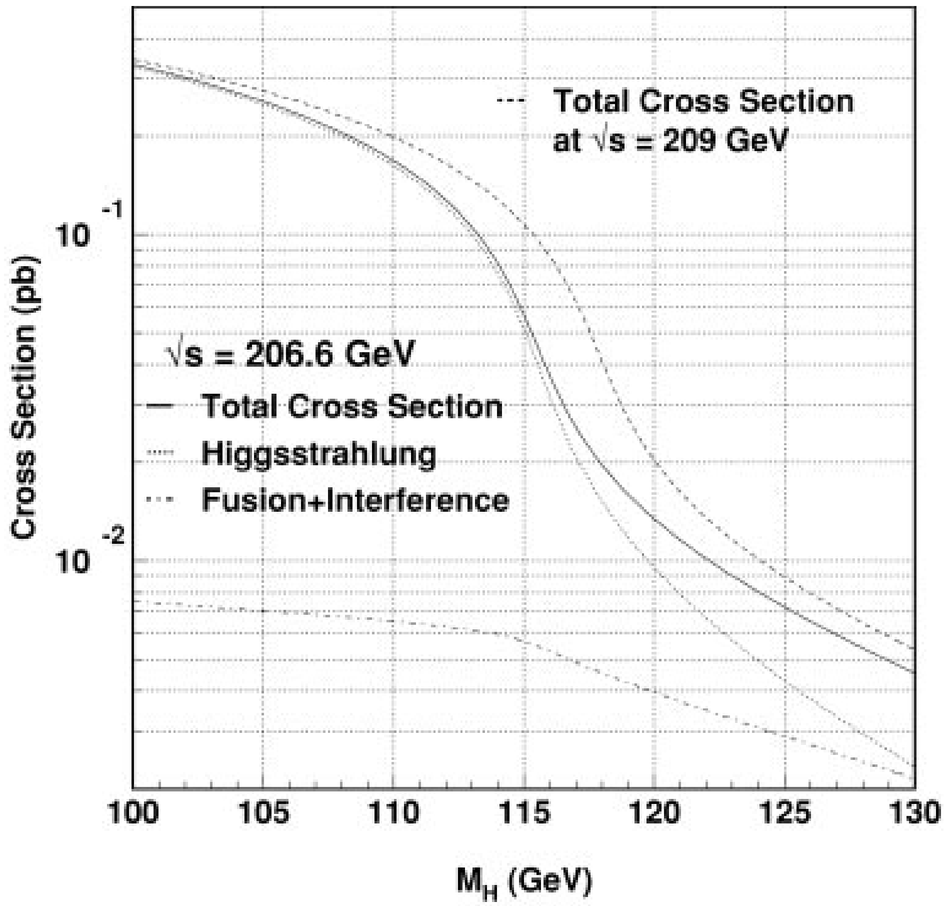
Here again Higgs-strahlung, $e^+e^- \rightarrow HZ^* \rightarrow Hff$, expected to be the dominant production mechanism

Also some contribution from WW fusion.

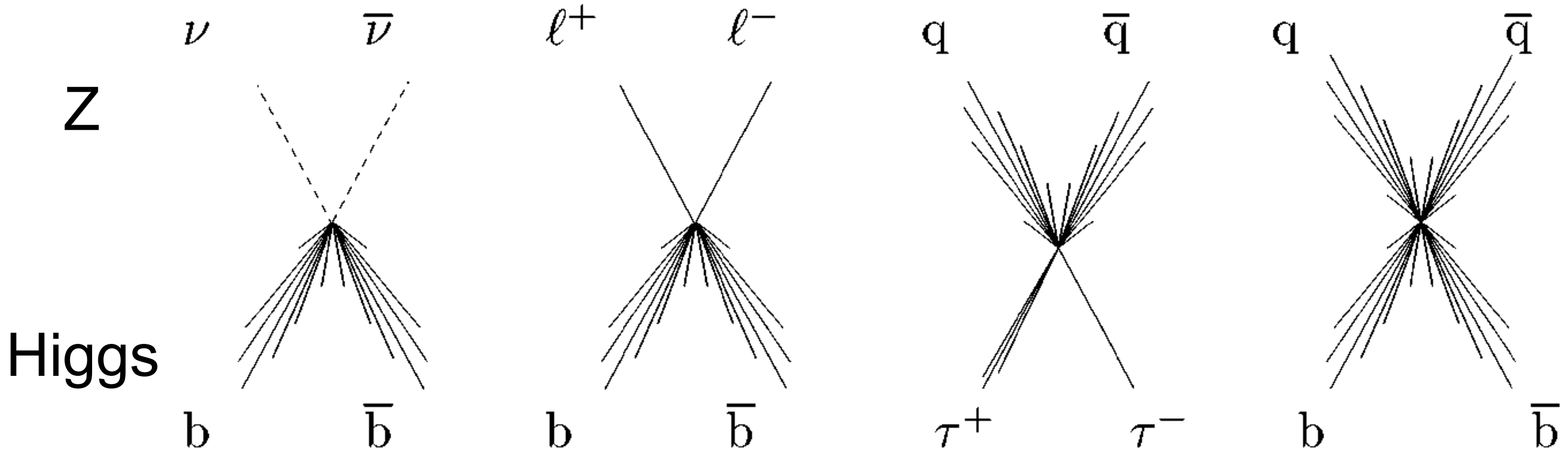


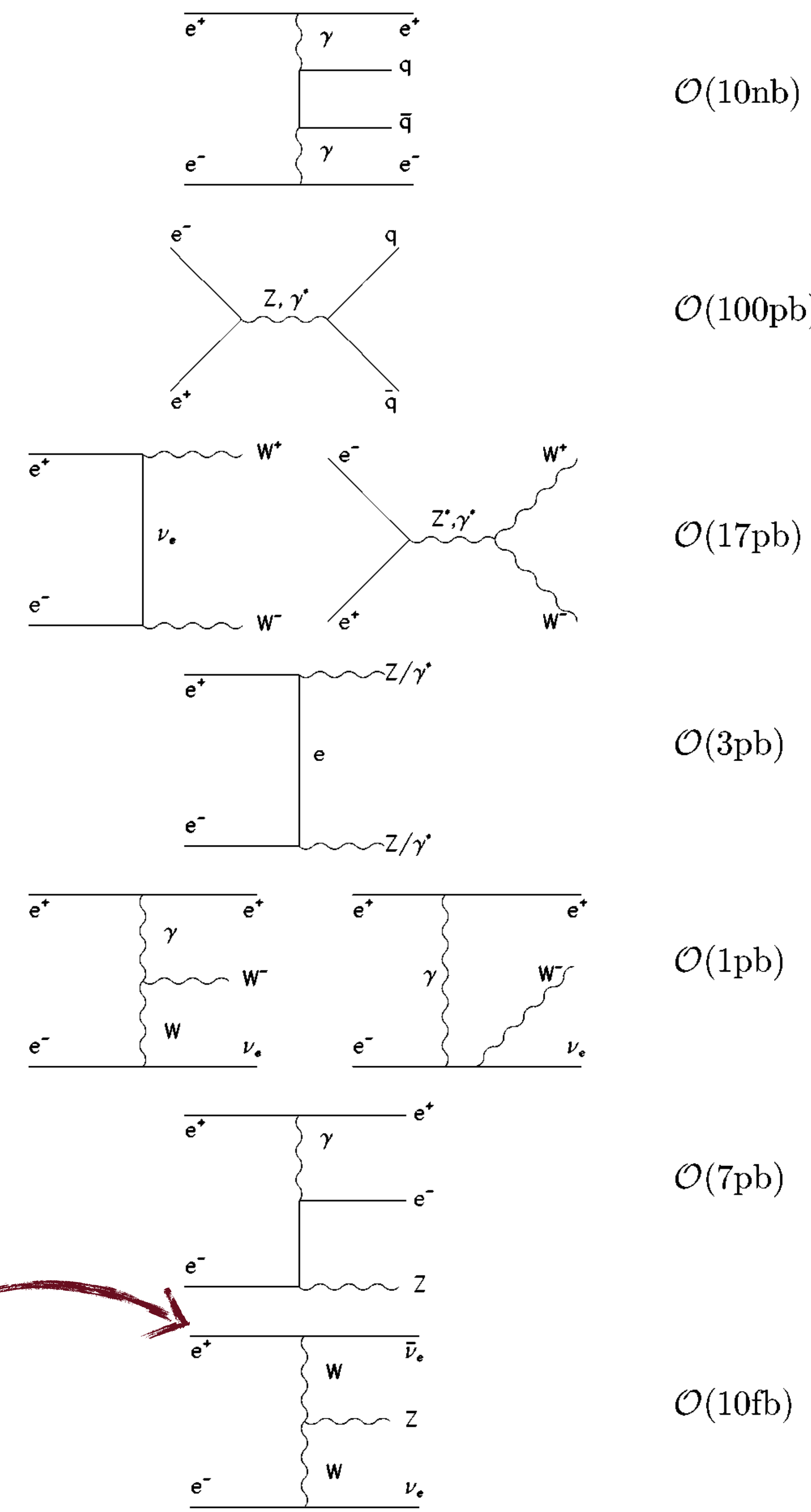




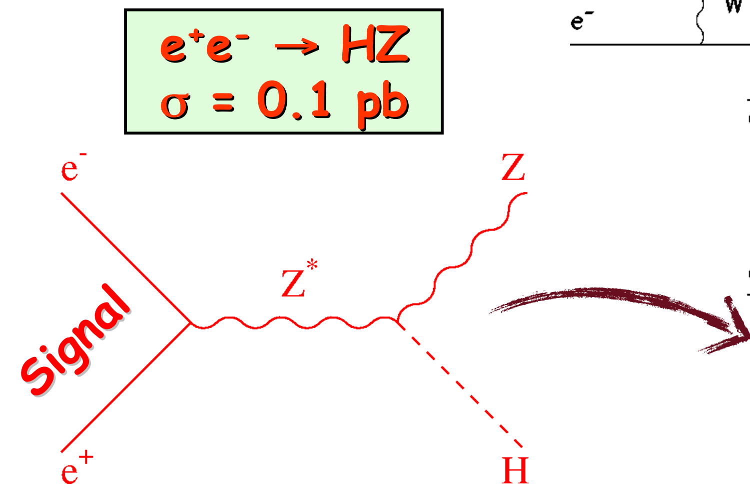


LEP 2 : Search channels and backgrounds

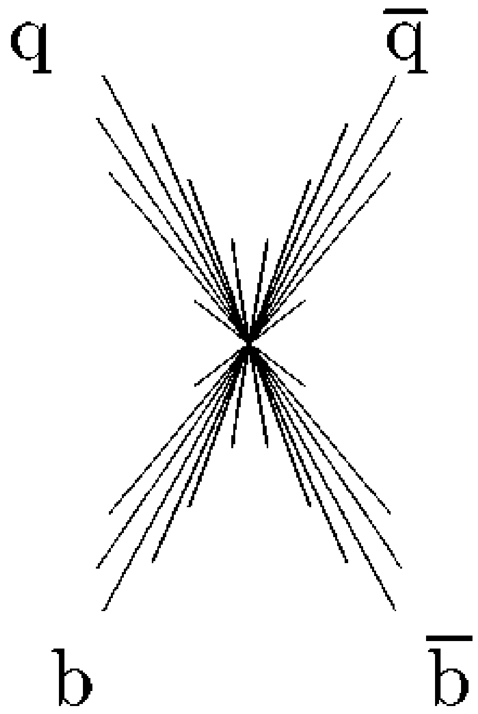




The main channels at LEP2 were:
- Four jets
- Missing Energy
- l^+l^- pairs (e,μ)
- $\tau^+\tau^-$



LEP 2: Four jets searches



The most sensitive topology in LEP2
Only the Higgs-strahlung contributes in production
- Higgs assumed to decay to pair of b-quarks [b-tagged events]
- Z decays to two jets

For low Higgs boson masses (i.e., significantly below the kinematic threshold), each of the di-jets forms a plane, and these two planes do not necessarily coincide. However, when the Higgs boson mass is near the kinematic threshold, the Z and the H are produced almost at rest and the two jets in each di-jet are produced back-to-back, and all jets are in a plane by construction.

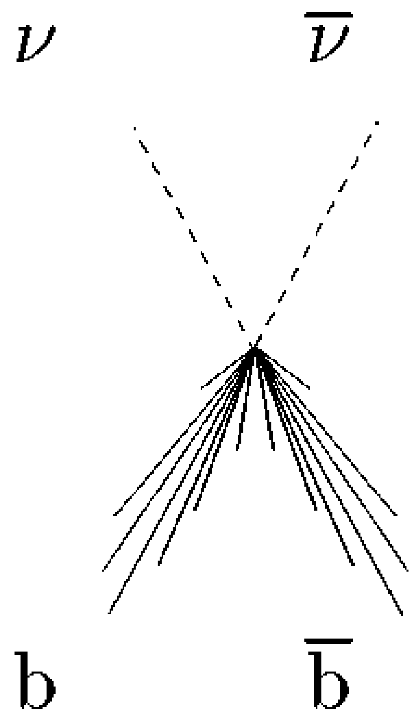
Main backgrounds: ee→ZZ, ee→WW, ee→qq
The four fermion final states usually tend to give acoplanar topologies, while the QCD process tend to be coplanar
The 4b-jets and 2b-jets cases are treated as separate channels. Former has:
- higher s/b
- larger jet pairing ambiguities

4b-jets: the ee→ZZ is the dominant background, with some contributions from ee→bbg
2b-jets: the ee→ZZ is dominant away from the kinematic threshold, in this latter case the ee→bbg is dominant
The ee→WW has relatively high cross-section, but only contributes through b-jet mis-identification or trough CKM suppressed W→bc/bu

To improve mass resolution, a kinematic fit is performed taking advantage of the known initial collision energy and the energy-momentum conservation. Typical mass resolutions of 3 GeV.

Although b-tagging and mass resolutions are the most important handles, all collaborations used event shape variables and their correlations through MVA

LEP 2: Missing energy searches



Both Higgs-strahlung and W-fusion contribute in production
- Higgs decay to pair of b-quarks [b-tagged events]
- Z decays to neutrinos

The signature is a large missing mass compatible with the Z boson and two b-tagged jets

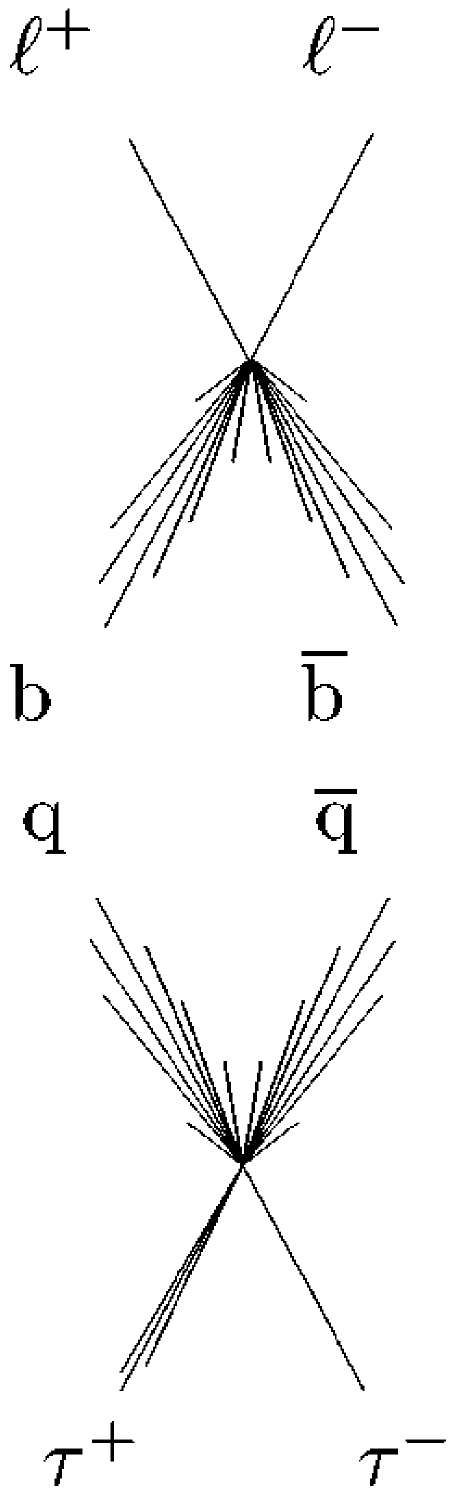
Several background contribution but main backgrounds:
- ee→ZZ main irreducible background
- ee→WW when one W→τν and the other W→qq where jets are mis-identified as b-jets
- ee→Weν could give a contribution because the spectator e is lost in the beam pipe, but b-tagging greatly reduces this
- ee→Zee when one e lost in the beam-pipe and the other has low momentum
- ee→Zνν with Z→bb. could be important near threshold but small cross section

Most important background is ee→qq, where the missing mass is due to two ISR photons lost in the beam pipe,one ISR photon and a mismeasured jet, or two mismeasured jets

Furthermore, this background tends to peak near the threshold in reconstructed mass, which is an artifact of the mass reconstruction algorithm.

In the missing- energy channel, the two jet energies cannot be rescaled independently because of the lack of kinematic constraints. In this case, only the recoil to the Z mass can be used. The visible mass is rescaled with a single parameter, which is equiv- alent to applying a unique rescaling coefficient to the four-momentum of both jets. The typical peak resolution is of the order of 3 GeV, comparable to the four-jet channel. But in this channel and especially for Higgs boson masses near threshold, where the fusion-plus-interference contribution can add up to almost half of the total signal cross section, this resolution is degraded by large and wide tails.

LEP 2: Di-lepton (e,μ + τ) searches



The topology of the lepton channel is a pair of electrons or muons and a pair of b-quark jets. This is a very distinctive signature, but it has a very small rate because of the small branching of the Z to electrons and muons, and, to a much lesser extent, because of the interference between the Higgs-strahlung production and ZZ fusion, which is destructive. The backgrounds to this channel originate almost exclusively from the $e^+e^- \rightarrow ZZ$ process. Practically none of the other processes can yield a similar topology. Its rejection relies greatly on the mass reconstruction and on the tagging of b-quark jets. The Higgs boson mass is reconstructed from the recoil to the two-lepton system.

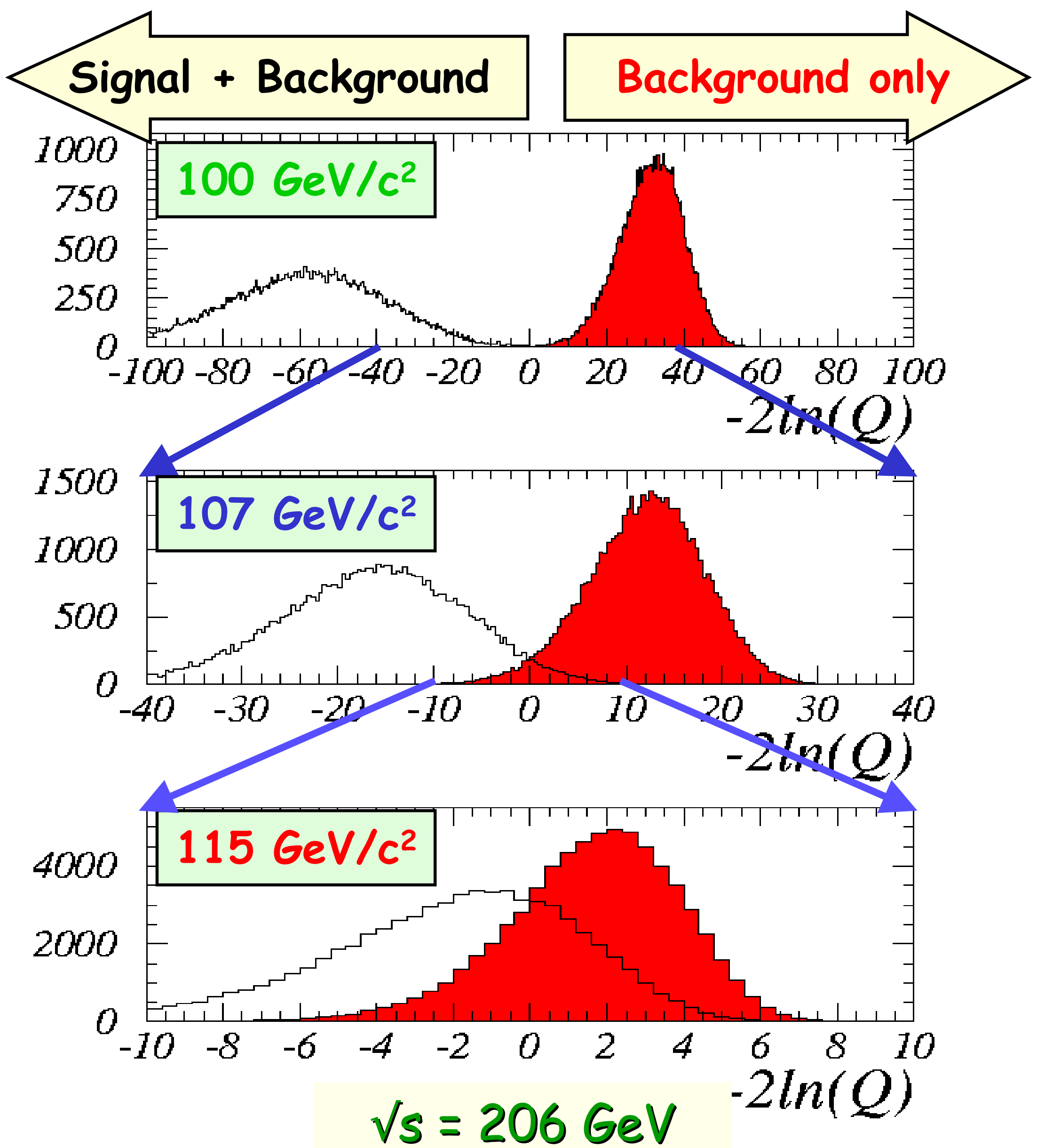
The topology in the $\tau^+\tau^-$ channel is a pair of tau leptons and a pair of jets. This channel is separated from the l^+l^- channel for two main reasons:

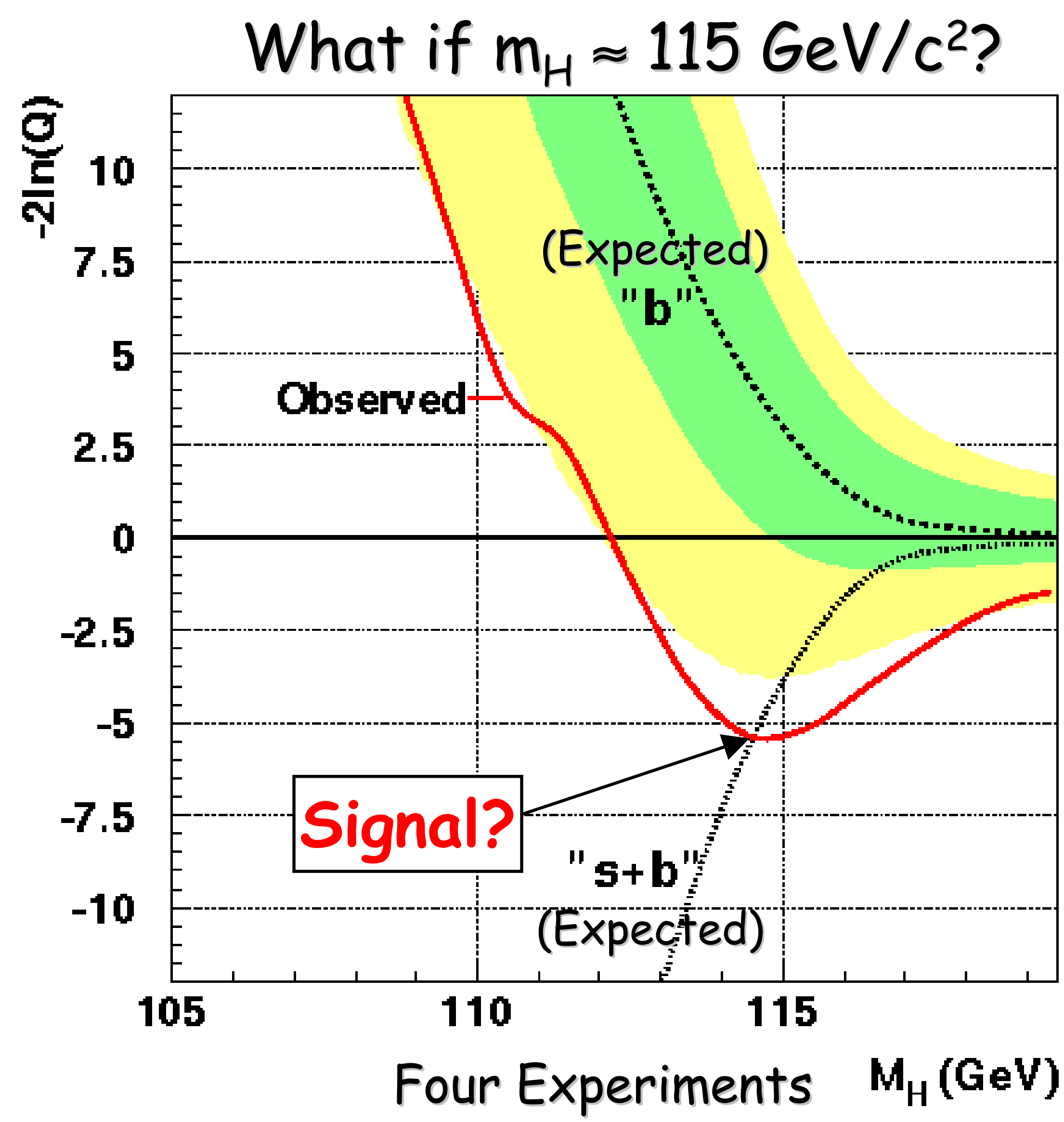
- The invariant mass of the $\tau^+\tau^-$ pair cannot be accurately measured because of the unmeasured energy carried by the neutrinos of the $\tau^\pm$ decays; the mass reconstruction procedure is thus very different from that used in the lepton channel but is actually very similar to that used in the four-jet channel.
- This channel also receives contributions from the $Z \rightarrow b\bar{b}$ and $H \rightarrow Z^+Z^-$ events

LEP 2: Test statistic

$$-2\ln Q = 2 \cdot s_{\mathrm{tot}} - 2 \cdot \sum_i n_i \ln\left(1 + \frac{s_i}{b_i}\right).$$

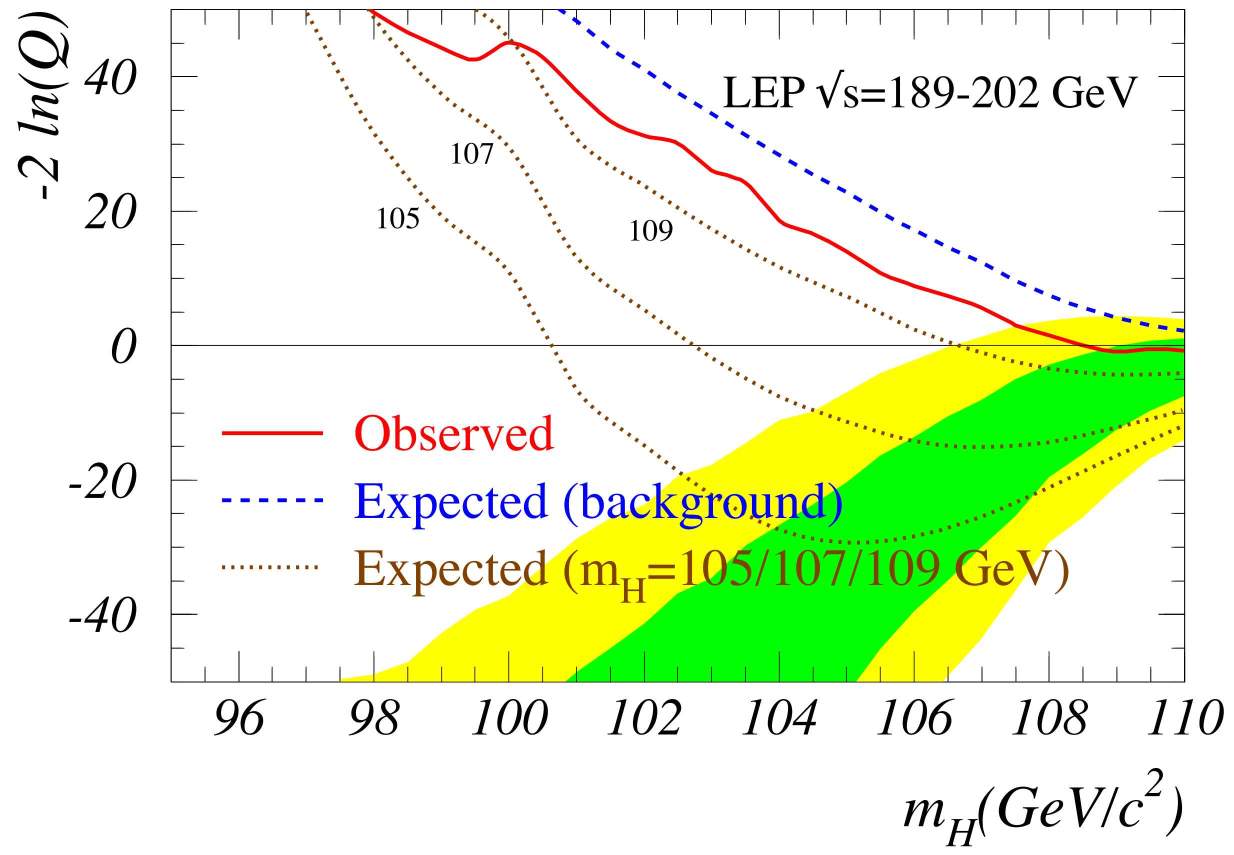
Basically, the likelihood ratio of the signal+background hypothesis over the background-only hypothesis. More negative values of -2lnQ, means more S+B-like result

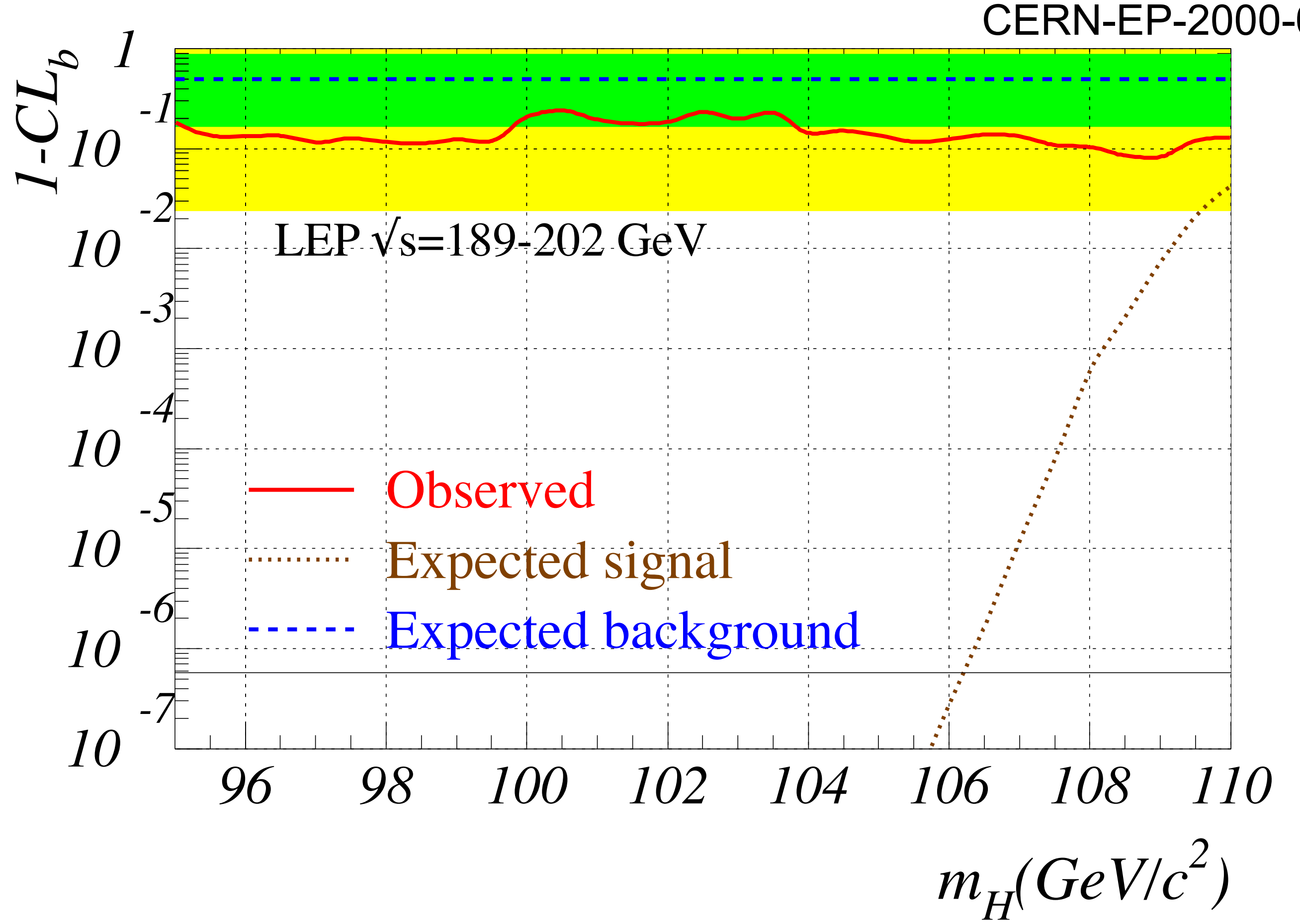


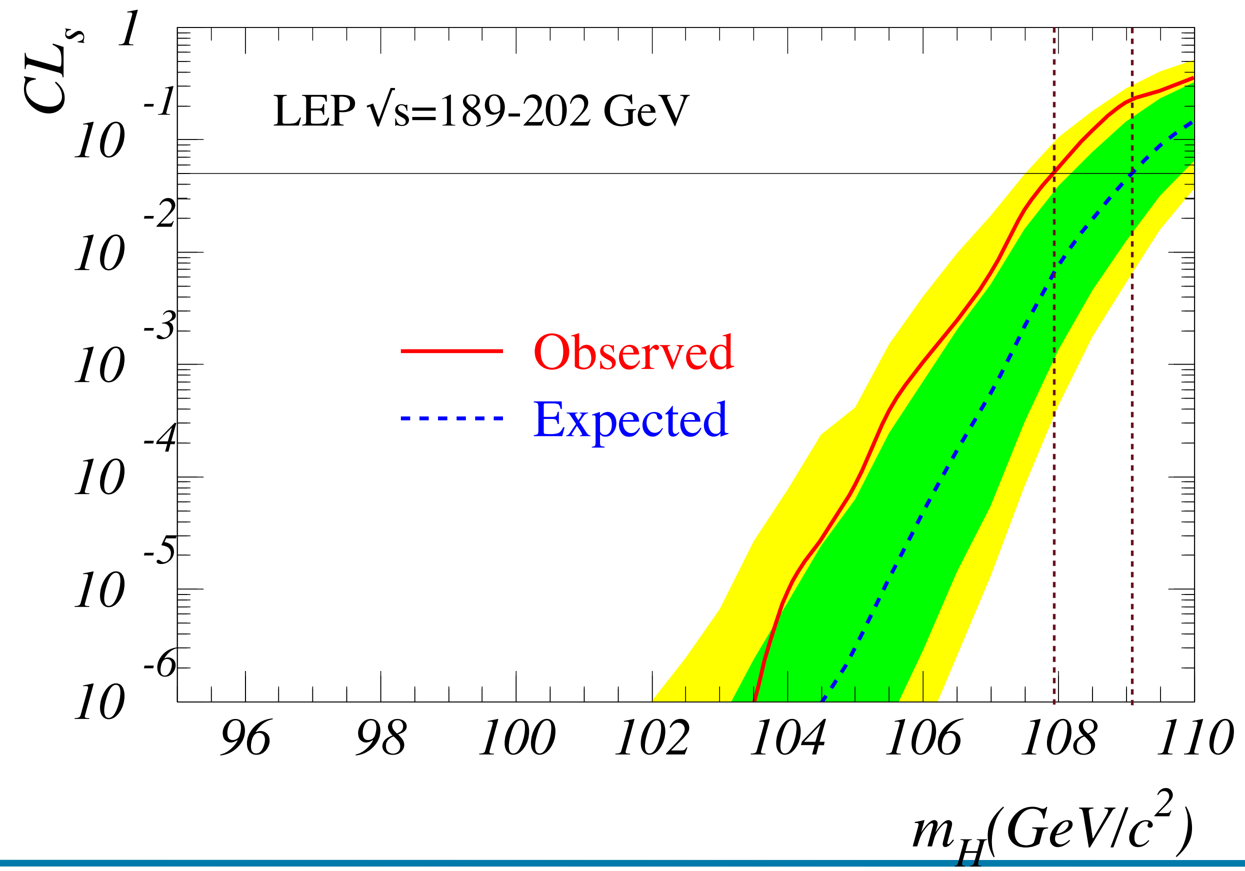


LEP 2: Higgs boson searches before 2000

CERN-EP-2000-055







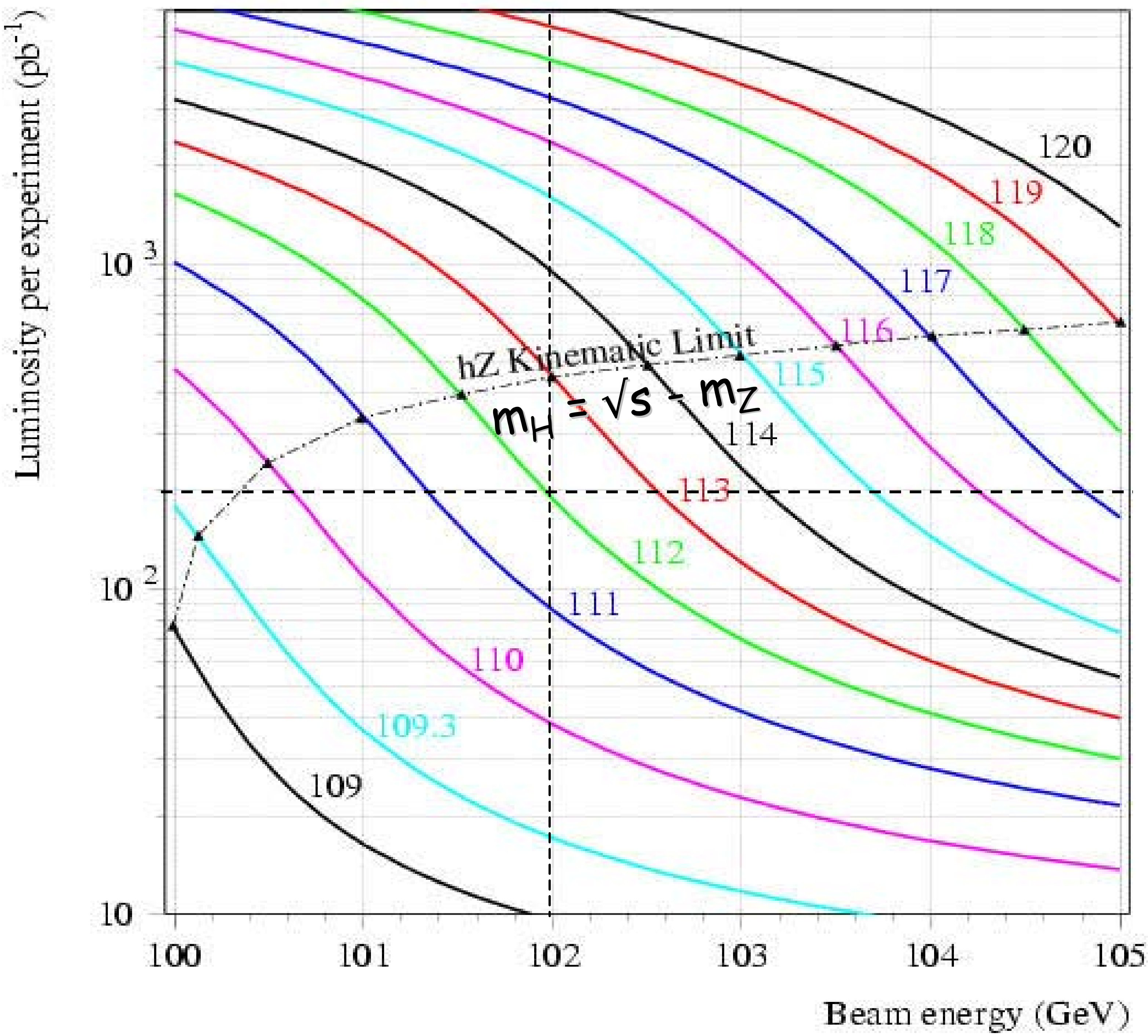
The LEP experiments updated and combined their searches for Standard Model Higgs boson including the data collected in 1999 at energies between 192 and 202 GeV, for a total integrated luminosity of approximately 900 pb^{-1}.

In the absence of a statistically significant excess in the data, the lower bound of 107.9 GeV (expected 109.1GeV) has been obtained at the 95% CL.

LEP 2: Optimization

P. Janot

Higgs mass 3σ sensitivity = f(Lumi, E)



Example:
- Beam Energy : 102 GeV
- Luminosity : 200pb^{-1}/experiment

The 3σ sensitivity is ~112 GeV, i.e. ~1 GeV from the kinematic threshold of $\sqrt{s} - m_Z$ ~113 GeV

To gain 2 GeV in sensitivity one could either:
- increase luminosity by factor 4-5
- increase beam energy by ~1GeV

The latter is the only feasible option... so, the idea is to achieve the highest possible energy with reasonable luminosity

i.e. sacrifice luminosity to gain in energy

LEP 2 beyond the design: Beam Energy

The √s of a circular e^+e^- collider is limited by:
- **magnetic field of the dipole magnets**,
- **the RF power available to compensate for the synchrotron radiation losses ($\propto E^4_{beam}$)**

Nominal accelerating gradient of superconducting RF cavity 6 MV/m → √s=192 GeV → m_H~100GeV

A series of upgrades and ingenious ideas allowed LEP to surpass the design capabilities:
- Upgraded cryogenic facilities, allowing the cavities to operate up to 7.5 MV/m, with improved stability of the cryogenic system → √s=204 GeV → m_H~112GeV
- Reduce klystron safety margin: Average time between klystron trips ~1h. To maintain stable beams, operate with margin ≥2 klystrons. However, with improved stability became possible to run with margin of 1 klystron, without greatly increasing beam losses → +1.5 GeV in √s and ~ +1 GeV in m_H
- "Mini-ramp" technique: increase beam energy within a fill, in a short period of time (typically a few minutes), without increasing the background in the detectors. Allowed LEP to run at the highest energy, with no RF margin. On top of that a lot of effort to reduce turn-around time once beams where lost → +1.5 GeV in √s and ~ +1 GeV in m_H
- Change beam orbit: Reducing the nominal 350 MHz RF by ~100 Hz resulted in a small shift of the beam orbit → the beams were exposed to the dipole component of the focusing quadrupoles. The smaller frequency also allowed shorter bunches and therefore increased the available RF margin → +1.4 GeV in √s and ~ +0.6 GeV in m_H
- Unused orbit correctors were powered in series to act as dipoles, increasing the effective bending length → +0.4 GeV in √s and ~ +0.25 GeV in m_H
- Reinstalled 8 LEP1 Cu RF cavities (+30MV in RF gradient) → +0.4 GeV in √s and ~ +0.25 GeV in m_H

Overall, ~15.7-17.2 GeV increase in beam energy, with ~stable run at √s~207 GeV and ultimately up to 209.2 GeV

P. Janot

Beam Energy increases in LEP

Energy Loss per Turn ∝ E^4/ρ (Synchrotron Radiation)

Maximum Beam Energy ∝ [RF Voltage × Bending Radius]$^{1/4}$

- Increase RF Voltage;

  (130 MV for E = 45.6 GeV;

  ≥ 3 GV for E = 100 GeV;

  → Go for SC RF Cavities)

- Increase Bending Radius!
- Or increase both.

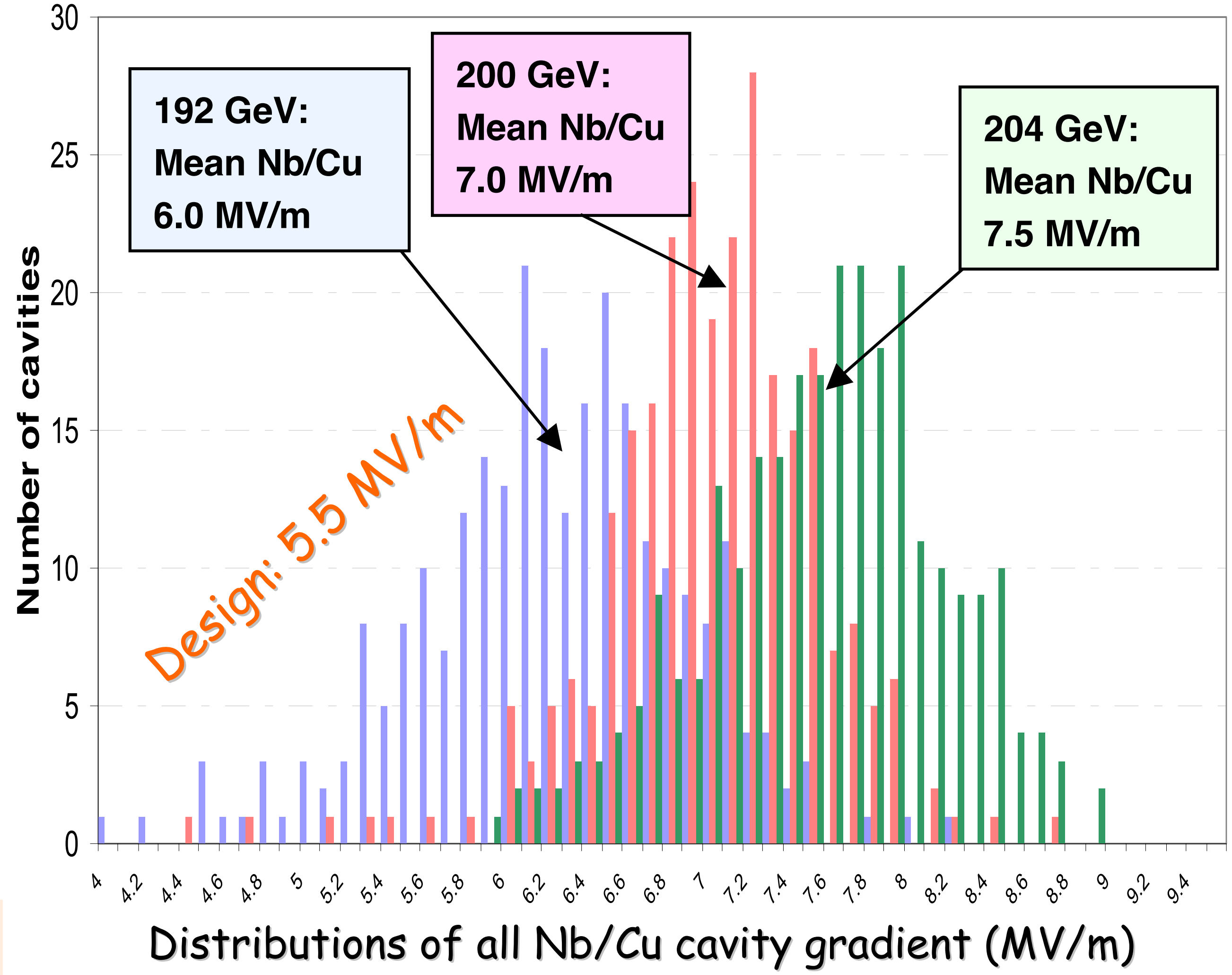
Year	√s (GeV)	# Cu Cavities	# SC Cavities	RF (MV)
1989-95	m_Z	128	None	180
1996	161 172	128	144 176	1600 2000
1997	183	52	240	2500
1998	189	52	272	2850
1999	192 196 200 202	48	288	3000 ↓ ↓ 3550
2000	205 ↓ 209.2	56	288	3650

P. Janot

LEP Improvements in 1999/2000

1) Increase RF Gradient & Upgrade Cryogenics

- 272 Nb/Cu cavities in 1998; 2850 MV available, 189 GeV
- 288 Nb/Cu cavities in 1999; 3000 MV available, 192 GeV
- Condition all cavities, damp the oscillations, install part of LHC cryogenics, improve the phasing… 3500 MV available (end 1999) 3650 MV available (2000)



E: 192 → 200 → 204 GeV;

m_H: 100 → 108 → 112 GeV/c^2

It was concluded at the Xth Chamonix Workshop (35) that the best scheme was to operate LEP with one klystron margin for about one hour and then mini-ramp to no margin until the first klystron tripped.

P. Janot

Improvements in 1999/2000 (Cont'd)

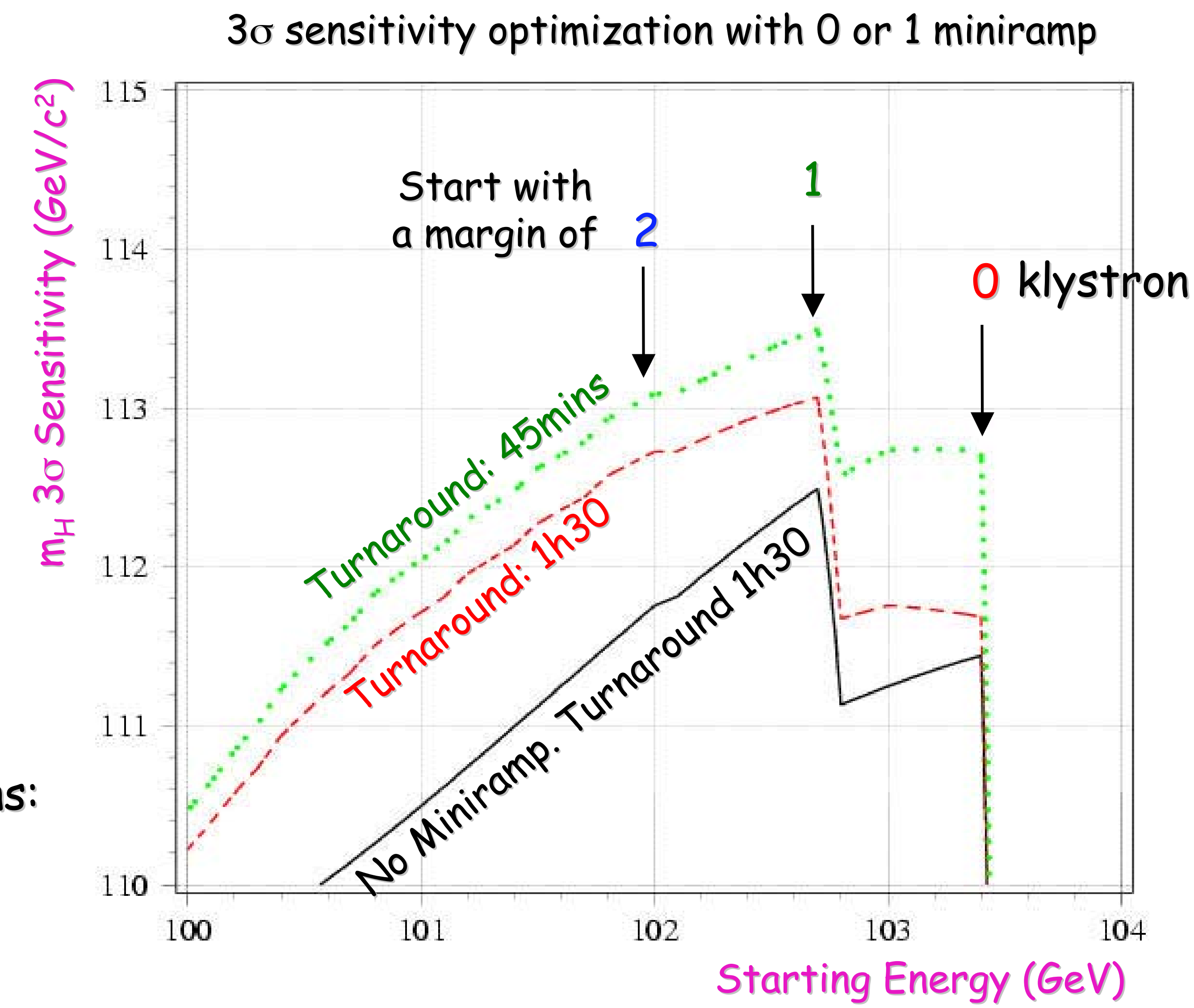
2) Improve stability & Decrease security margin

- Two- to one-klystron margin (Fill duration 2h30 → 1h30):

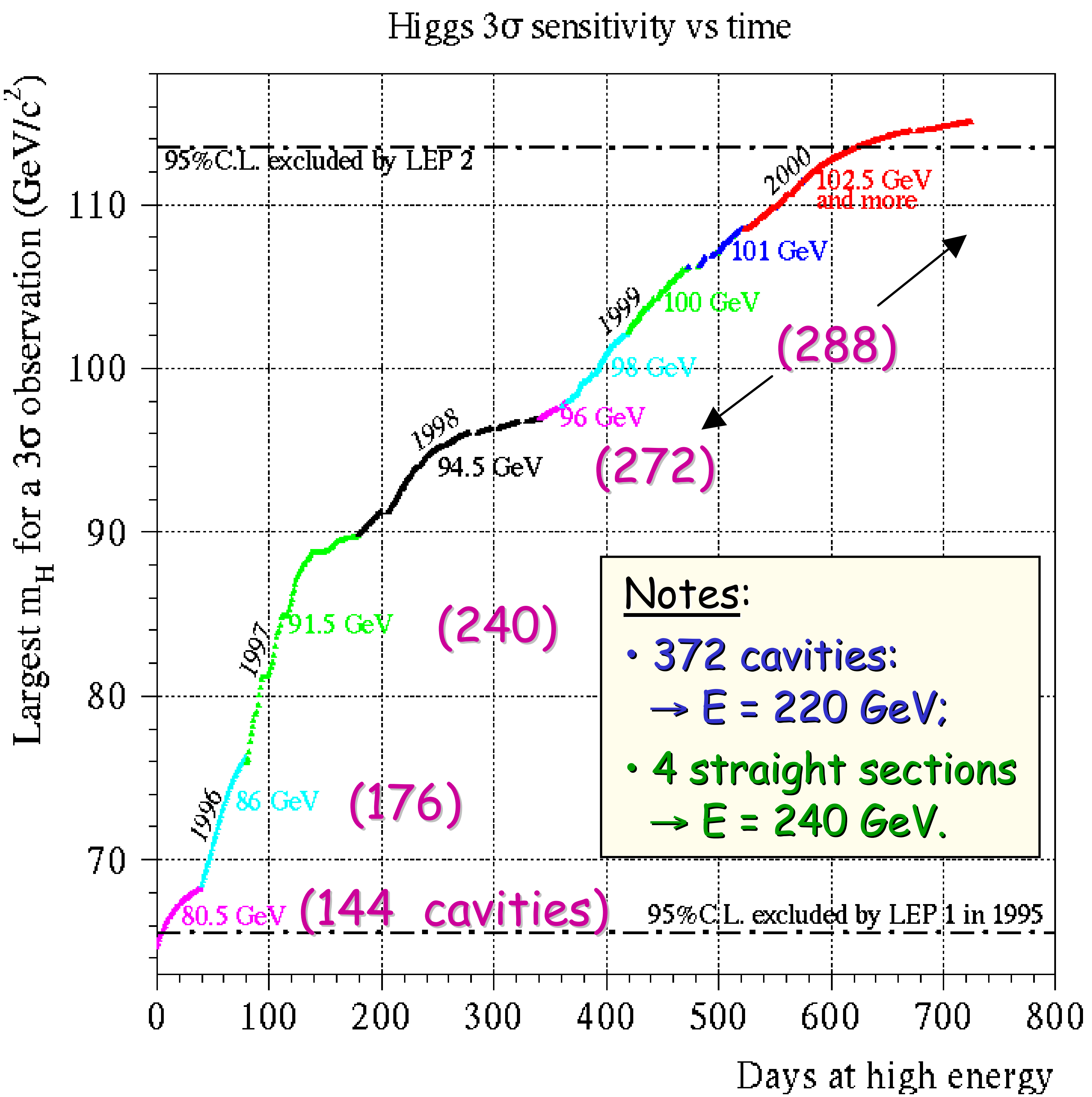
E: 204 → 205.5 GeV;
m_H: 112 → 113 GeV/c^2

- Mini-ramp to no margin at all (Fill duration 15 minutes!)
- Turnaround time reduced to 45 mins:

E: 205.5 → 207 GeV;
m_H: 113 → 114 GeV/c^2



LEP 2: Evolution of sensitivity with time



Notes:

- 372 cavities:
  → E = 220 GeV;
- 4 straight sections
  → E = 240 GeV.

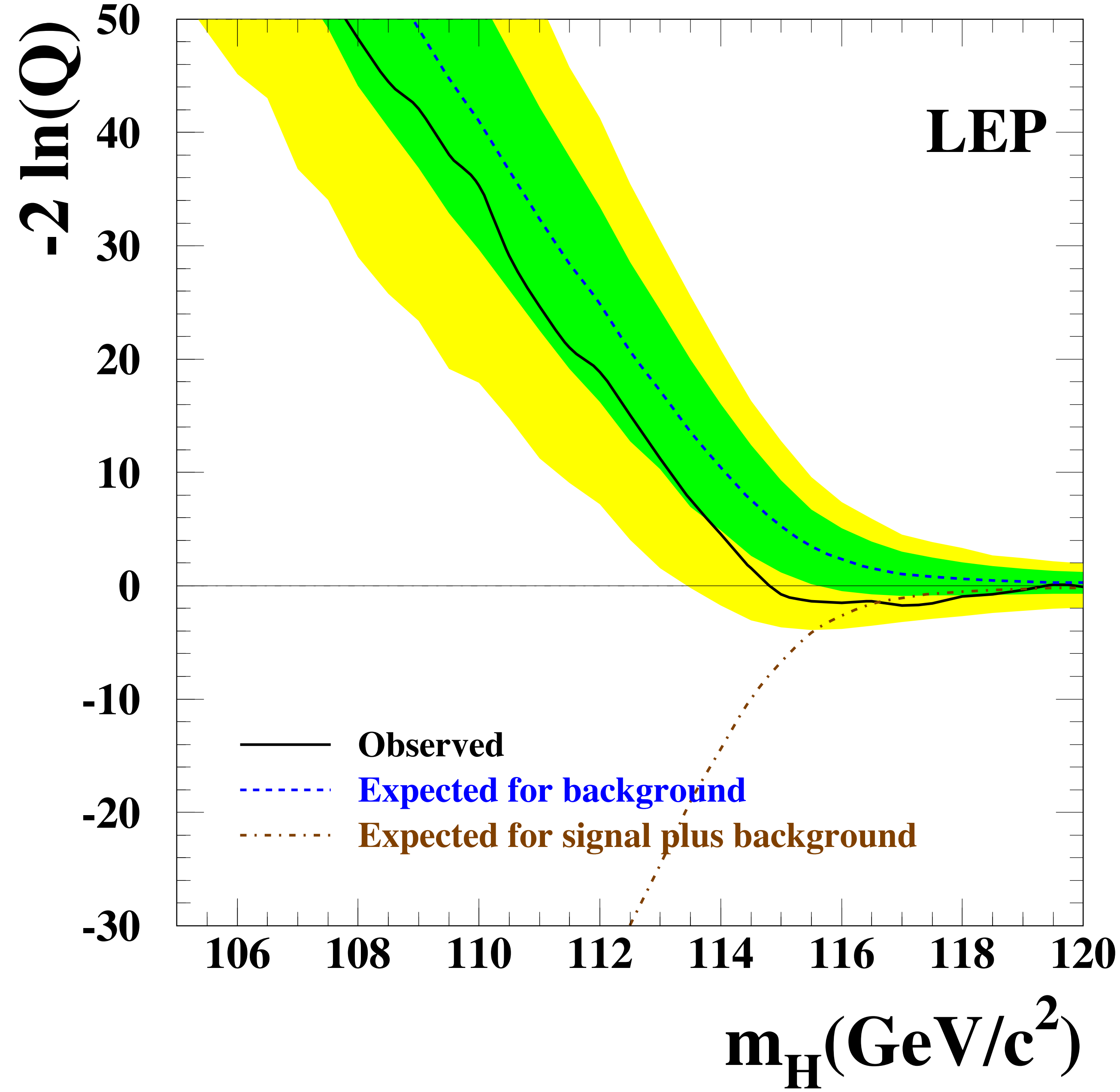
LEP 2 : The final result

Integrated luminosities of the data samples of the four experiments and their sum (LEP). The subsets taken at energies exceeding 206 GeV and 208 GeV are listed separately

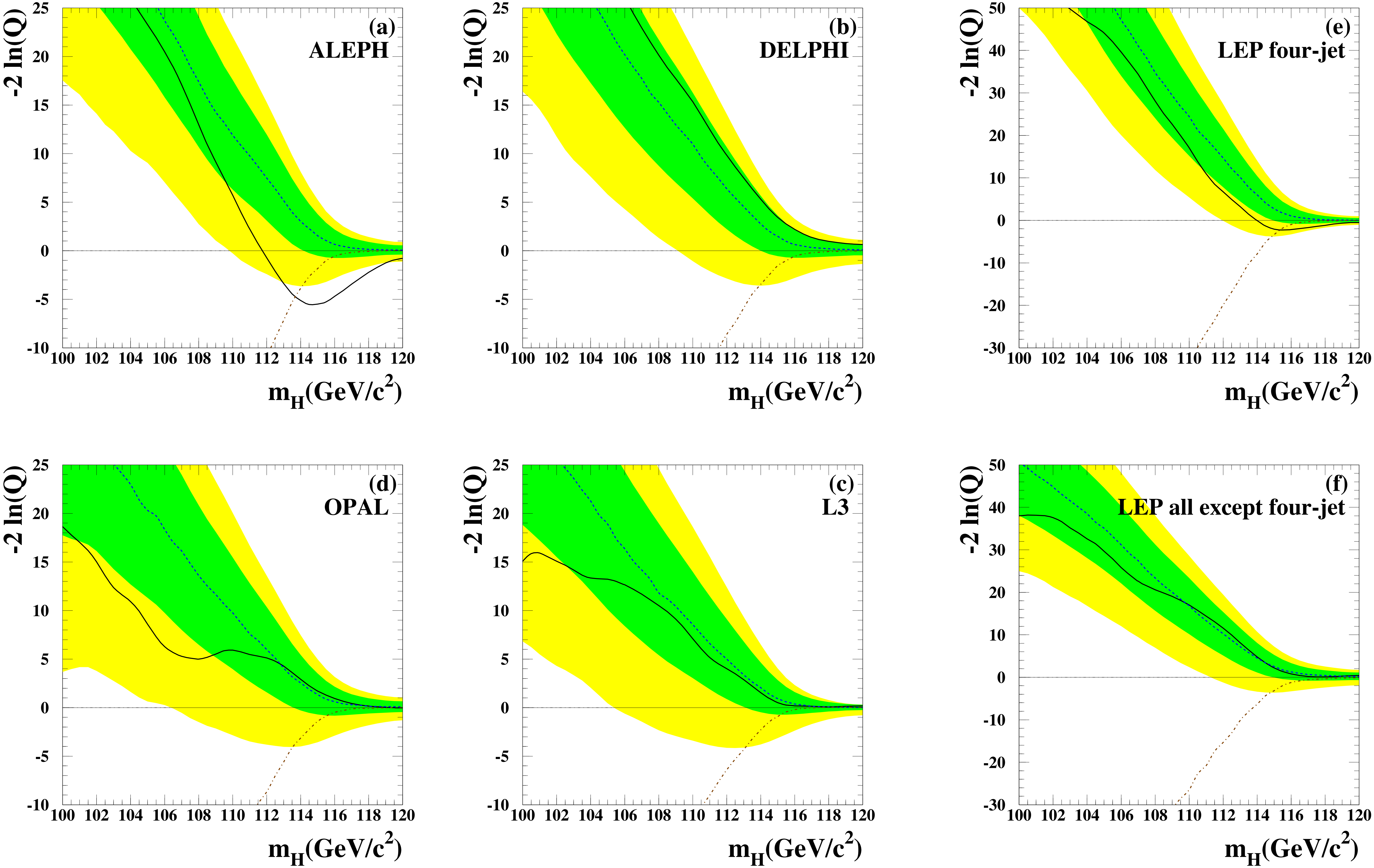
	Integrated luminosities in pb^{-1}				
	ALEPH	DELPHI	L3	OPAL	LEP
$\sqrt{s} \geqslant 189$ GeV	629	608	627	596	2461
$\sqrt{s} \geqslant 206$ GeV	130	138	139	129	536
$\sqrt{s} \geqslant 208$ GeV	7.5	8.8	8.3	7.9	32.5

Expected (median) and observed 95% confidence level lower bounds on the Standard Model Higgs boson mass, for all LEP data combined and for various subsets of the data. The numbers for the four-jet and all but the four-jet final states are obtained with the data of the four experiments combined.

	Expected limit (GeV/c^2)	Observed limit (GeV/c^2)
LEP	115.3	114.4
ALEPH	113.5	111.5
DELPHI	113.3	114.3
L3	112.4	112.0
OPAL	112.7	112.8
Four-jet channel	114.5	113.3
All but four-jet	114.2	114.2



LEP 2 : The final result per experiment



The individual LEP experiment publications

After the end of data taking at LEP (November 2000), each collaboration published one paper in Physics Letters B:

- ***ALEPH**: 'Observation of an excess in the search for the SM Higgs boson at ALEPH'. Phys.Lett. B 495, 1 (2000), link*

  Abstract: An excess of 3σ beyond the background expectation is found, consistent with the production of the Higgs boson with a mass near 114GeV/c^2. Much of this excess is seen in the four-jet analyses, where three high purity events are selected. (link)

- ***DELPHI**: 'Search for the SM Higgs boson at LEP in the year 2000'. Phys. Lett. B 499, 23 (2001), link*

  Abstract: No evidence for a Higgs signal is observed in the kinematically accessible mass range, and a 95% CL lower mass limit of 114.3 GeV/c^2 is set (link)

- ***L3**: 'SM Higgs boson with the L3 experiment at LEP'. Phys. Lett. B 517, 319 (2001), link.*

  Abstract: A lower limit on the mass of the standard model Higgs boson of 112.0 GeV is set at the 95% confidence level. The most significant high mass candidate is a Hvv event. It has a reconstructed Higgs mass of 115 GeV and it was recorded at $\sqrt{s}$ = 206.4 GeV. (link).

- ***OPAL**: 'Search for the SM Higgs boson in e+e- collisions at $\sqrt{s}$≈192-209 GeV'. Phys. Lett. B 499, 38 (2001), link.*

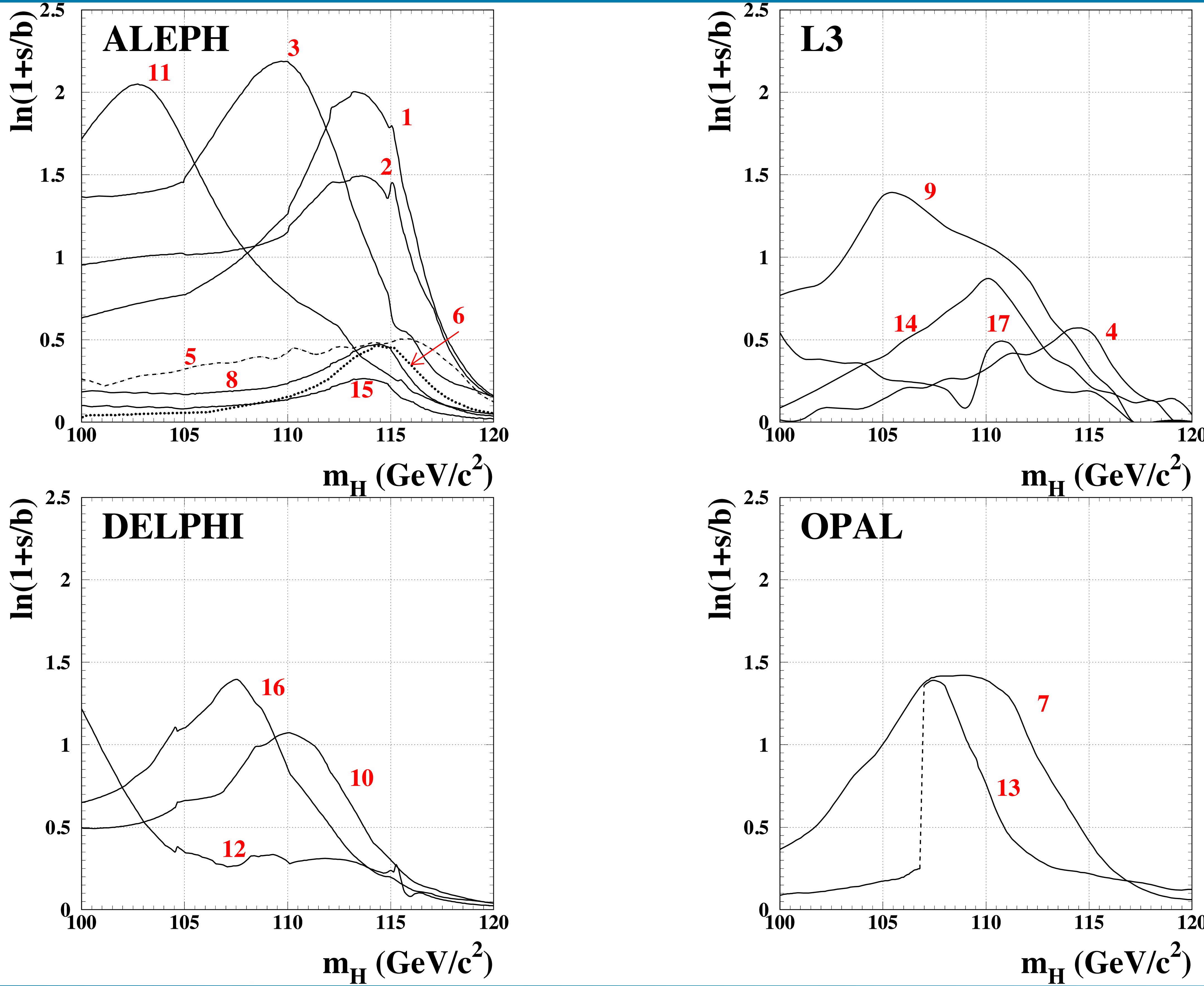
  Abstract: A lower bound of 109.7 GeV is obtained on the Higgs boson mass at the 95% confidence level. At higher masses, the data are consistent with both the background and the signal-plus-background hypotheses (link).

LEP 2 : The candidate events

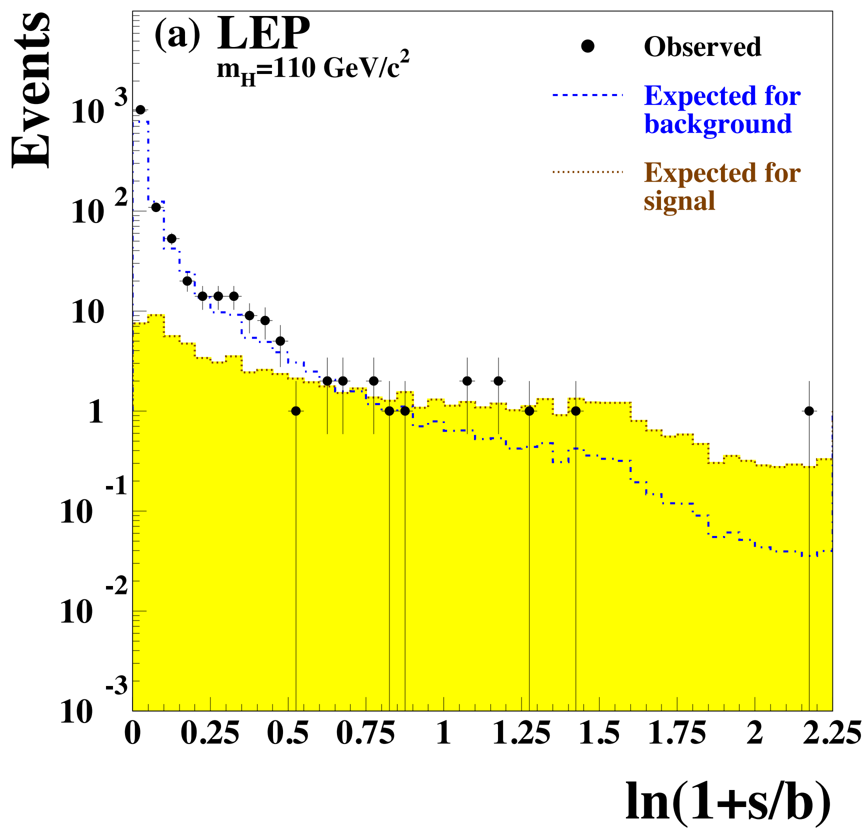
Properties of the candidates with the largest contribution to $-2\ln Q$ at $m_{\mathrm{H}} = 115$ GeV$/c^2$. For each candidate, the experiment, the centre-of-mass energy, the final-state topology, the reconstructed Higgs boson mass and the weight at $m_{\mathrm{H}} = 115$ GeV$/c^2$ are listed. The applied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

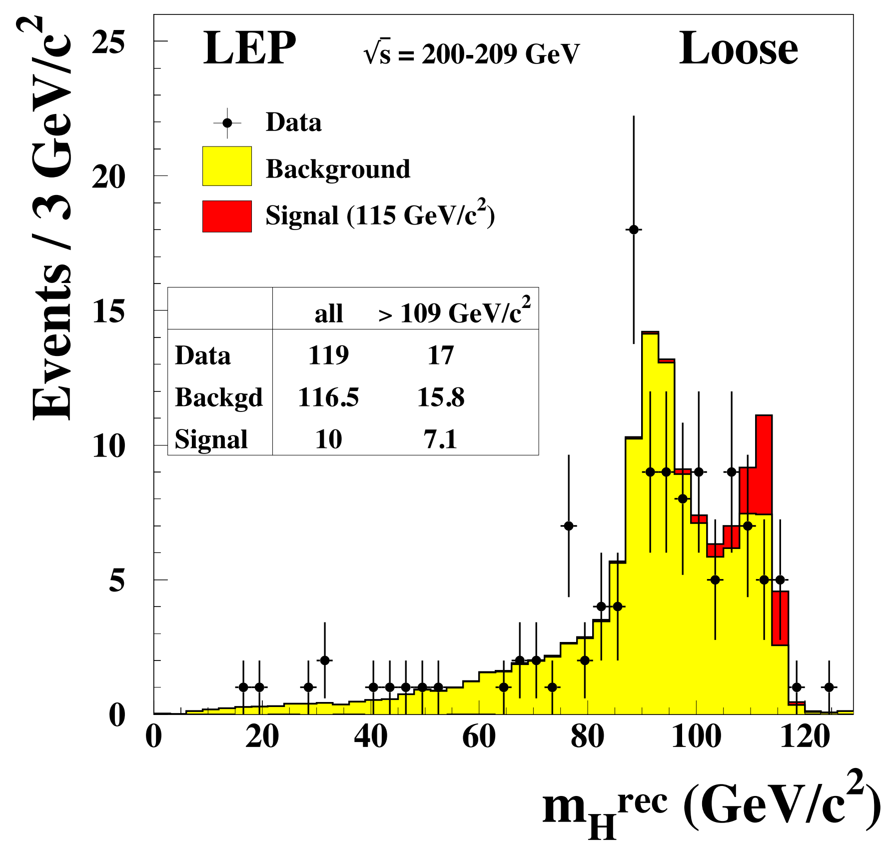
	Experiment	$\sqrt{s}$ (GeV)	Final state topology	$m_{\mathrm{H}}^{\mathrm{rec}}$ (GeV$/c^2$)	$\ln(1+s/b)$ at 115 GeV$/c^2$
1	ALEPH	206.6	Four-jet	114.1	1.76
2	ALEPH	206.6	Four-jet	114.4	1.44
3	ALEPH	206.4	Four-jet	109.9	0.59
4	L3	206.4	Missing energy	115.0	0.53
5	ALEPH	205.1	Leptonic	117.3	0.49
6	ALEPH	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

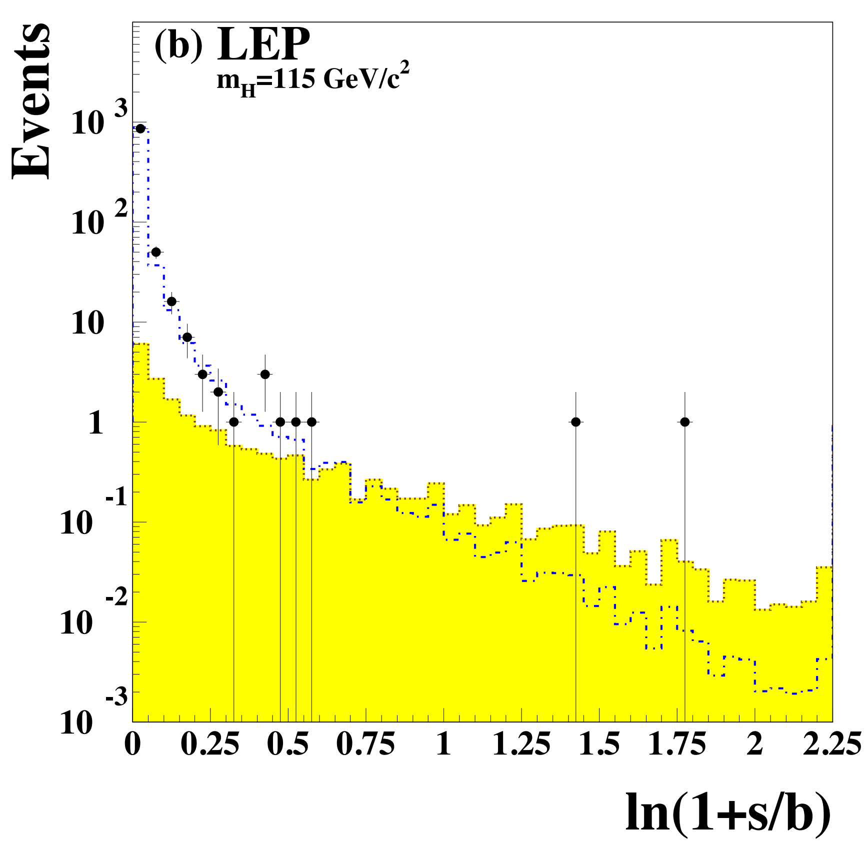
LEP 2 : The candidate events

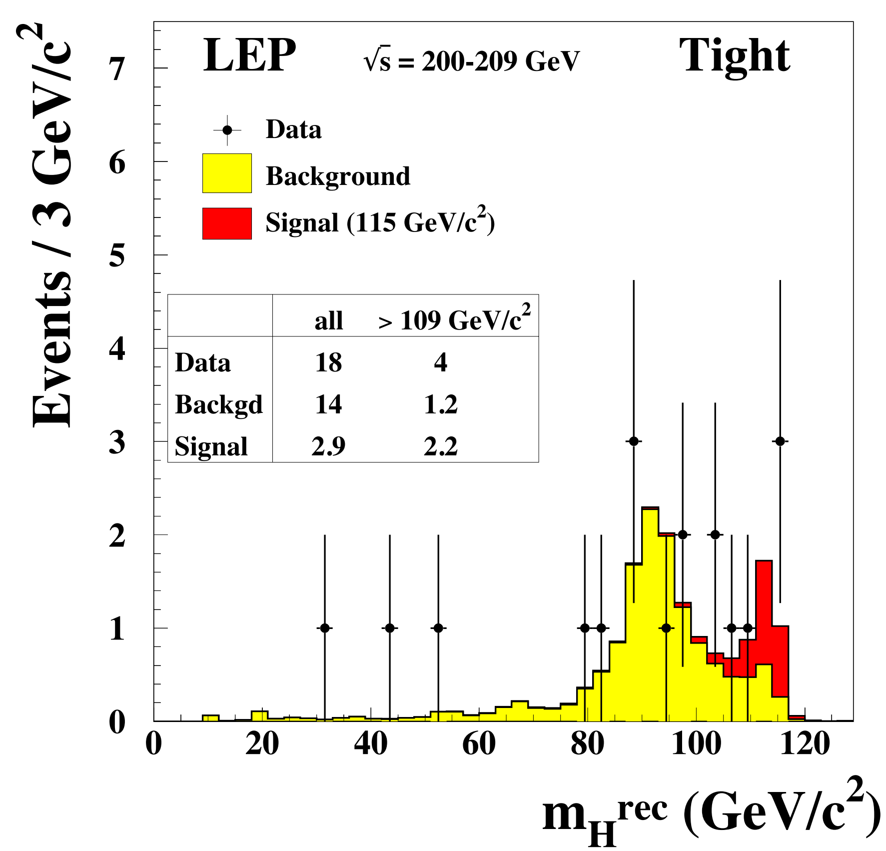


LEP 2 : m_H distributions

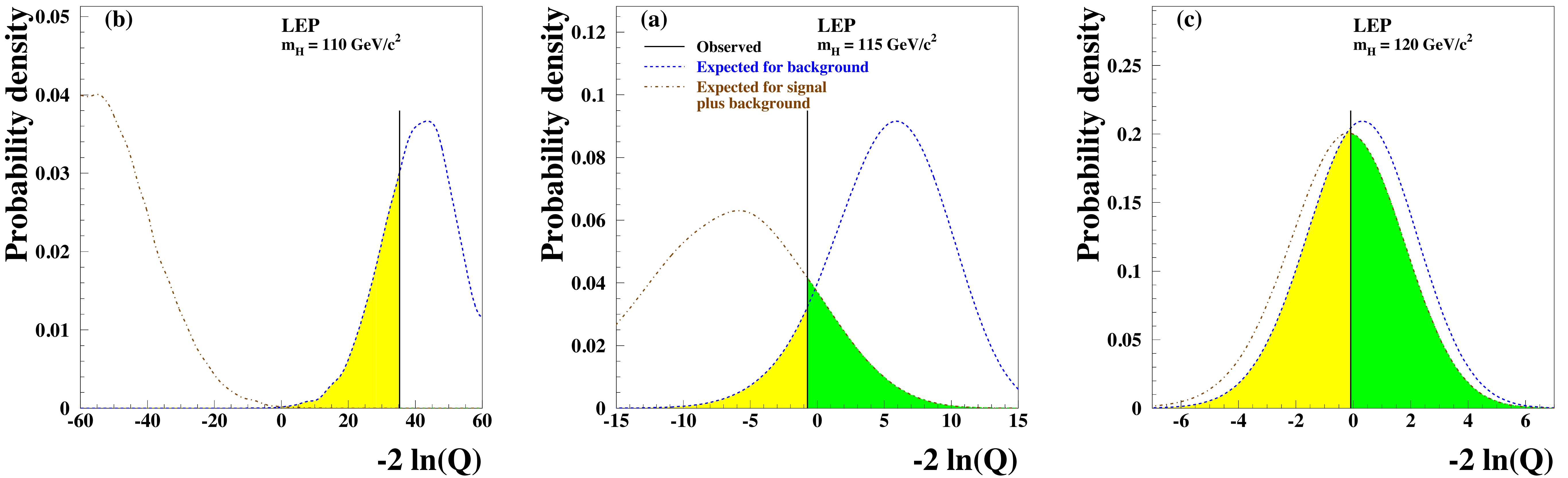


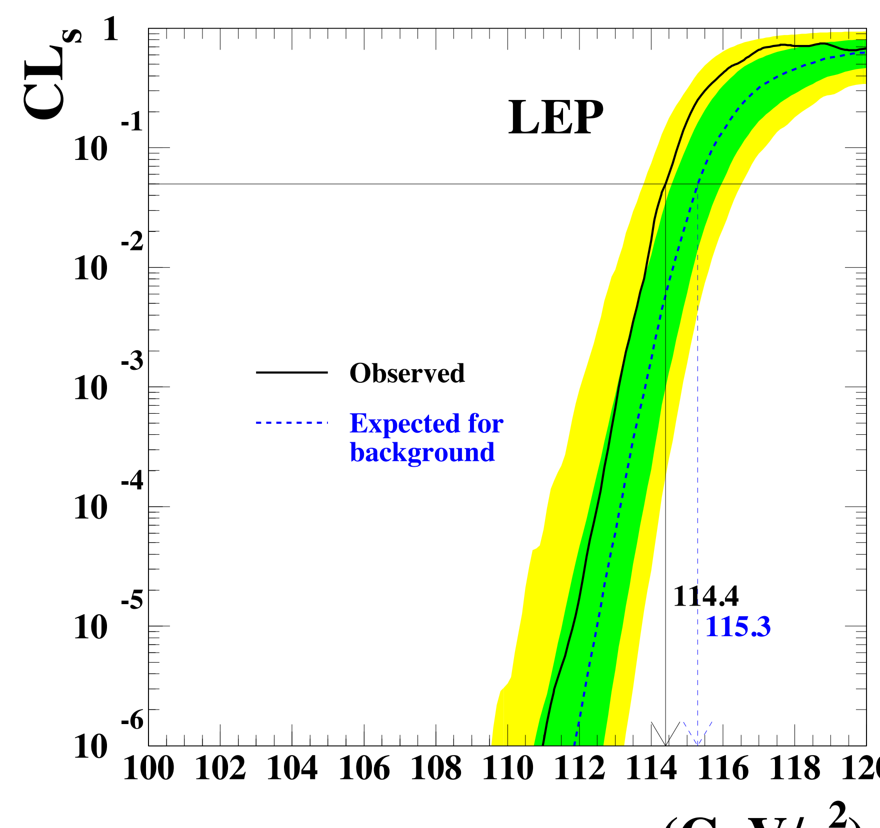


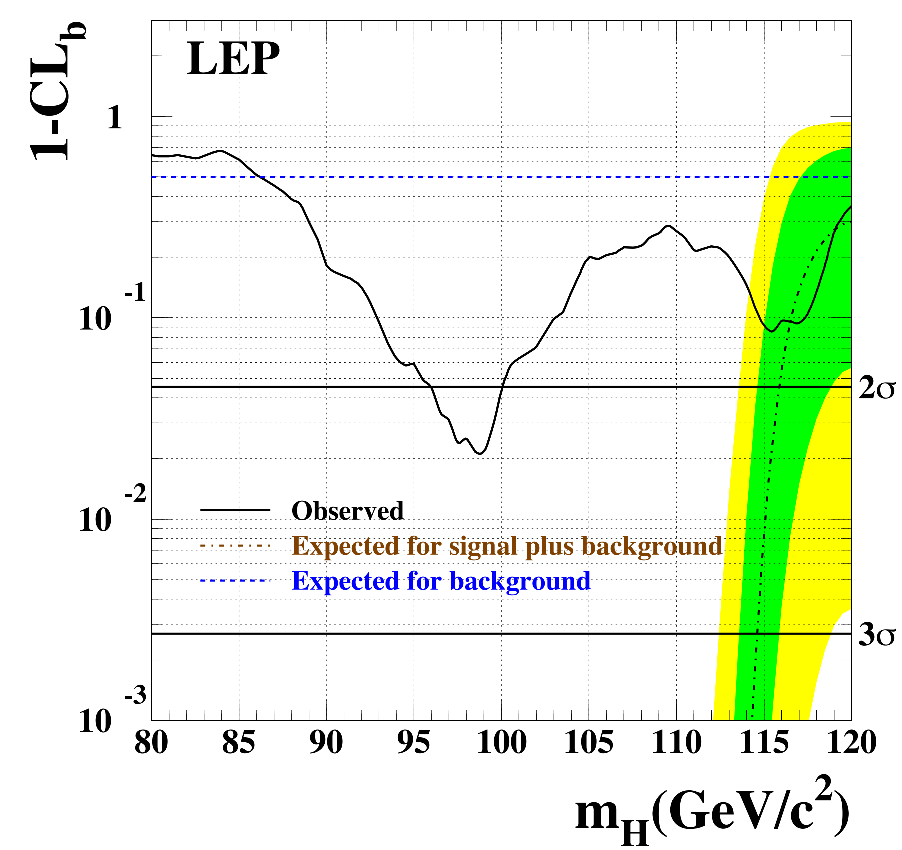




LEP 2: Final Limit







LEP operation ended at 8AM Nov 2, 2000