Higgs Searches at LEP, Tevatron and LHC

Particle Physics Course

"Dottorato di Ricerca Internazionale"

LECTURE 1.

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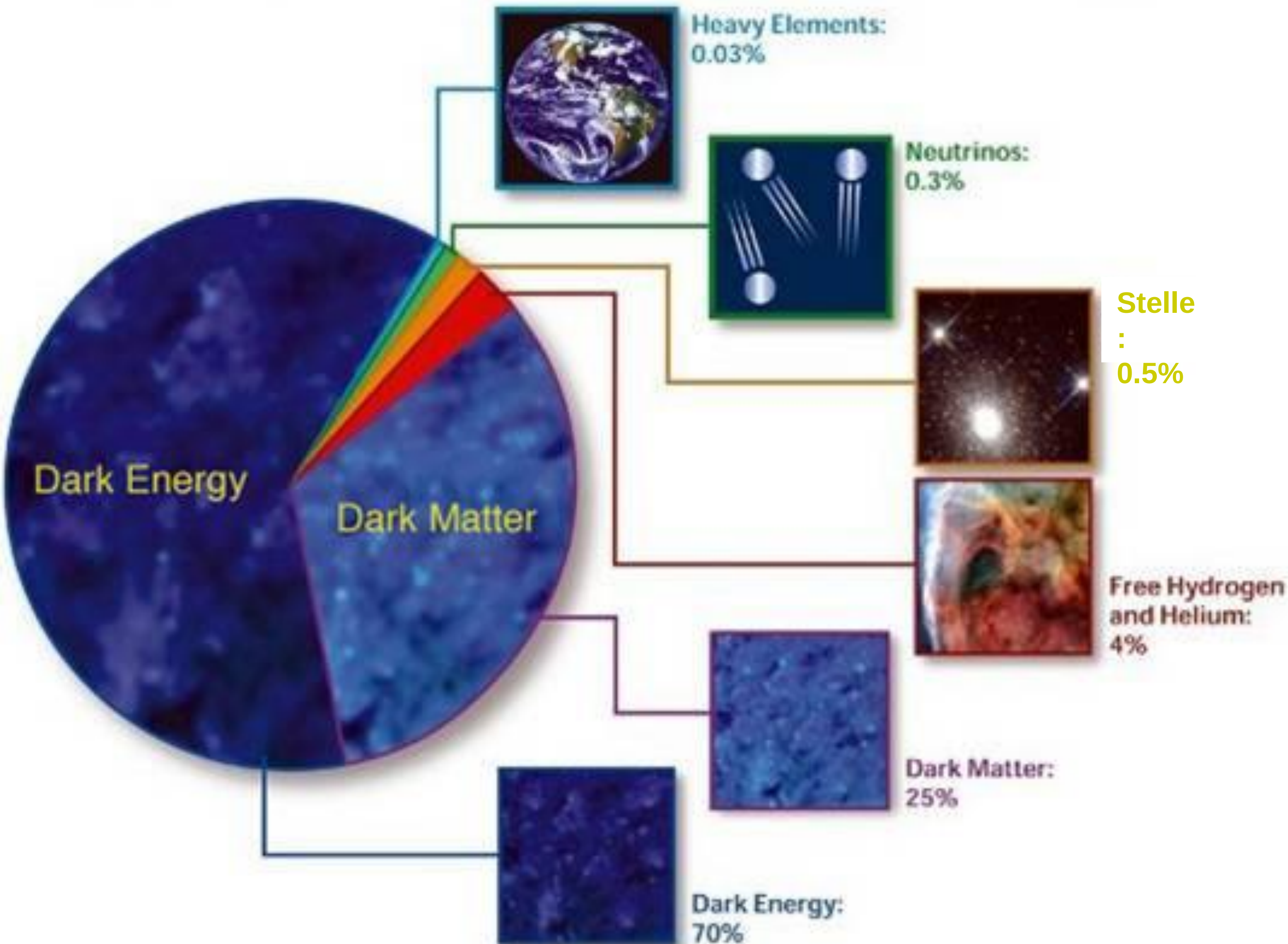
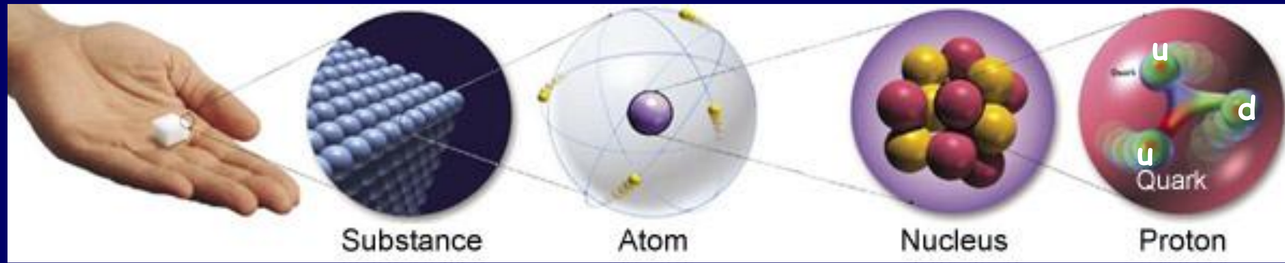
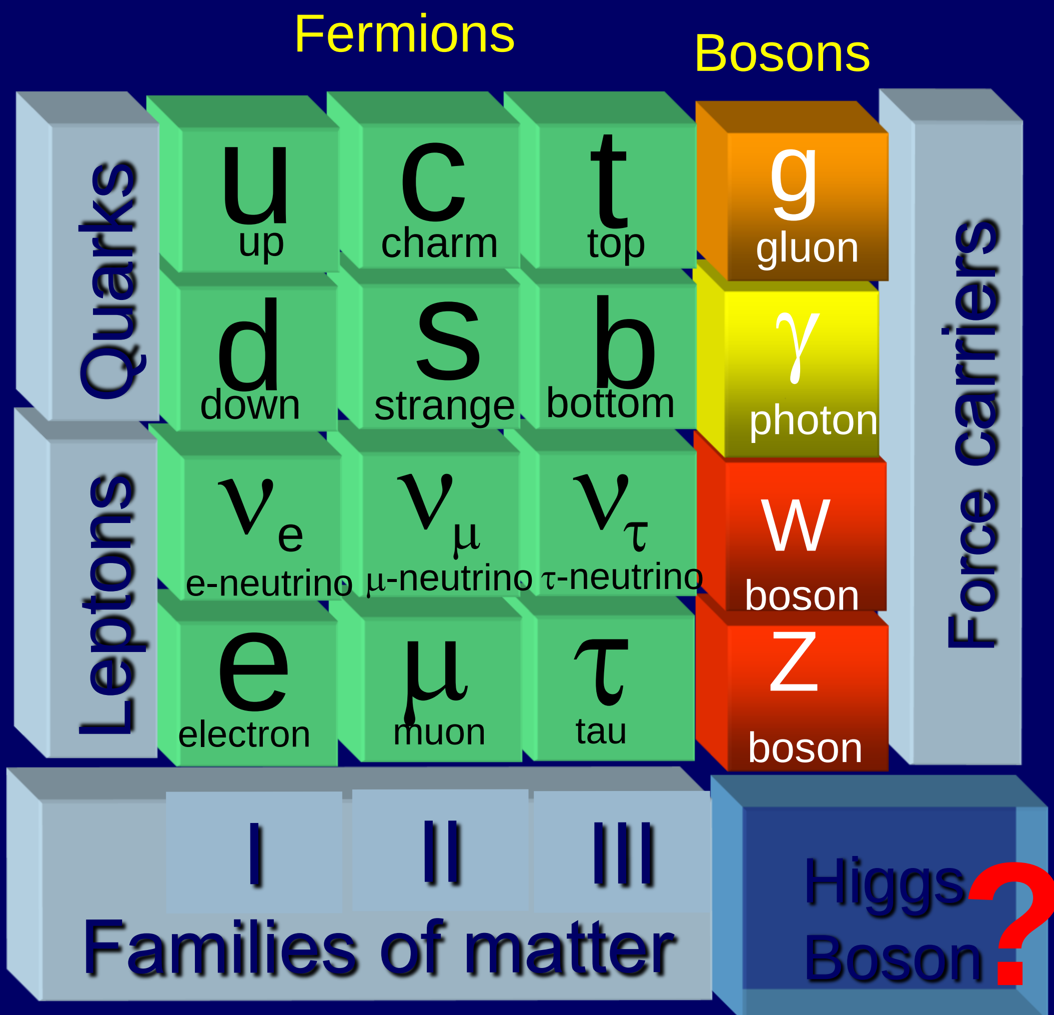
CATANIA 2009

Ordinary matter is only ≈ 5% of the energy in the Universe





The Standard Model



Questions:
why masses of matter particles and forces carriers are so different ?
The bare SM could be consistent with massless particles but matter particles range from almost 0 to about 170 GeV while force carriers range from 0 to about 90 GeV.

The simplest solution:
all particles are massless !!
A new scalar field pervades the Universe (the Higgs field). Particles interacting with this field acquire mass: the stronger the interaction the larger the mass...

BUT

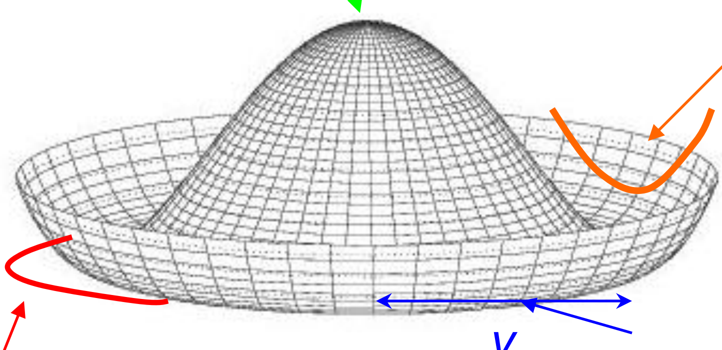
the Higgs boson have not yet been found !

Higgs Mechanism

Brout, Englert, Guralnik, Hagen, Higgs, Kibble (1964)

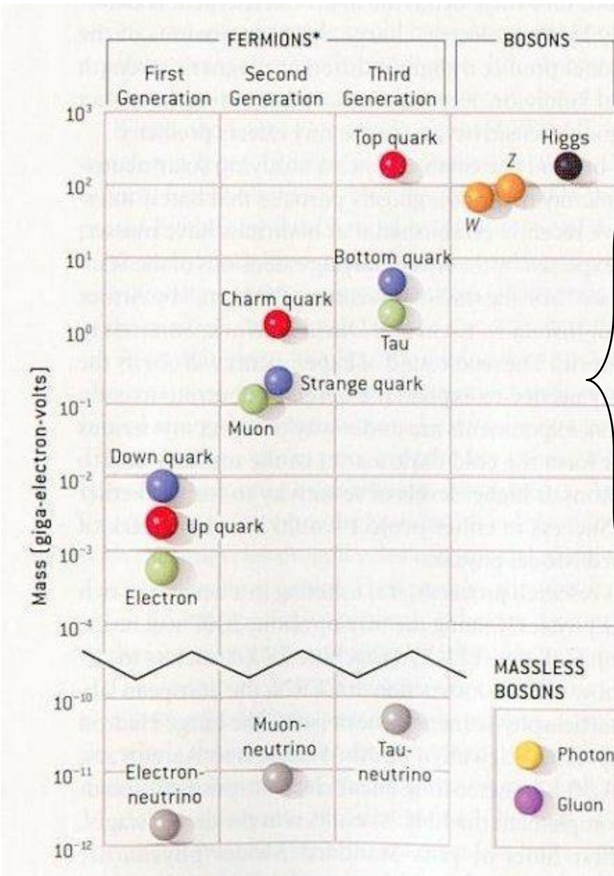
$m_W, m_Z = 0$

physical Higgs boson



$m_W, m_Z \neq 0$

modes "eaten" by *W,Z*



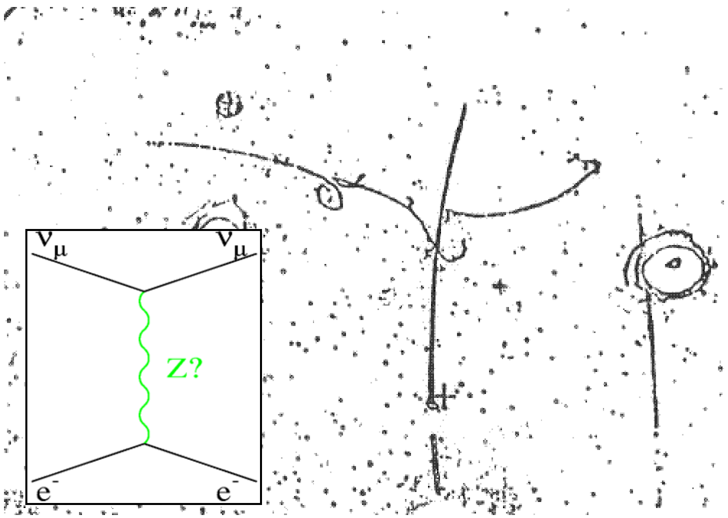
all masses due to Higgs

- **Breaks symmetry while maintaining local gauge invariance (→renormalizability)**
- **Add complex weak isospin doublet with "mexican hat" potential $V = \lambda|\Phi|^4 - \mu^2|\Phi|^2$**
- **3 components of Φ form longitudinal components of $W^{\pm}$ and Z (→massive)**
- **1 component → real scalar particle: Higgs boson**
- Couple fermion fields to Φ → fermion mass terms

A Little Bit of History

1967: Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam);

1973: Discovery of neutral currents in $\nu_\mu e$ scattering (Gargamelle, CERN)

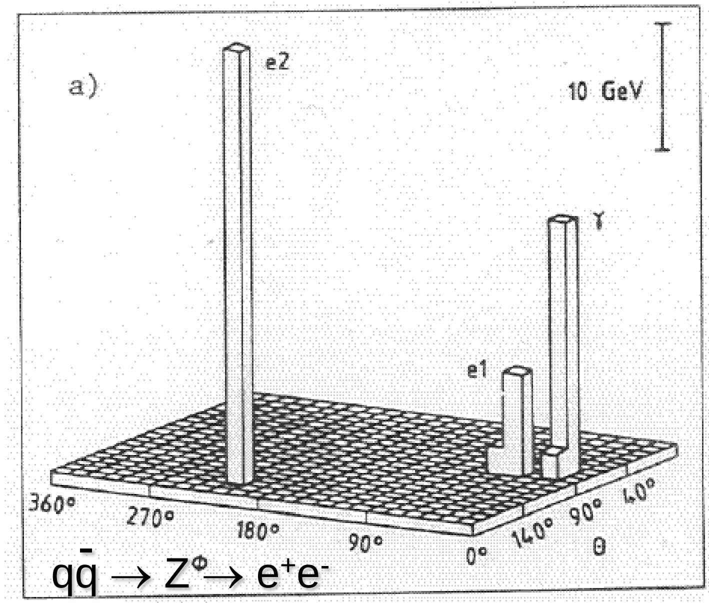


1974: Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$ (Illiopoulos)

1981: The CERN SpS becomes a $p\bar{p}$ collider; LEP and SLC approved before W/Z discovery;

1983: W and Z discovery (UA1, UA2); LEP and SLC construction start;

First Z detected in the world:



1989: First collisions in LEP and SLC; Precision tests of the SM (m_{top});

1995: Discovery of the top (FNAL); Precision tests of the SM (m_H);

2000: First hints of the Higgs boson?

"Theory": SM Higgs Boson Mass and Couplings

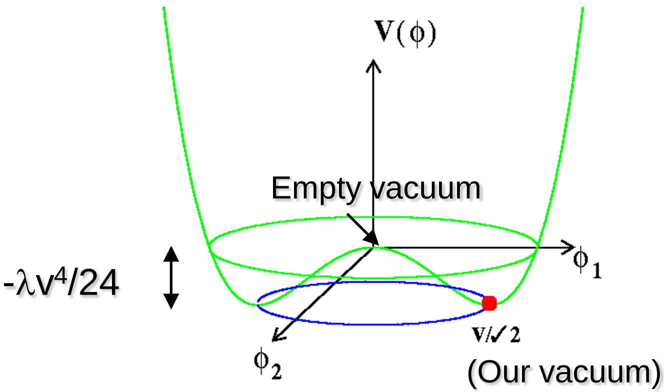
From the Higgs Mechanism …

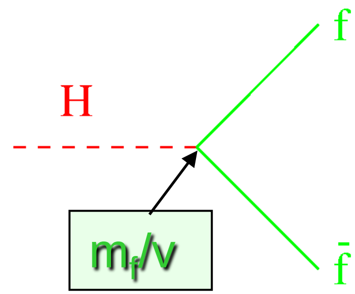
and from Gauge Invariance :

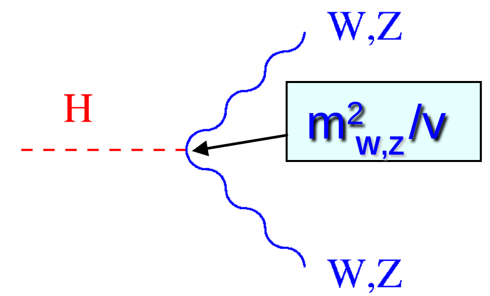
$m_Z = m_W/\cos\vartheta_W$;

$m_W = gv/2$; ($\to$ v ~ 250 GeV).

vacuum expectation value



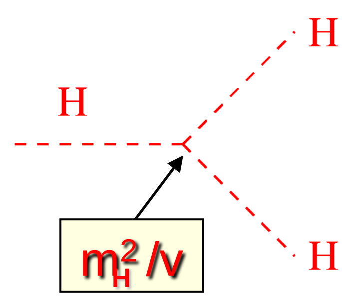


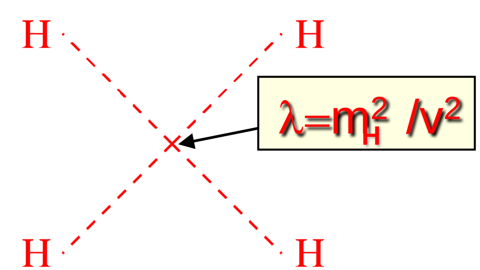


$$V(\phi) = \frac{\lambda}{3!}\left\{\bar{\phi}\phi - v^2/2\right\}^2$$

$$= \frac{1}{2}\frac{\lambda v^2}{3}H^2 + \frac{\lambda v}{3!}H^3 + \frac{\lambda}{4!}H^4$$

All couplings predicted





(unknown)

$m_H^2 = \lambda v^2/3$

Mass unknown

SM Higgs: what we know from theory

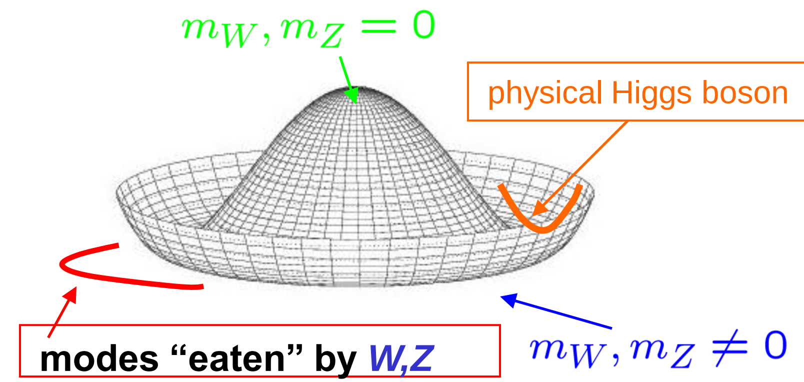
One pseudo-scalar doublet Φ (4 degrees of freedom)

Potential $V = \lambda|\Phi|^4 - \mu^2|\Phi|^2$

After spontaneous symmetry breaking:
- $W^{\pm}$ and Z acquire masses (3 degrees of freedom)
- the last remaining degree of freedom (4-3=1):

scalar CP-even Higgs of unknown mass

$m^2_H = \lambda v^2/3$



λ, as any other coupling constant, runs up to a scale Q at which the model is not longer valid:

- small m_H at 1-TeV scale

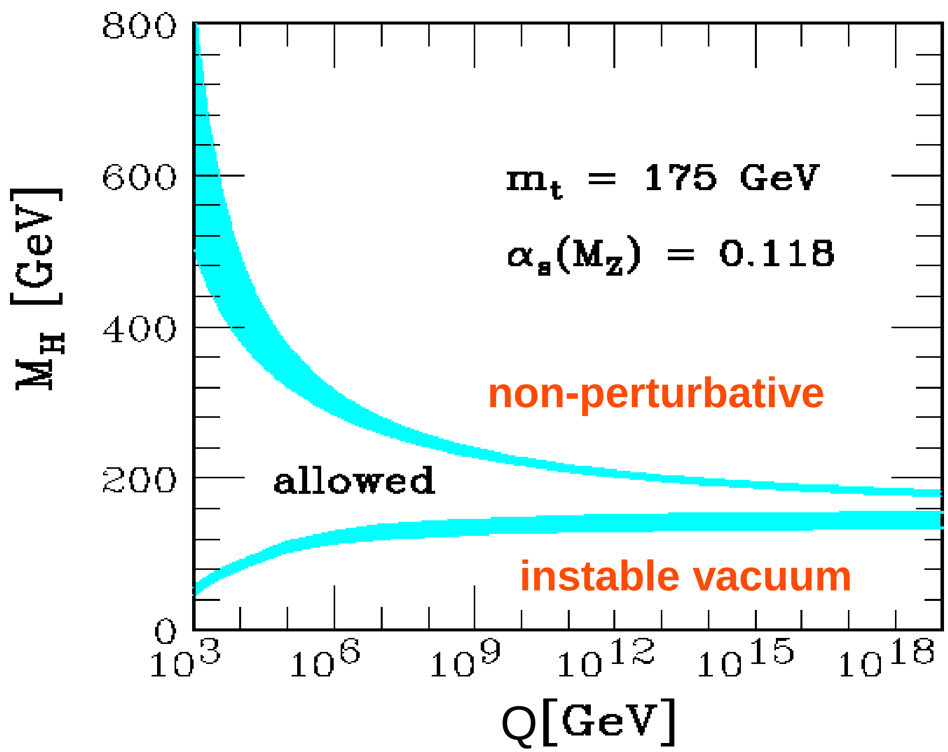
at some Q, $\lambda(Q) < 0$ V has no minimum (vacuum breaks loose)

- large m_H at 1-TeV scale

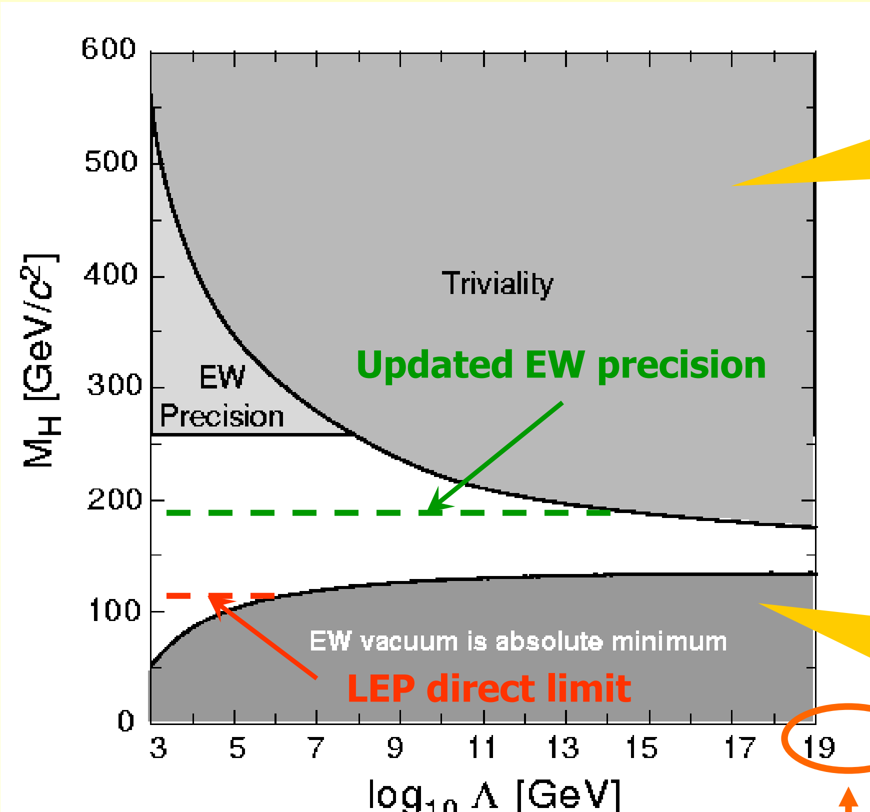
at some Q, $\lambda(Q) = \infty$ theory becomes non-perturbative

→ chimney

m_H must be within ~ 50-600 GeV range (if the SM is valid up to Q ~ 1 TeV scale)



Theoretical Limits on Higgs Mass



M_H too large:
Higgs self coupling blows up at some scale Λ

M_H too small:
for scalar field values $O(\Lambda)$ the Higgs potential becomes unstable

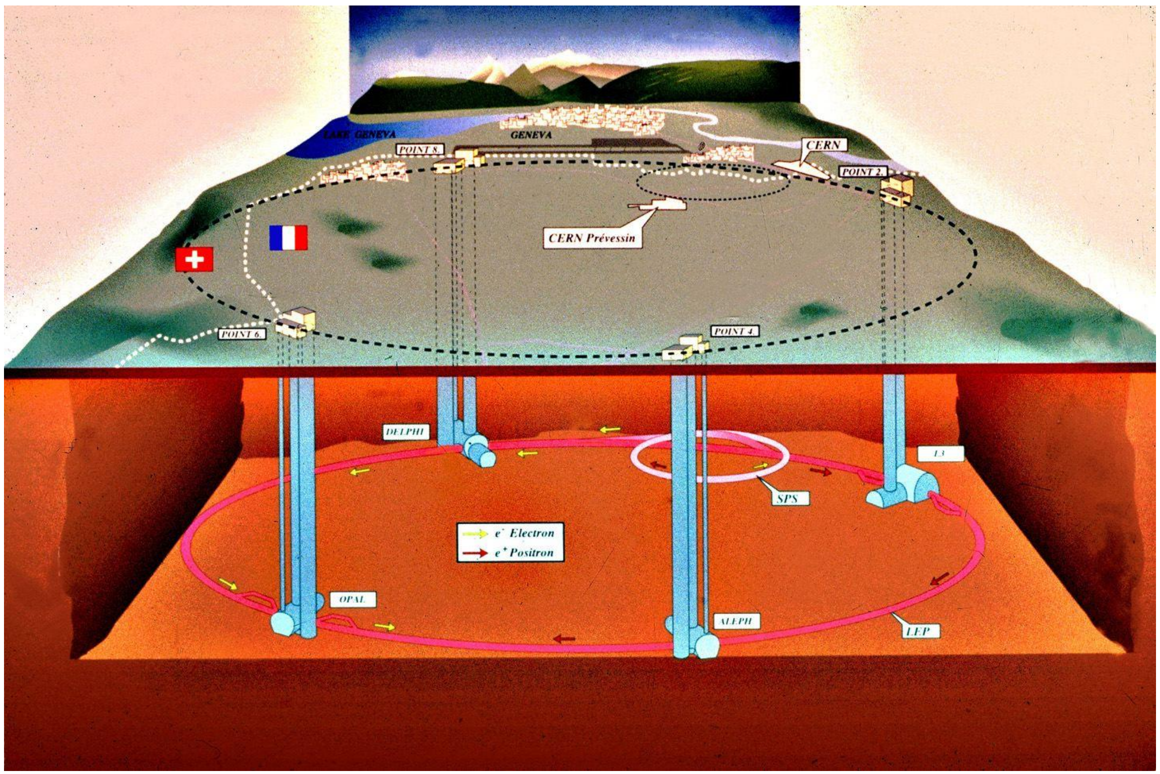
M_{Planck}, gravity

If SM is valid up to Planck Scale

$130 < M_H < 180$ GeV

e.g. Riseelmann, hep-ph/9711456

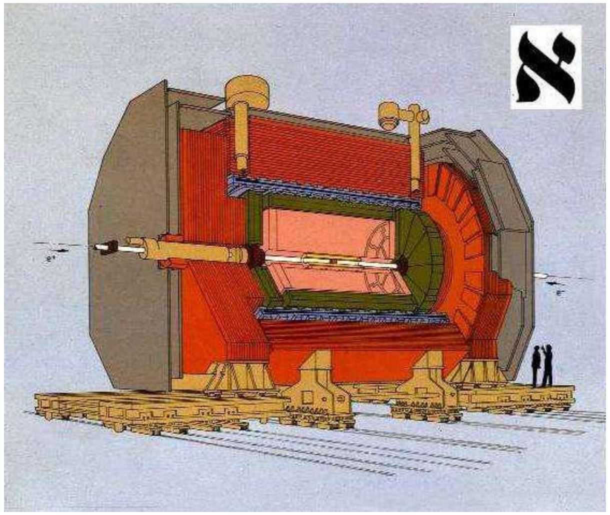
LEP



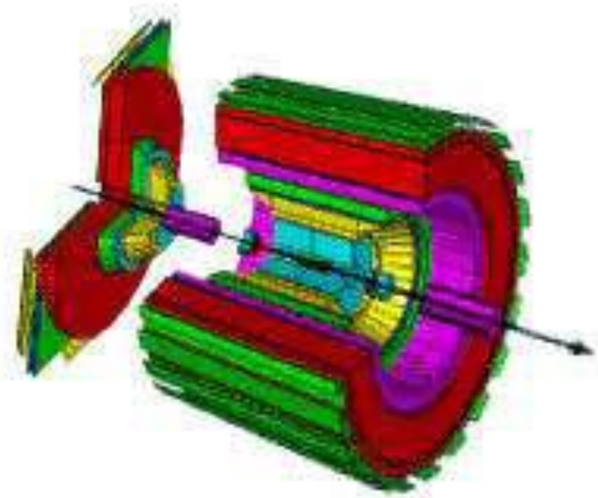
- Operation
  1989 - 2000, CERN, Geneva
- Circumference
  27 km
- Particles
  electrons - positrons
- Beam energy
  45 GeV $\rightarrow$ 104.5 GeV
- Luminosity
  10^{31} - 10^{32} cm^{-2} sec^{-1}
- L_{int}
  1000 pb^{-1}
- Experiments
  ALEPH, DELPHI, L3, OPAL
- Characteristics:
  - very clean environment
  - very small backgrounds

Four Experiments at LEP

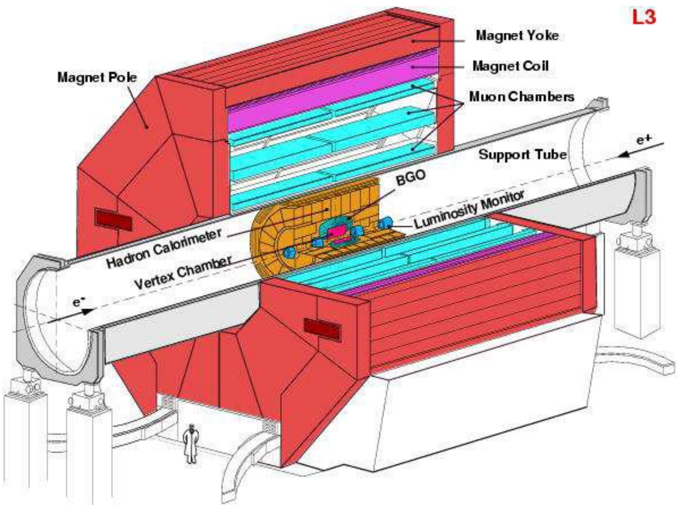
ALEPH



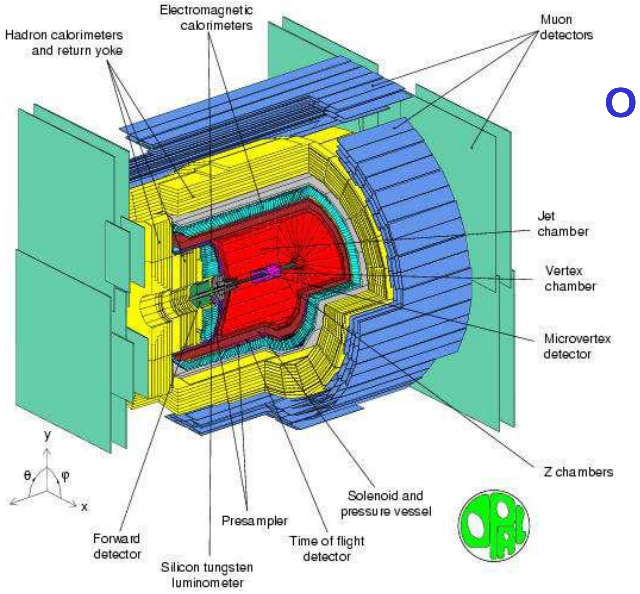
DELPHI



L3

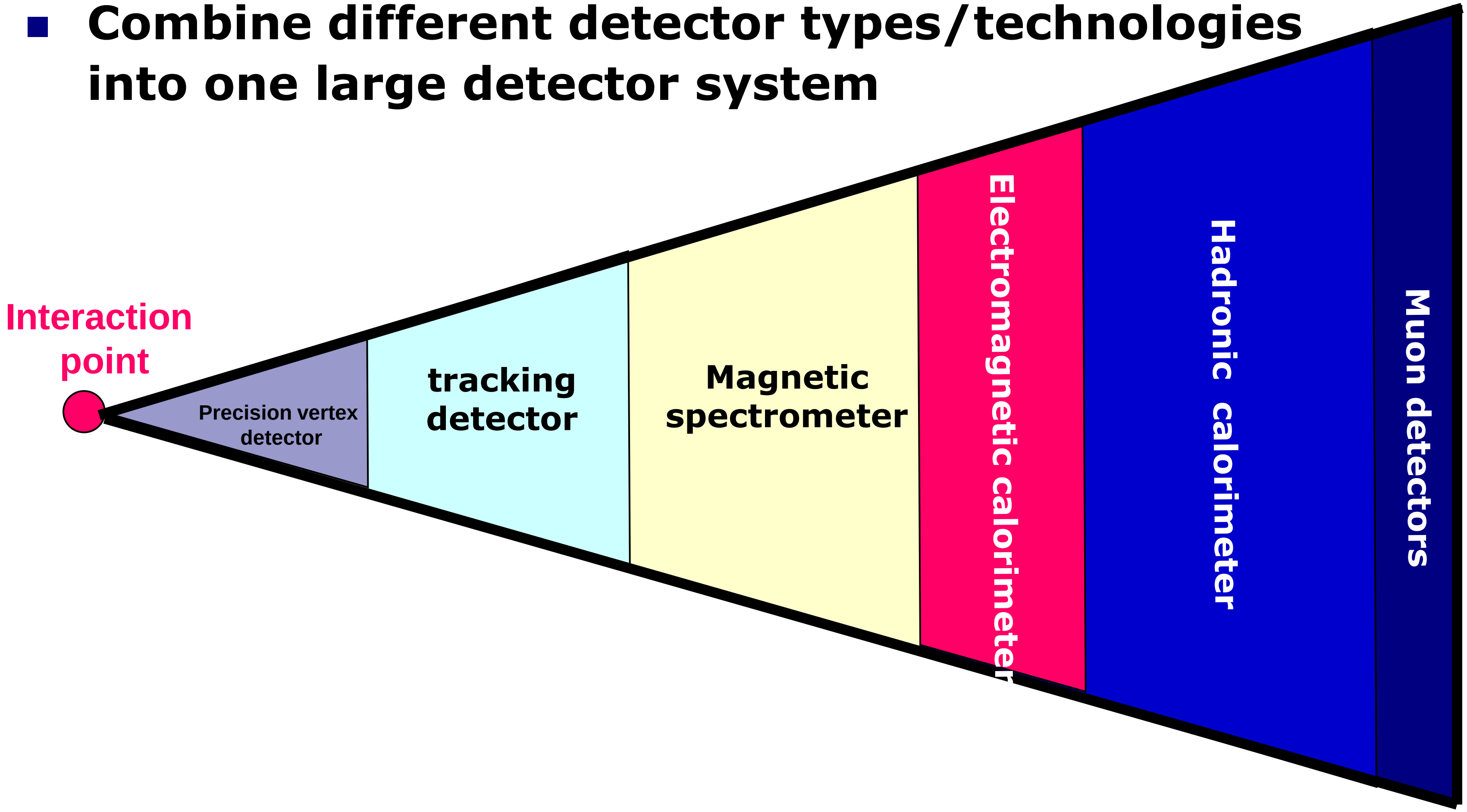


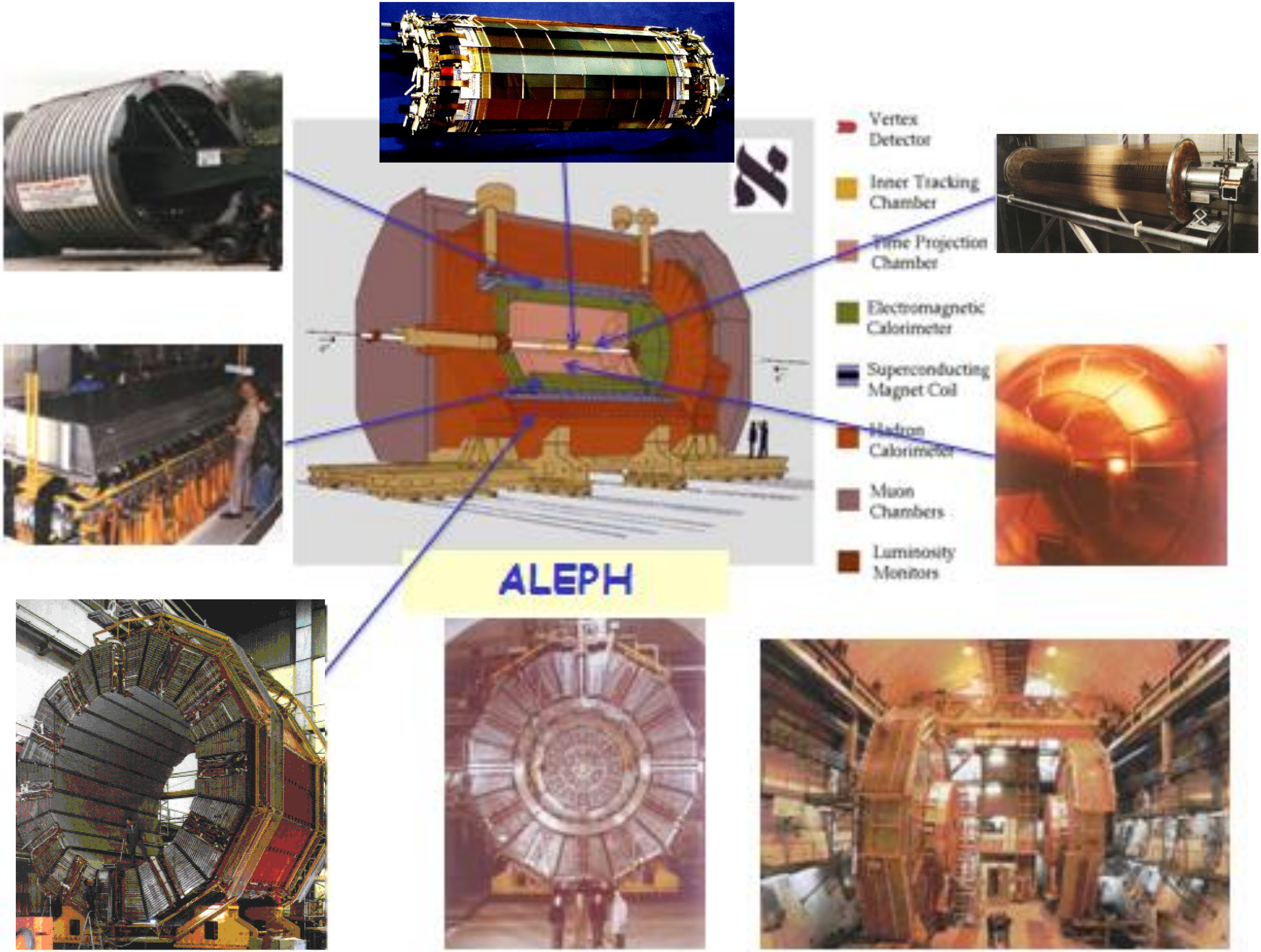
OPAL



Typical detector concept

- **Combine different detector types/technologies into one large detector system**




Vertex Detector
Inner Tracking Chamber
Time Projection Chamber
Electromagnetic Calorimeter
Superconducting Magnet Coil
Hadron Calorimeter
Muon Chambers
Luminosity Monitors
ALEPH

Search for the SM Higgs at LEP

- LEP: e+e- collider at CERN
  four experiments: ALEPH, DELPHI, L3, OPAL

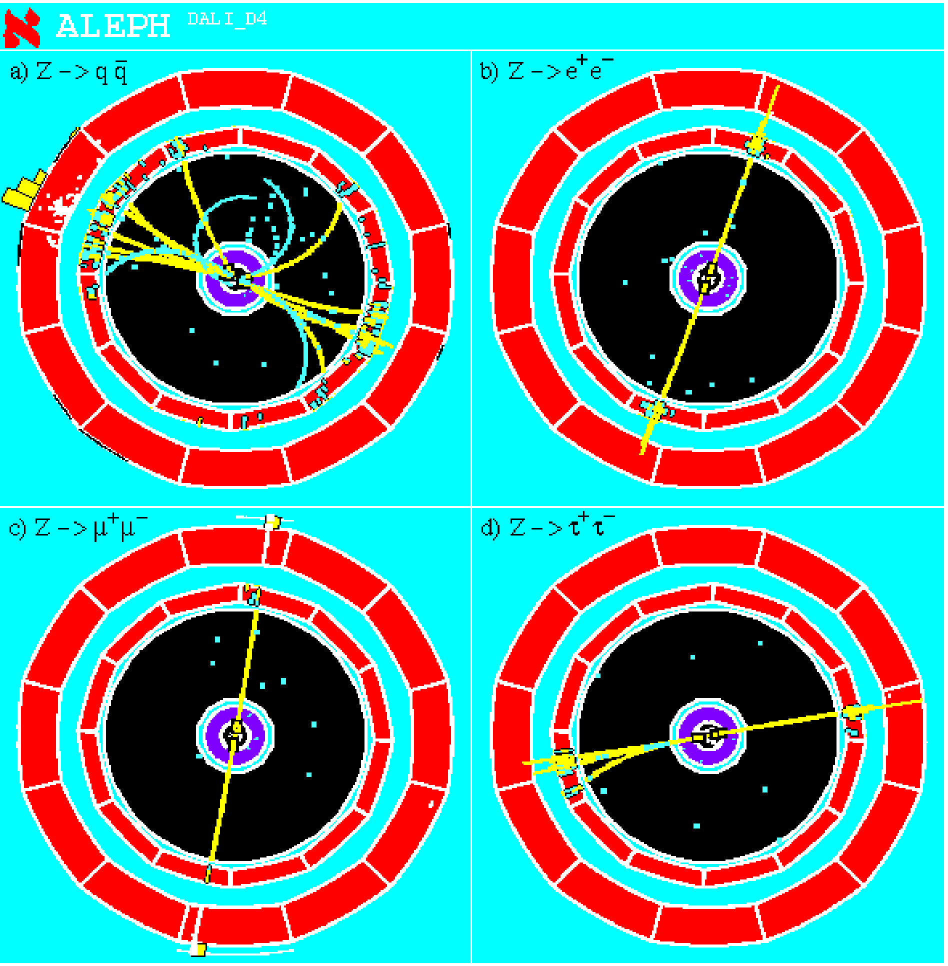
- LEP1: 1989-1995, √s=91 GeV,
  precision measurement of Z boson parameters

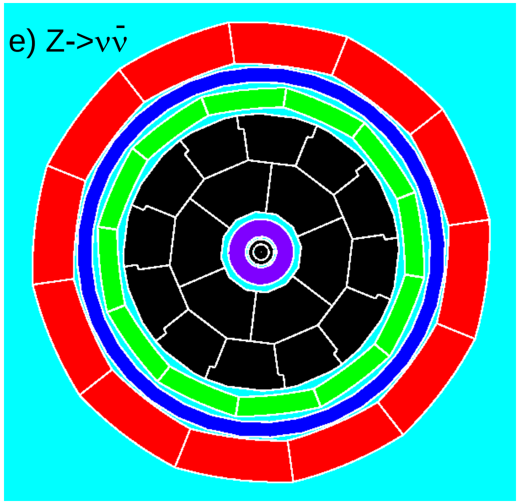
- LEP2: 1995-2000, √s =130-208 GeV

year	'95	'96	'97	'98	'99	2000
√s	130-136	161-172	183	189	192 196 200 202	204 205 207 208
Lum (pb^{-1})	3 3	11 11	55	160	25 80 80 40	9 72 130 8
Lum x4 exp	24	88	220	640	900	875

>2.5 fb^{-1} @ E_{cm}>180 GeV

Z Lineshape: Final State Identification





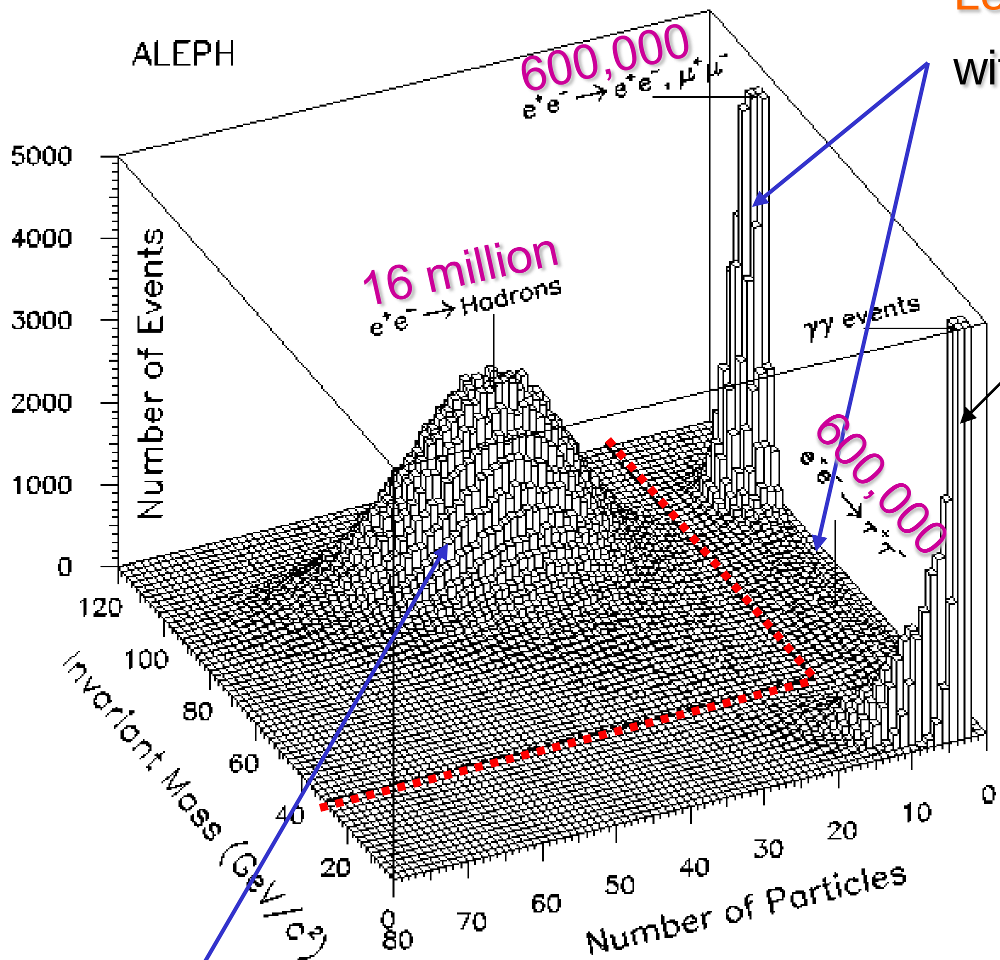
- $Z \to \nu\bar{\nu}$: Not detectable.

- $Z \to \tau^+\tau^-$: Two low multiplicity jets + missing energy carried by the decay neutrinos

Channel	Partial Width	Branching Ratio
Hadrons	1.739 GeV	70%
Neutrinos	0.497 GeV	20%
Leptons	0.250 GeV	10%

- $Z \to q\bar{q}$: Two jets, large particle multiplicity.
- $Z \to e^+e^-, \mu^+\mu^-$: Two charged particles (e or μ.)

Z Lineshape: Final State Identification

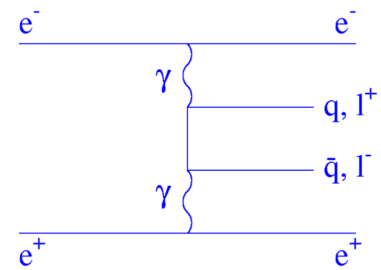


Leptonic decays: Low multiplicity, with (τ) or without (e, μ) missing energy

$\gamma\gamma$ Collisions:

Low multiplicity,

Low mass



Selections with

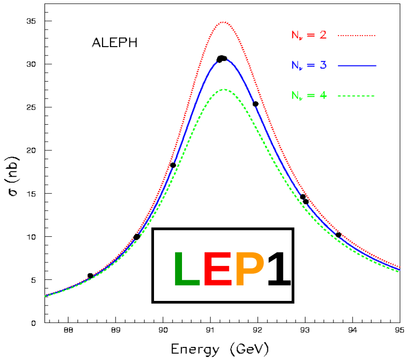
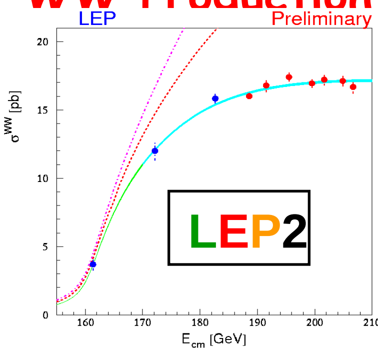
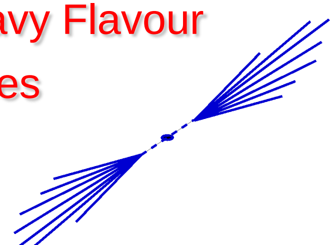
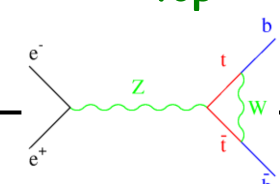
- ❑ High Efficiency;
- ❑ High Purity;

Hadronic decays:

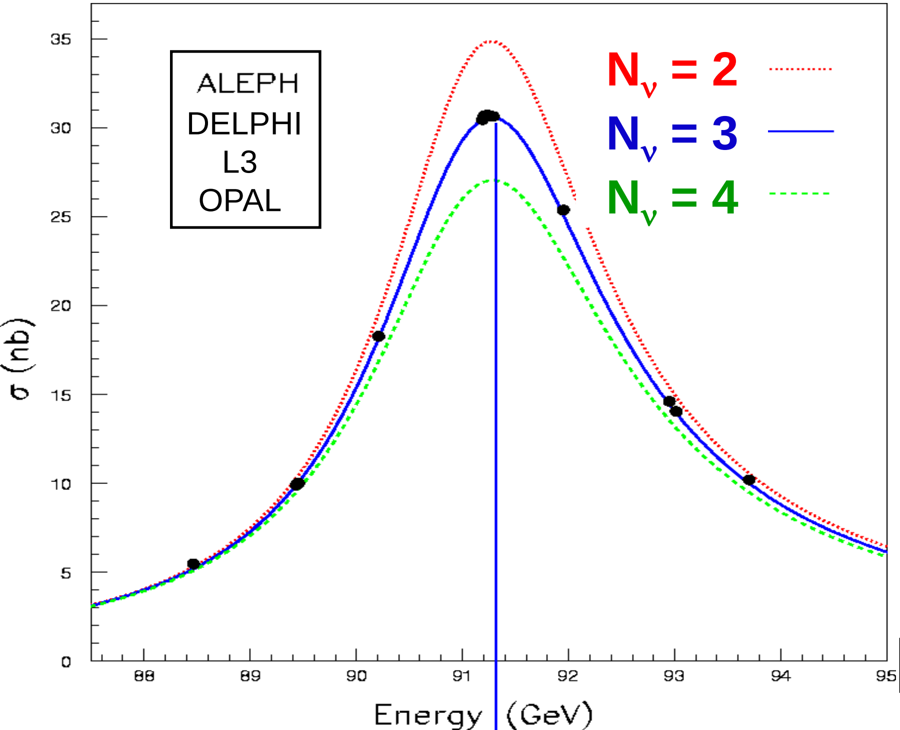
High multiplicity

High mass

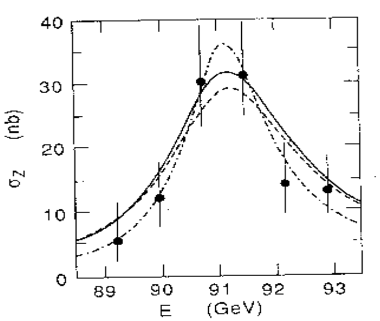
Precision Electroweak Observables

Experiment	Observable	Main technology	Precision	Physics output
Z Lineshape 	m_Z Γ_Z σ_{peak} $R_\ell = \frac{\Gamma_{hadron}}{\Gamma_{lepton}}$	Absolute beam energy (+ ISR QED calculations) Relative beam energy (+ ISR ...) Absolute luminosity Final state identification	2.10^{-5} 10^{-3} 10^{-3} $1.2.10^{-3}$	Input! $\Delta\rho, \alpha_s, N_\nu$ N_ν α_s, m_{top}
WW Production 	m_W	-Absolute *Beam energy *Luminosity -Final state Identification	5.10^{-4}	m_H vs m_{top}
Heavy Flavour Rates 	$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{hadron}}$ $R_\ell = \frac{\Gamma_{c\bar{c}}}{\Gamma_{hadron}}$	b-tagging (Vertex detector) c-tagging (mostly SLD)	3.10^{-3} 2%	m_{top} 

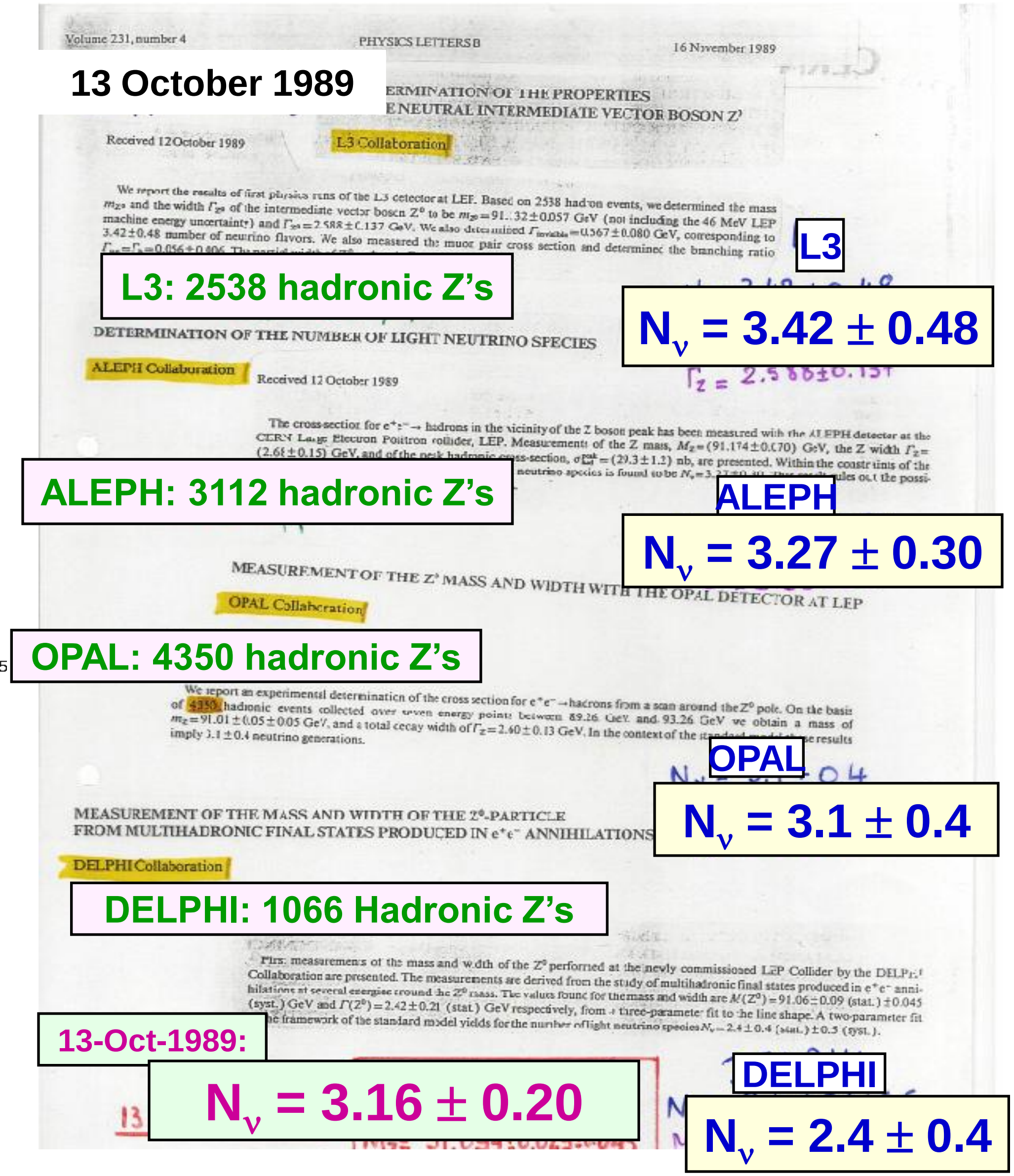
Z Lineshape: Results



$N_\nu = 2.984 \pm 0.008$



MarkII, Aug. 1989, with 106 Z decays: $N_\nu = 3.8 \pm 1.4$.



What LEP found from 1989 to 2000

Unprecedented accuracy on the measurement of SM parameters

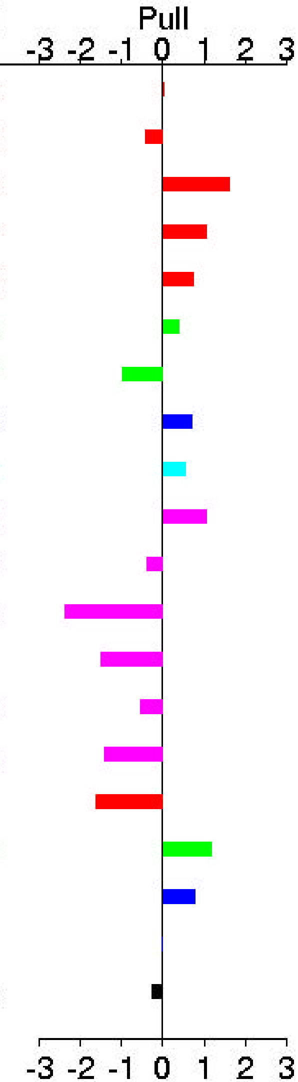
m_Z known at 21 ppm

Z couplings

m_W known at ±46 MeV

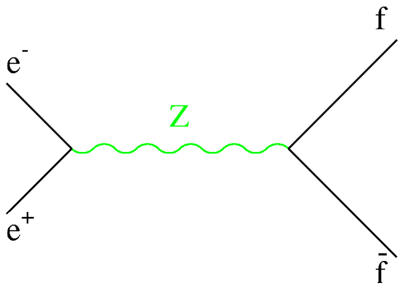
Osaka 2000

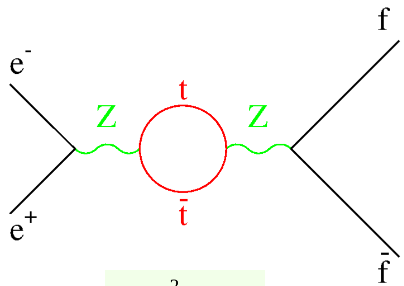
	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.07
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.75
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.70
m_W [GeV]	80.427 ± 0.046	.55
R_b	0.21653 ± 0.00069	1.09
R_c	0.1709 ± 0.0034	-.40
$A^{0,b}_{fb}$	0.0990 ± 0.0020	-2.38
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.51
A_b	0.922 ± 0.023	-.55
A_c	0.631 ± 0.026	-1.43
$\sin^2\theta^{lept}_{eff}$	0.23098 ± 0.00026	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.81
m_t [GeV]	174.3 ± 5.1	-.01
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.29



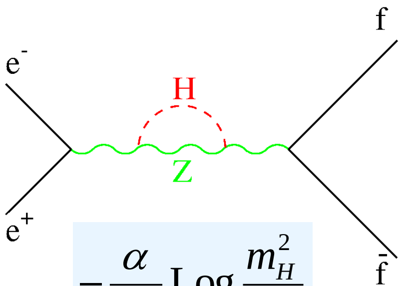
Dependence on m_{top} and m_H of Electroweak Observables

Electroweak Observables (i.e., related to W and Z) sensitive to vacuum polarization effects:

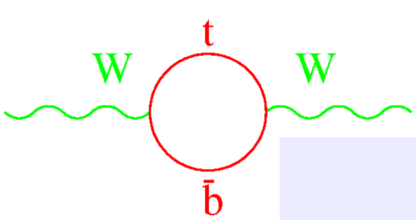




$$\frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} \approx 1\%$$



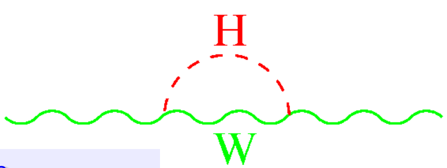
$$-\frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2}$$



$(m_W/m_Z)^2$

$\downarrow$

$(m_W/m_Z)^2 \times (1+\Delta r)$



Radiative corrections :

$\Delta r_{top} \sim m^2_{\;top}$

$\Delta r_H \sim \log m_H$

From precision electroweak measurements :

- **Predict m_{top} (and m_W) and compare with direct measurements;**
- **Predict m_H ……………and compare with direct measurements.**

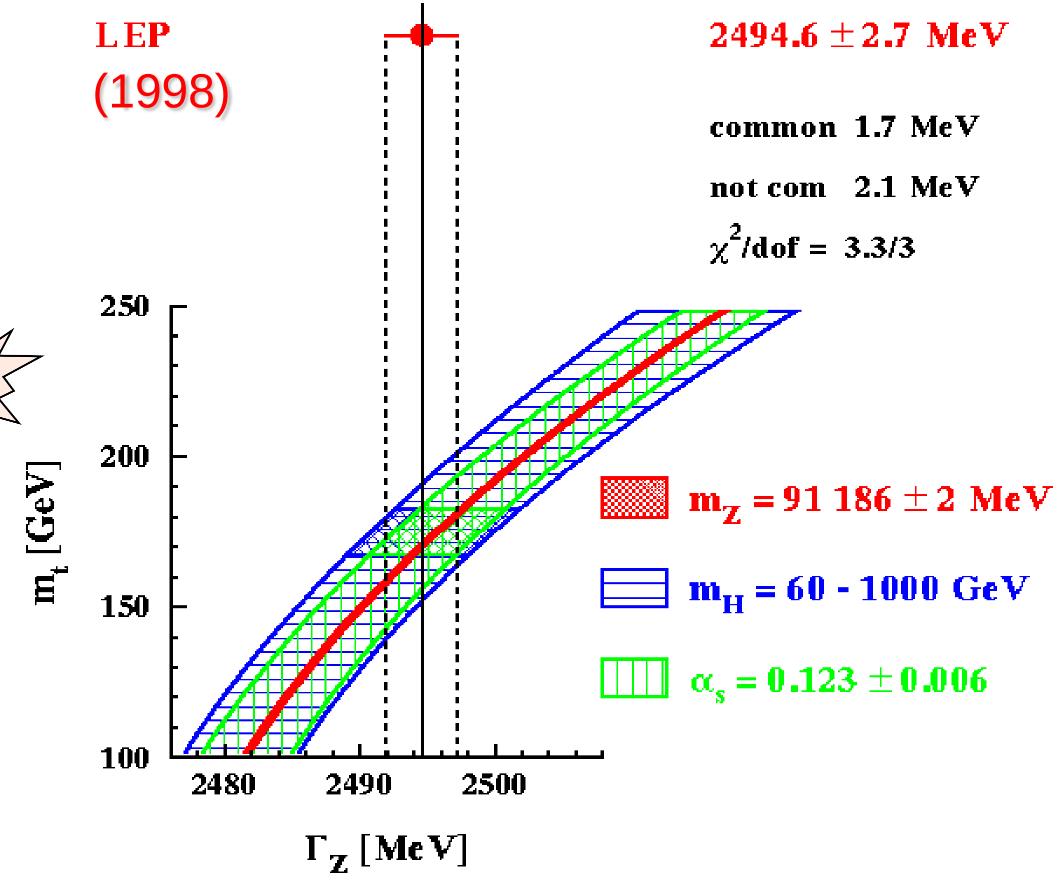
Z Lineshape: Results

Obs.	Value	Error
m_Z	91187.5	2.1 MeV
Γ_Z	2495.2	2.3 MeV
σ^0	41.540	0.037 nb
R_l	20.767	0.025

10^{-3}

$\sigma^0_{had}/\sigma^0_l$

500 MeV
in 1989



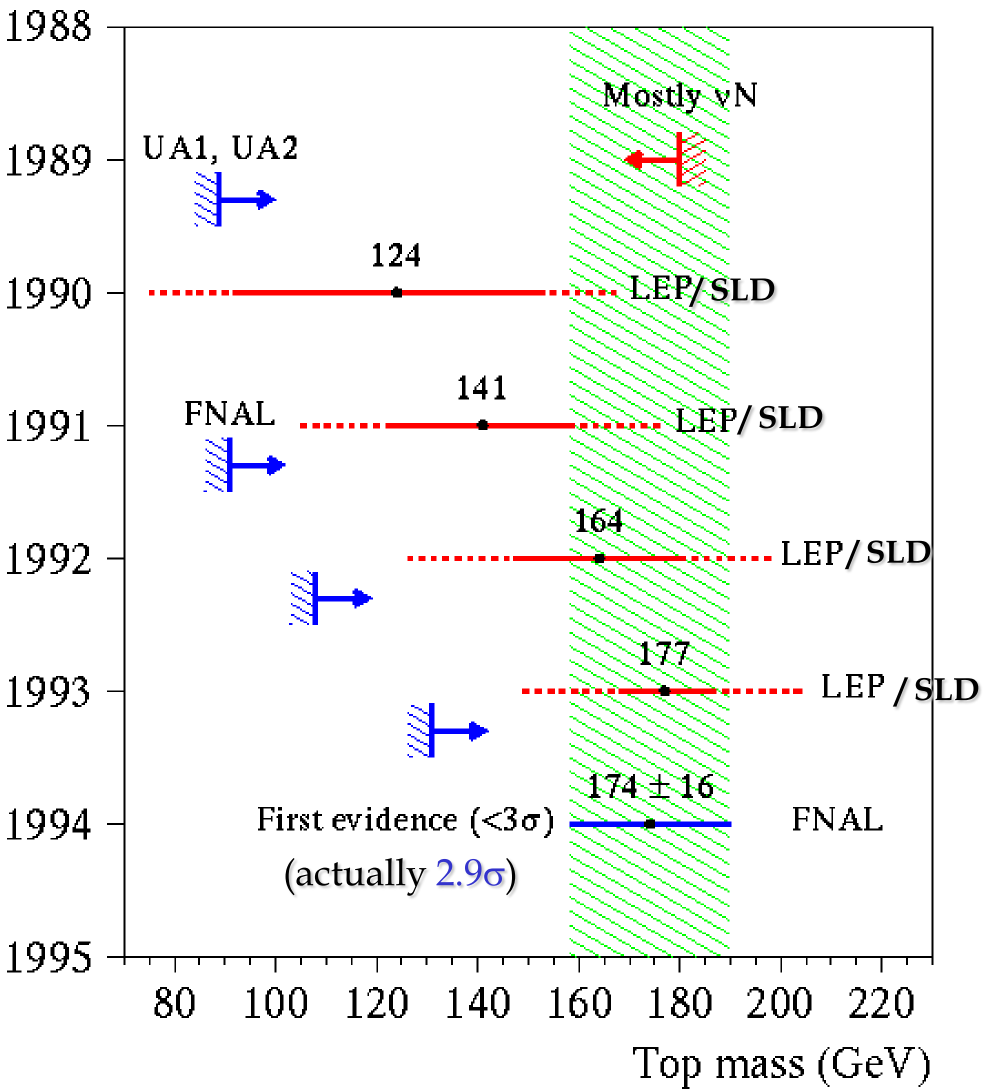
$\Gamma_Z \propto (1 + \Delta\rho)$

With this measurement alone:

$m_{top} \sim 165 \pm 25$ GeV/c^2

(+small sensitivity to m_H)

Prediction of m_{top} from EW Measurements



A top mass of 177 GeV/c² was predicted by LEP & SLC with a precision of 10 GeV/c² in March 1994.

One month later, FNAL announced the first 3σ evidence of the top.

In 2001:

$$m_{\rm top}^{\rm EW} = 180.5 \pm 10.0\,{\rm GeV}/c^2$$

$$m_{\rm top}^{\rm direct} = 174.3 \pm 5.1\,{\rm GeV}/c^2$$

Perfect consistency between prediction and direct measurement. Allows a global fit of the SM (with m_H) to be performed.

Global Fit of the Standard Model to m_H (2008)

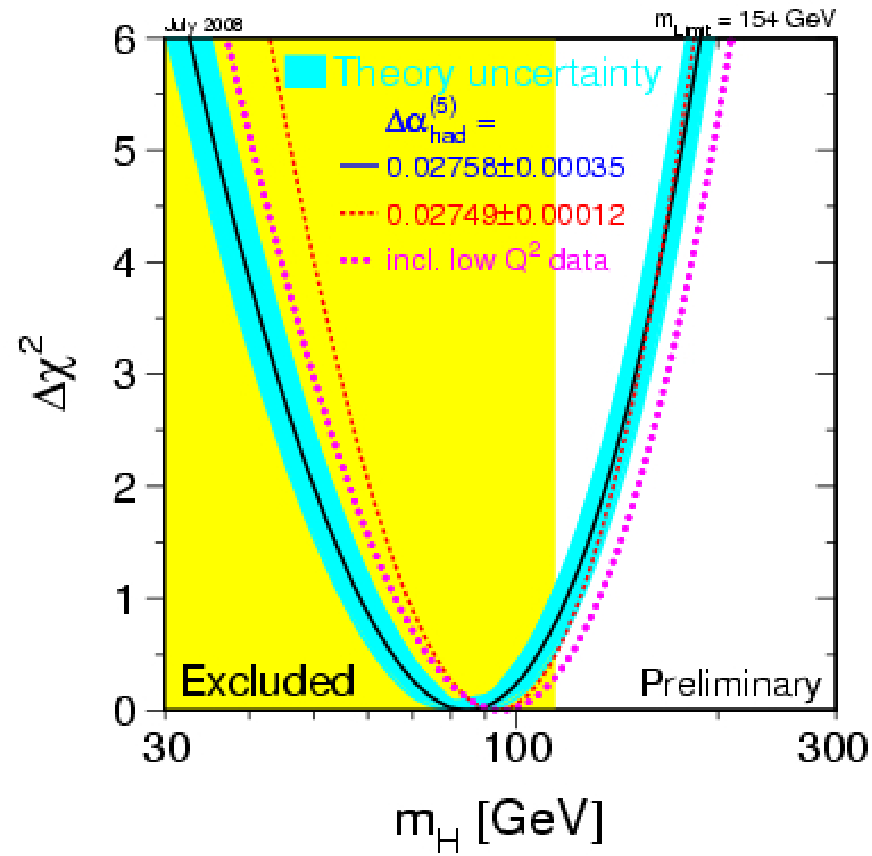
Precision electroweak data are sensitive to Higgs mass

$$m_W = \left(\frac{\pi \alpha_{em}}{\sqrt{2} G_F} \right) \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}}$$

$\Delta r = f\,(m^2_{top}\ ,\ \log m_H)$

Global SM electroweak fits provide upper limit :

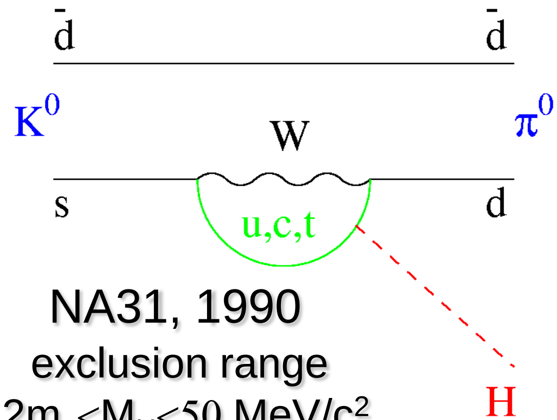
$M_H = 91 \pm^{45}_{32}$ <186 GeV @ 95% C.L.



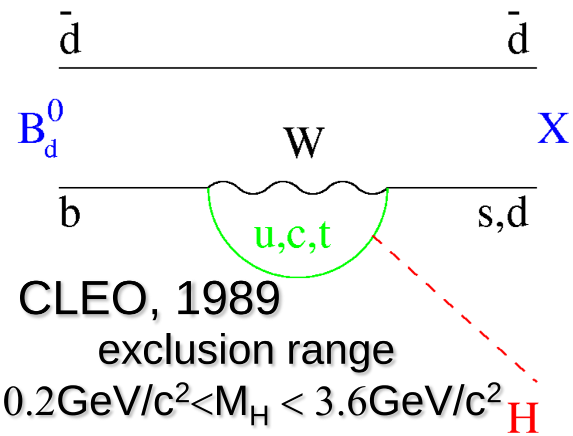
(July 2008, with recent Tevatron results)

Direct search: before LEP

Quite a few searches in hadron decays:



NA31, 1990
exclusion range
$2m_e$<M_H<50 MeV/c^2

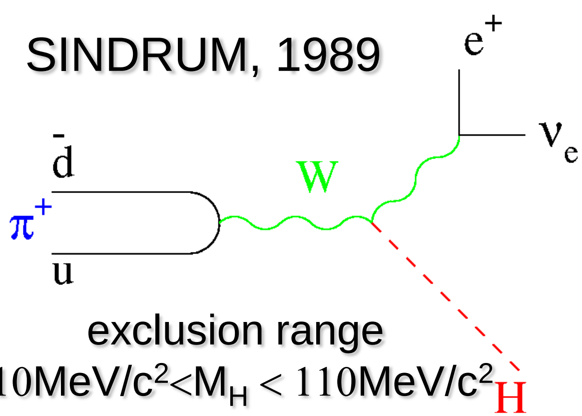


CLEO, 1989
exclusion range
0.2GeV/c^2<M_H < 3.6GeV/c^2

No excess seen, but…

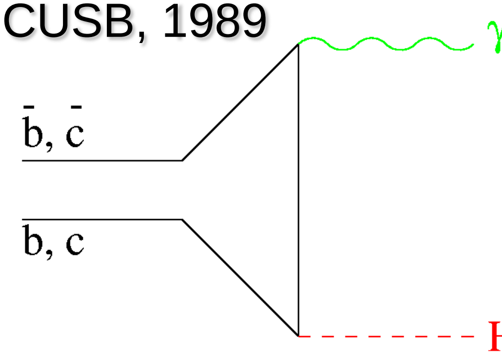
No unambiguous limit set

SINDRUM, 1989



exclusion range
10MeV/c^2<M_H < 110MeV/c^2

CUSB, 1989



exclusion range
$2m_\mu$<M_H < 5GeV/c^2

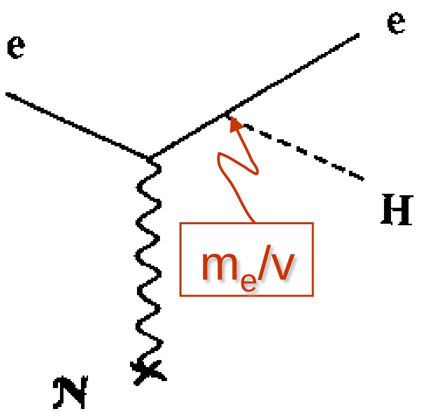
(Large theoretical uncertainties
on the predicted decay rates.)

The situation before LEP

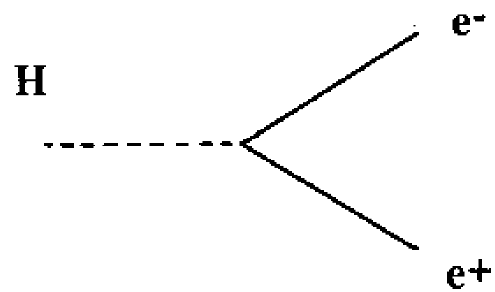
Only one unambiguous limit:

M. Davier and H. Nguyen Ngoc, 1990

1) Production:

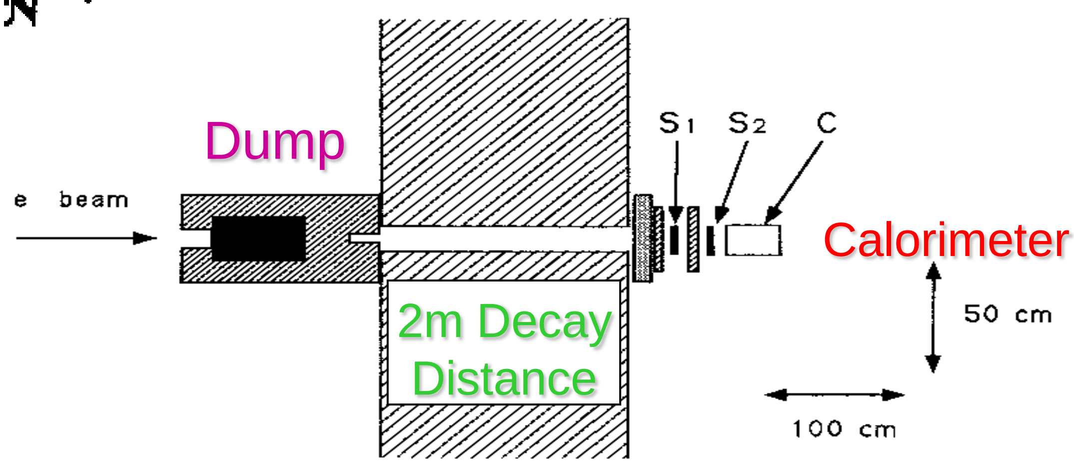


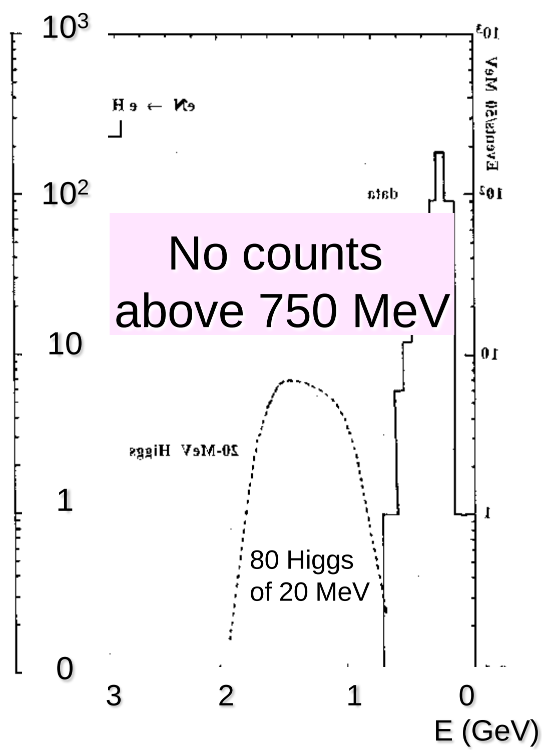
2) Decay (for m_H between $2m_e$ and $2m_\mu$):



$2\ 10^{16}$ e^-

(2 GeV)





$1.2\ \mathrm{MeV}/c^2 < m_H < 52\ \mathrm{MeV}/c^2$

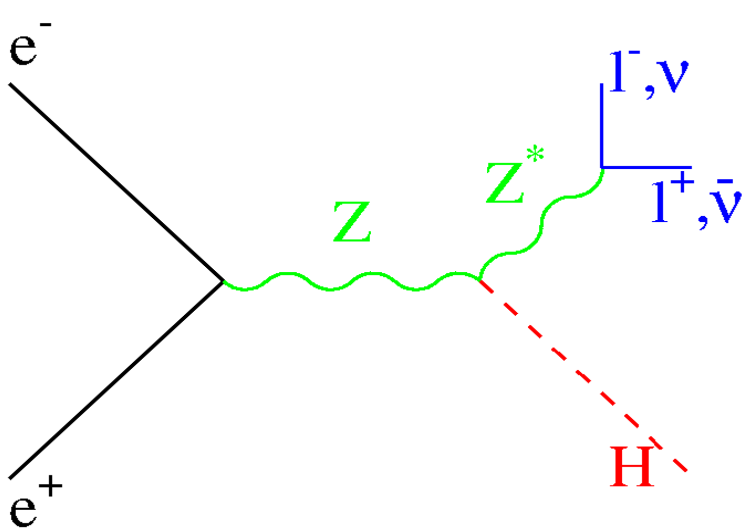
Excluded at 95% C.L.

SM Higgs Boson Production at LEP

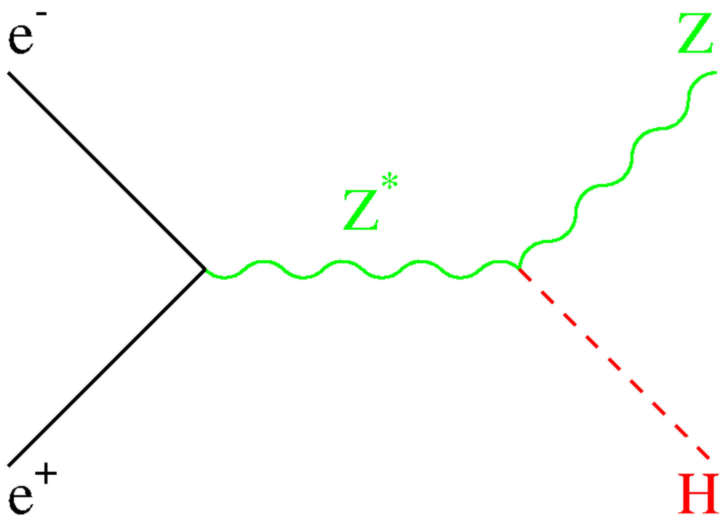
Dominant at LEP: The Higgs-strahlung process

(The production cross section depends only on m_H)

LEP 1: $\sqrt{s} \sim m_Z$



LEP 2: $\sqrt{s} \geq m_Z + m_H$

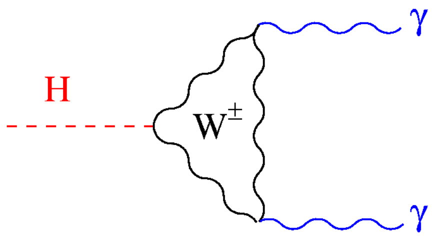


(Large coupling to the Z $\Rightarrow$ Only sizeable cross section)

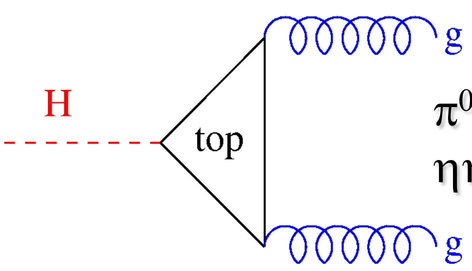
SM Higgs Boson Decays

The decay branching ratios depend only on m_H:

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



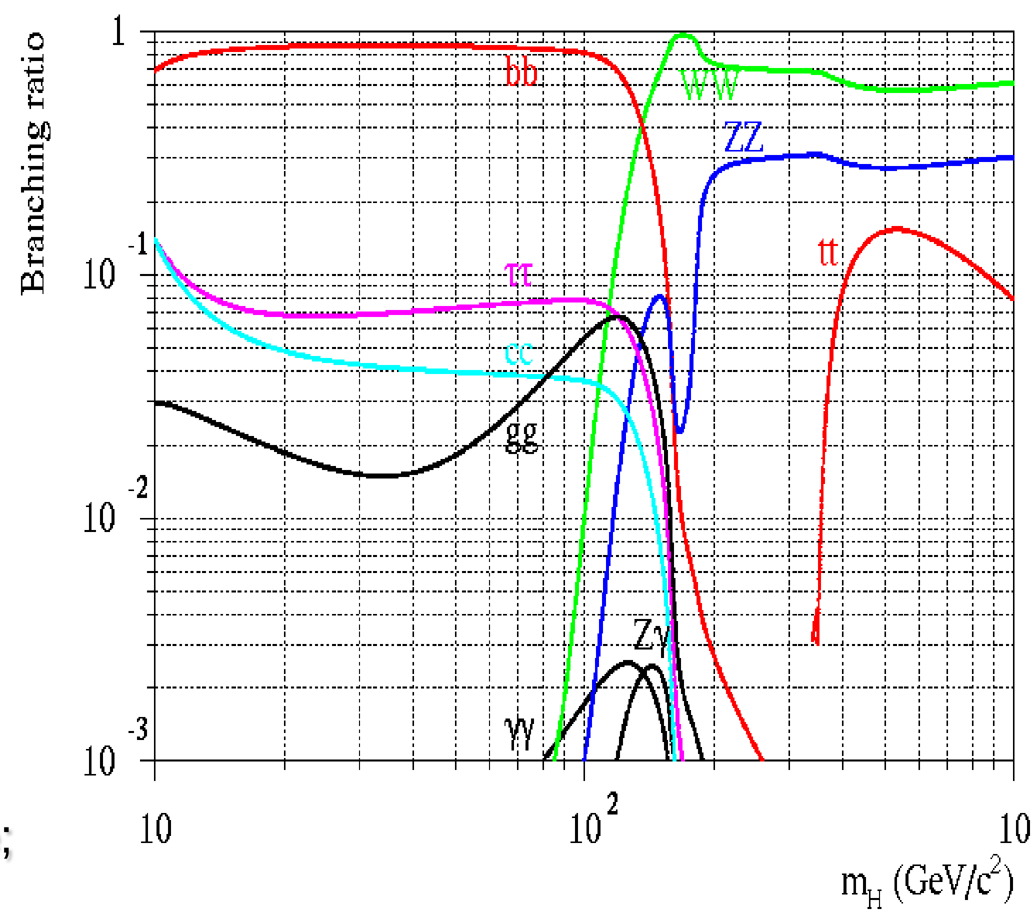
- ❑ $m_H < 2m_\mu$: $H \rightarrow e^+e^-$ dominates;
- ❑ $m_H < 2m_\pi$: $H \rightarrow \mu^+\mu^-$ dominates;
- ❑ $m_H <$ 3 - 4 GeV: $H \rightarrow gg$ dominates;



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

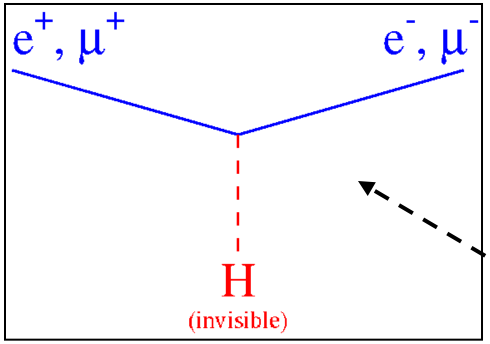
- ❑ $m_H < 2m_b$: $H \rightarrow \tau^+\tau^-$ and $c\bar{c}$ dominate;

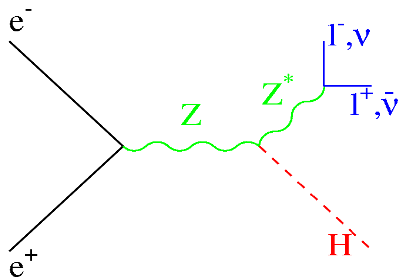
- ❑ $m_H > 2m_b$ up to 1000 GeV/c^2:



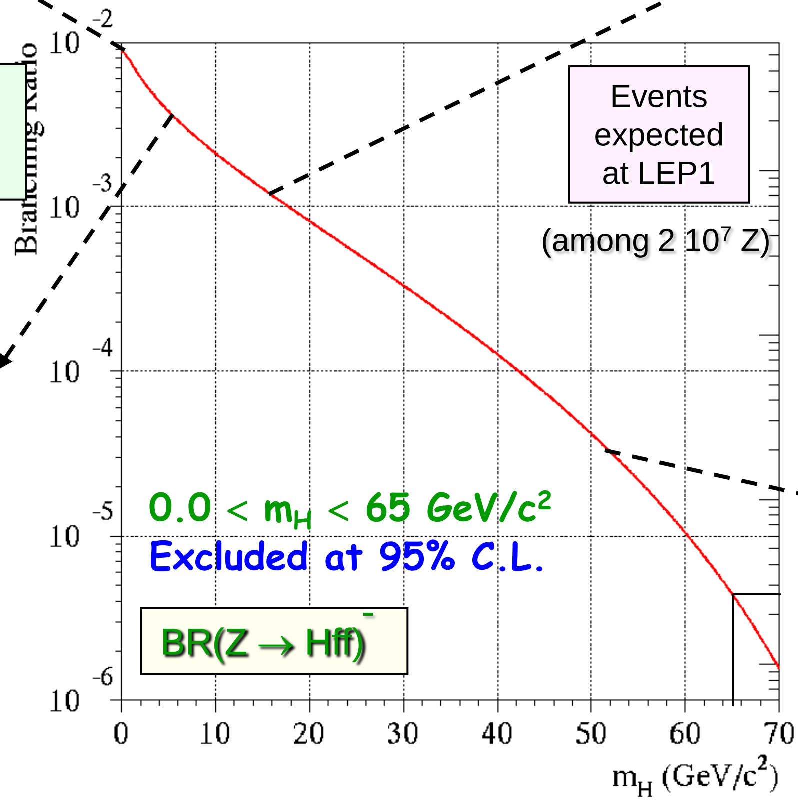
Direct Searches at LEP 1

Very little background expected

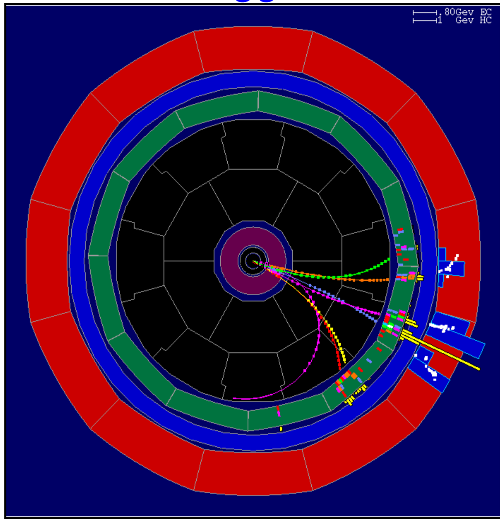




Acoplanar lepton pairs from Z^* and H invisible

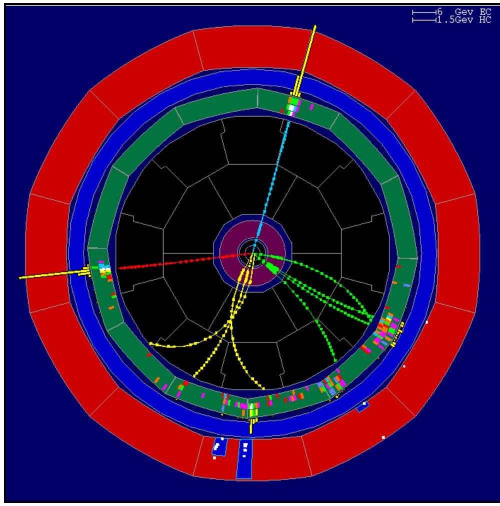


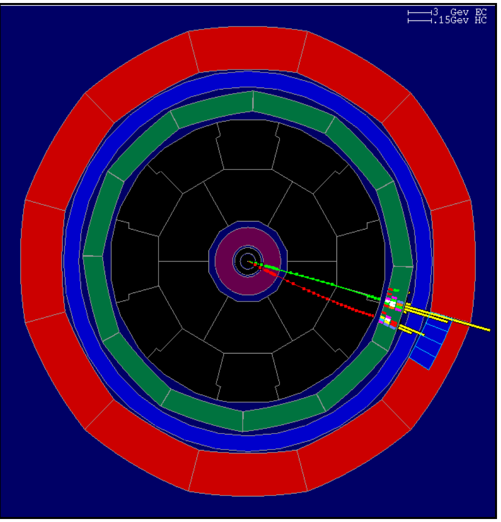
For $m_H < 2m_b$:
$H \to gg, cc, \tau\tau$



Monojets

Acoplanar jets





Acoplanar pairs from H decay

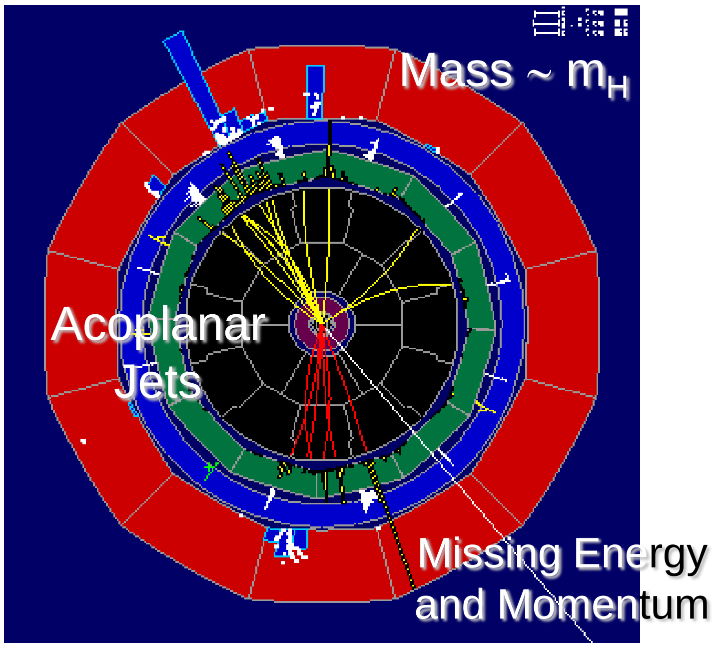
For $m_H < 2m_\pi$:
$H \to ee, \mu\mu$

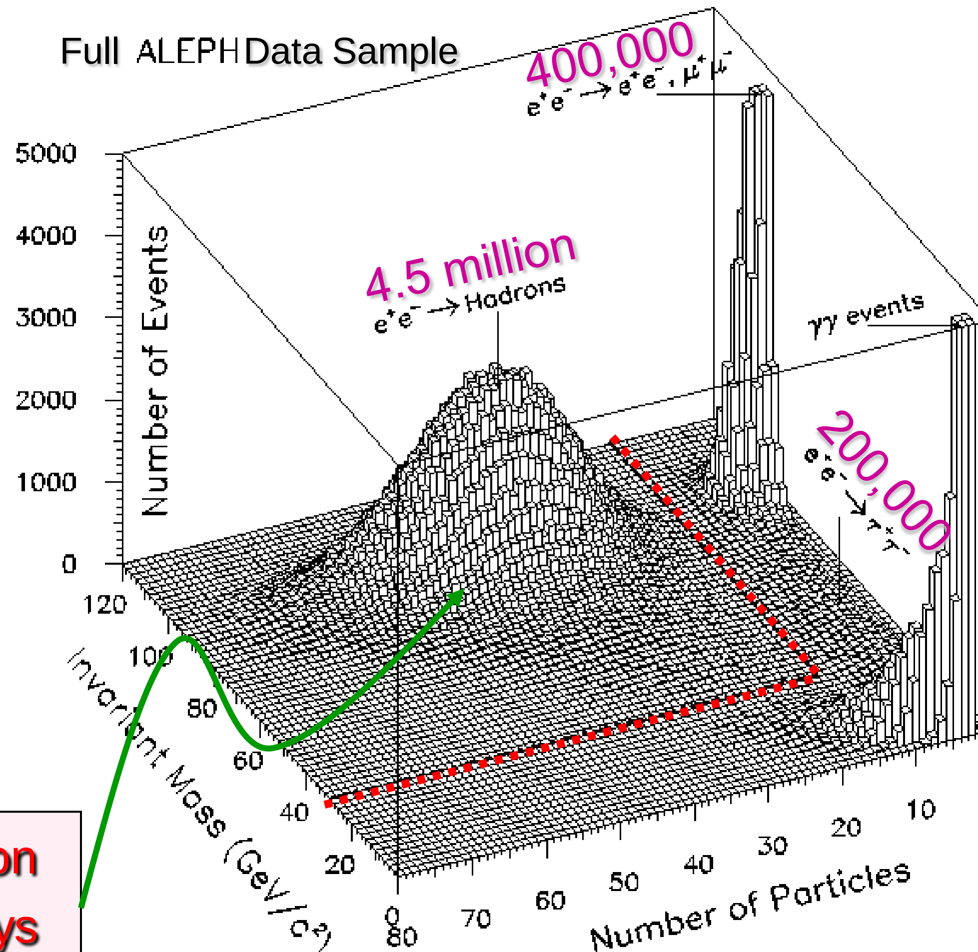
For $m_H < 2m_b$:
$H \to gg, cc, \tau\tau$

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

20 $H\bar{\nu}\nu$ events to be looked for

(4 expts, if m_H = 65 GeV/c^2)



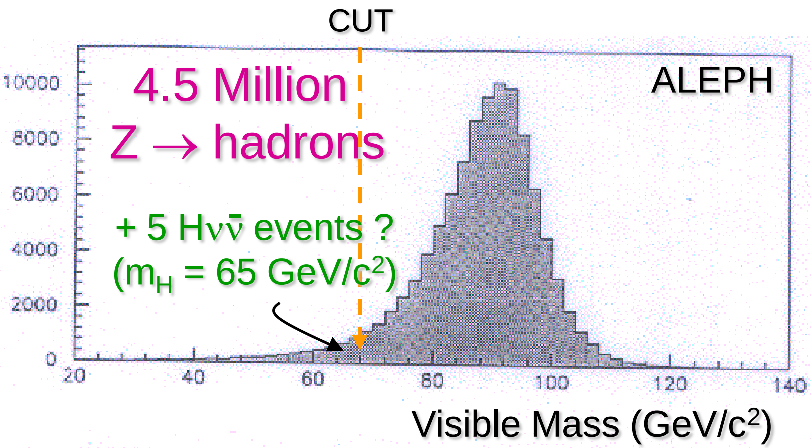


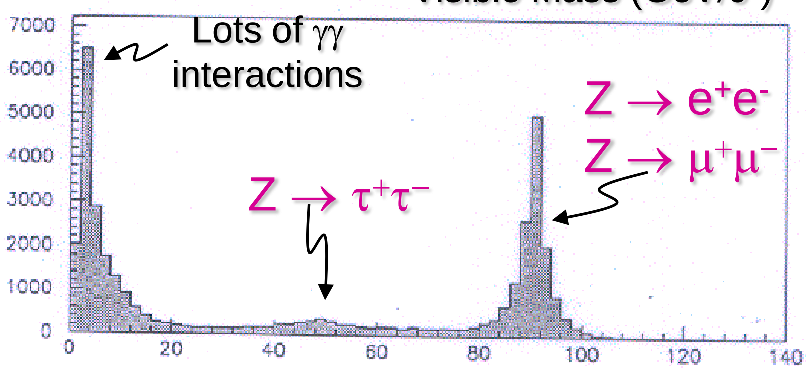
Within more than 20 million other events from Z decays (or from other processes)

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

Two main subsamples:

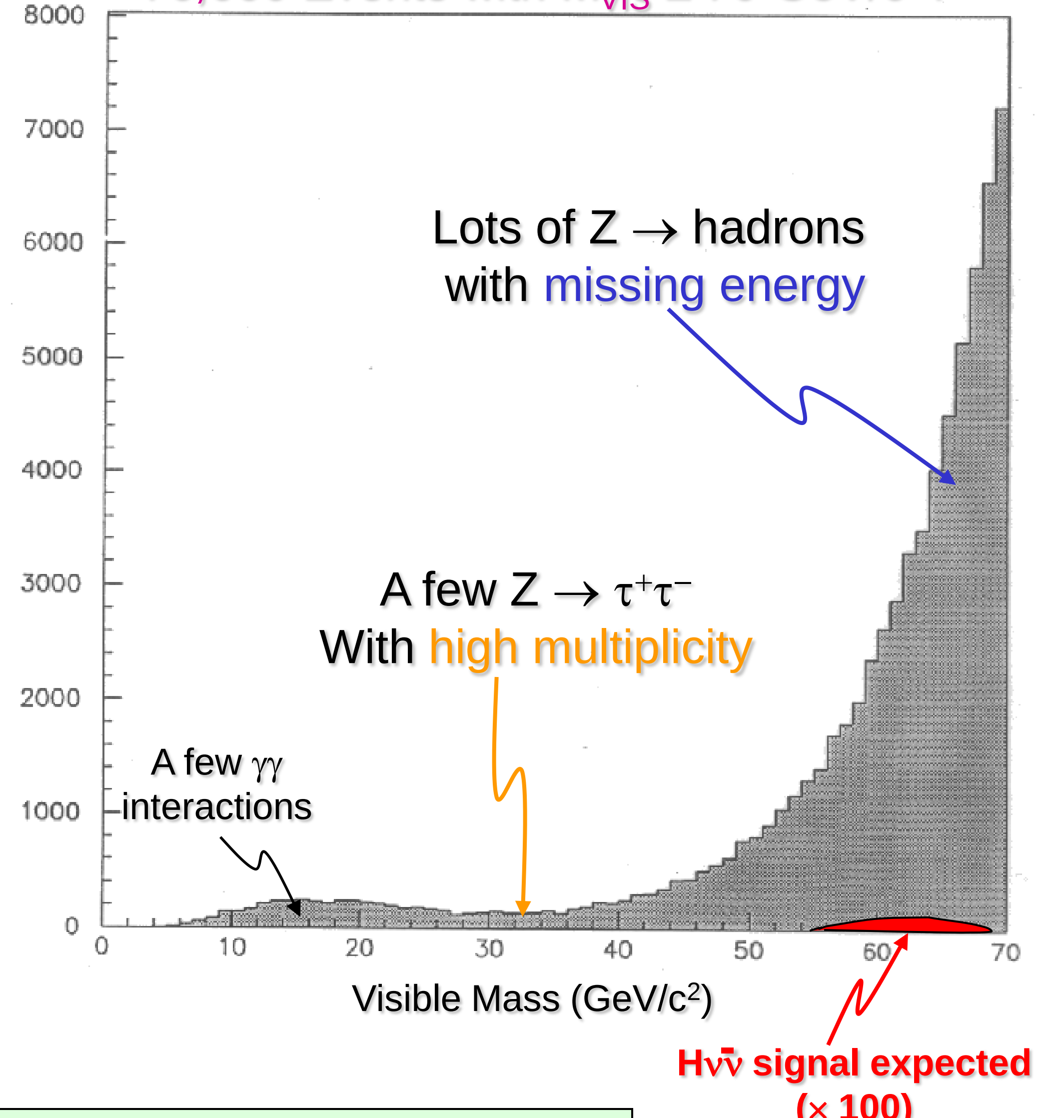
1) High Multiplicity (Selected)





2) Low Multiplicity (Rejected)

70,000 Events with $M_{VIS} \leq 70$ GeV/c² :



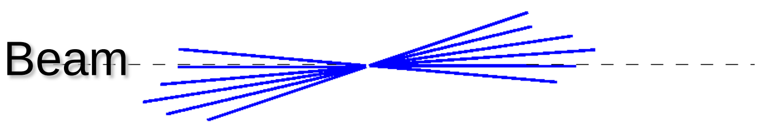
Origin of missing energy in $Z \to$ hadrons ?

Energy Losses :

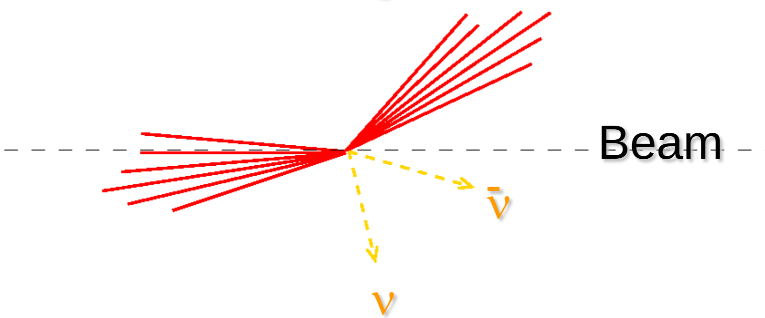
in the beam pipe

$Z \rightarrow q\bar{q}$ events:

Two back-to-back jets



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



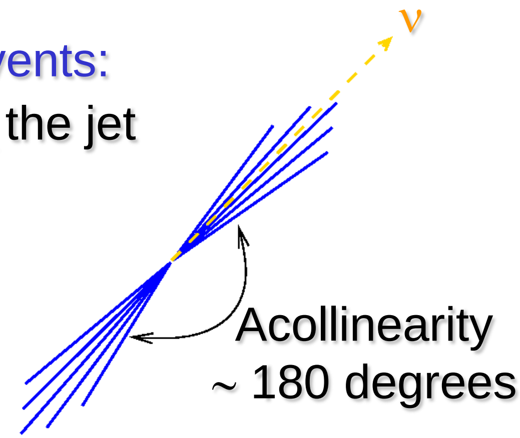
$X_{30} \geq 60\%$

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

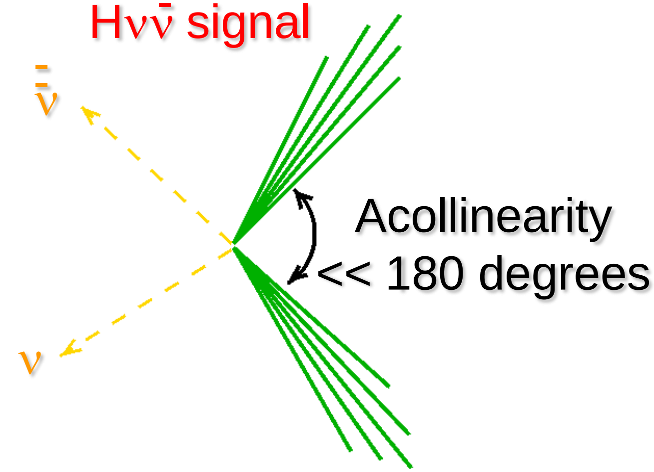
in Semi-Leptonic b decays

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

The ν is <u>in</u> the jet



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



Acoll. $\leq$ 165 deg.

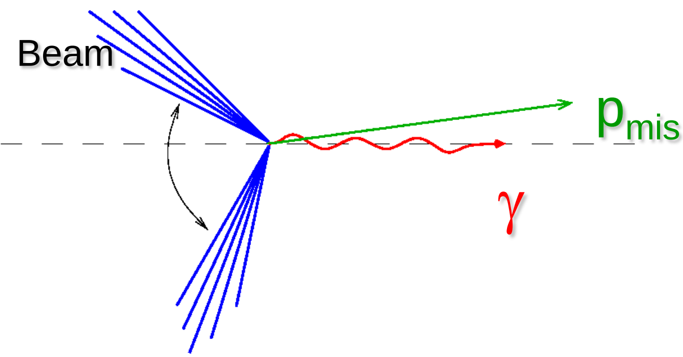
Energy Losses due to I.S.R.

(Initial State Radiation)

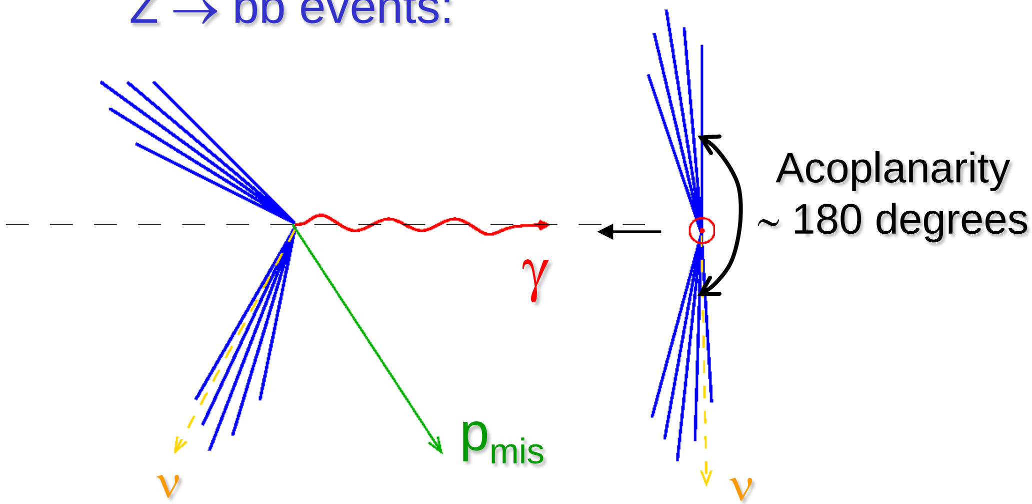
(+ Semi-Leptonic b decay)

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

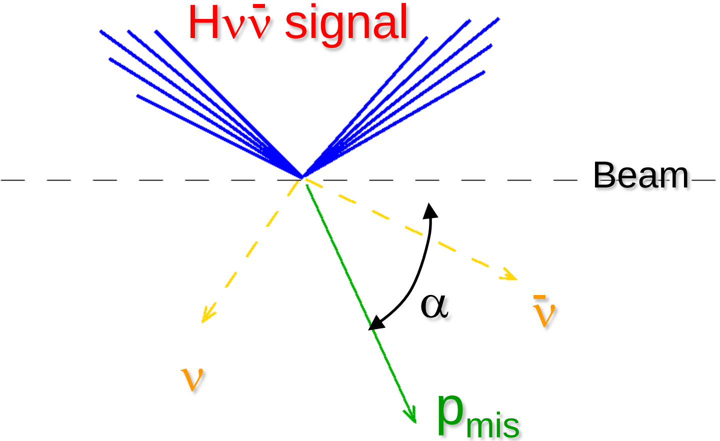
The p_{mis} is along the beam



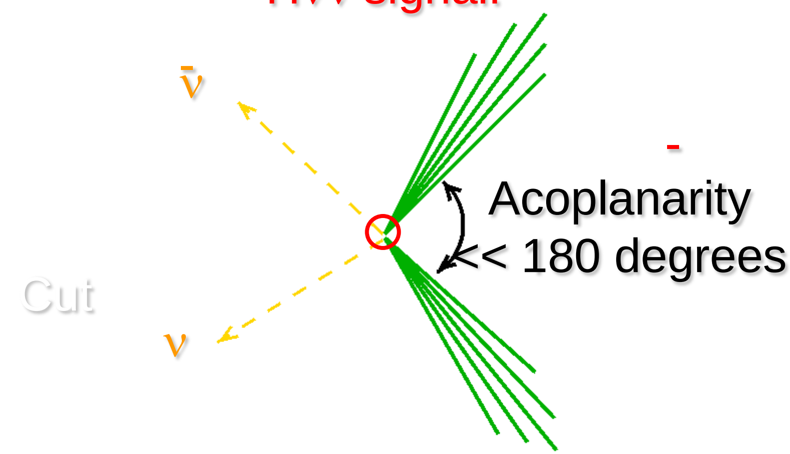
$Z \rightarrow b\bar{b}$ events:



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



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



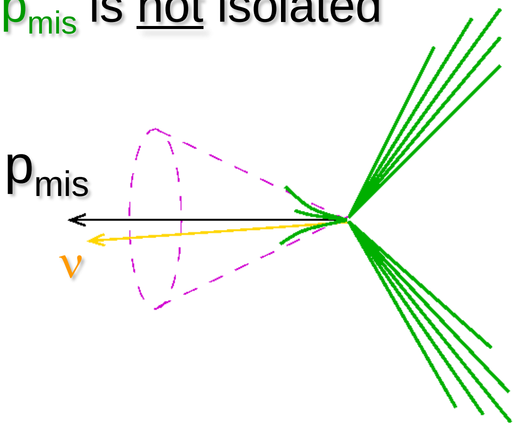
$\tan\alpha \geq 0.4$

Acop. $\leq$ 175 deg.

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

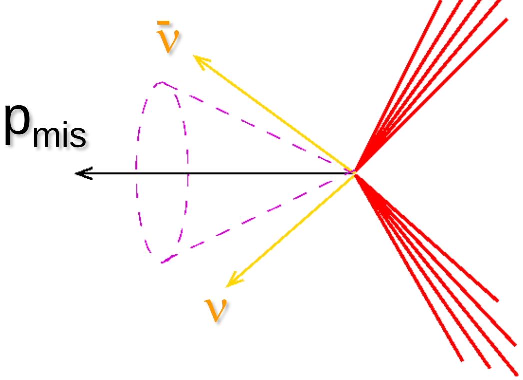
$Z \to b\bar{b}g$ events:

The p_{mis} is not isolated



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

The p_{mis} is isolated

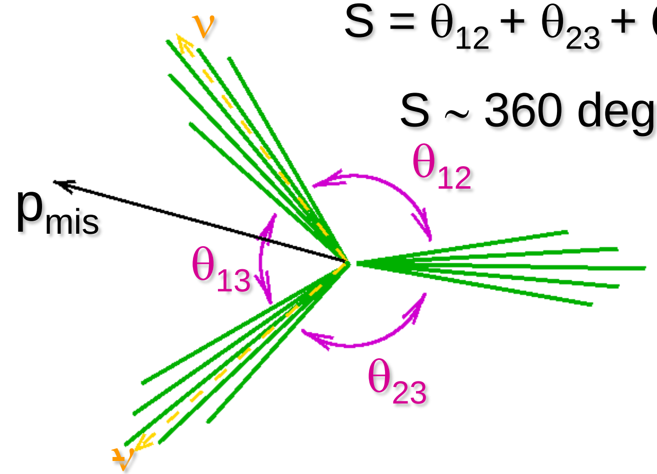


$E_{CONE} \leq 1$ GeV

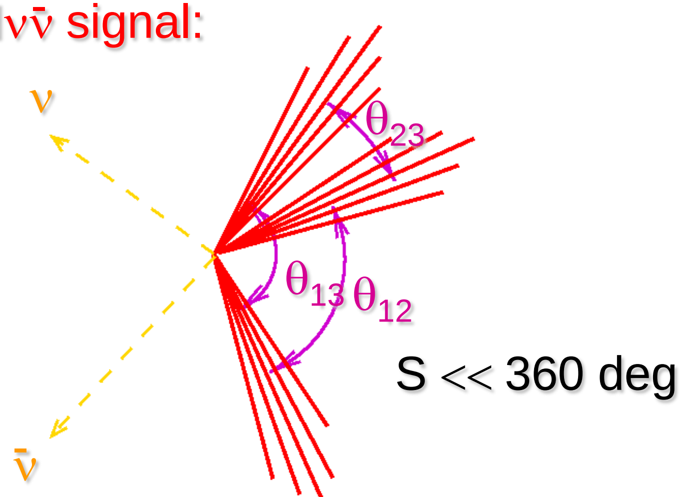
E_{CONE} (GeV) = Energy contained in a cone of half-angle 30 degrees around p_{mis}

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

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



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

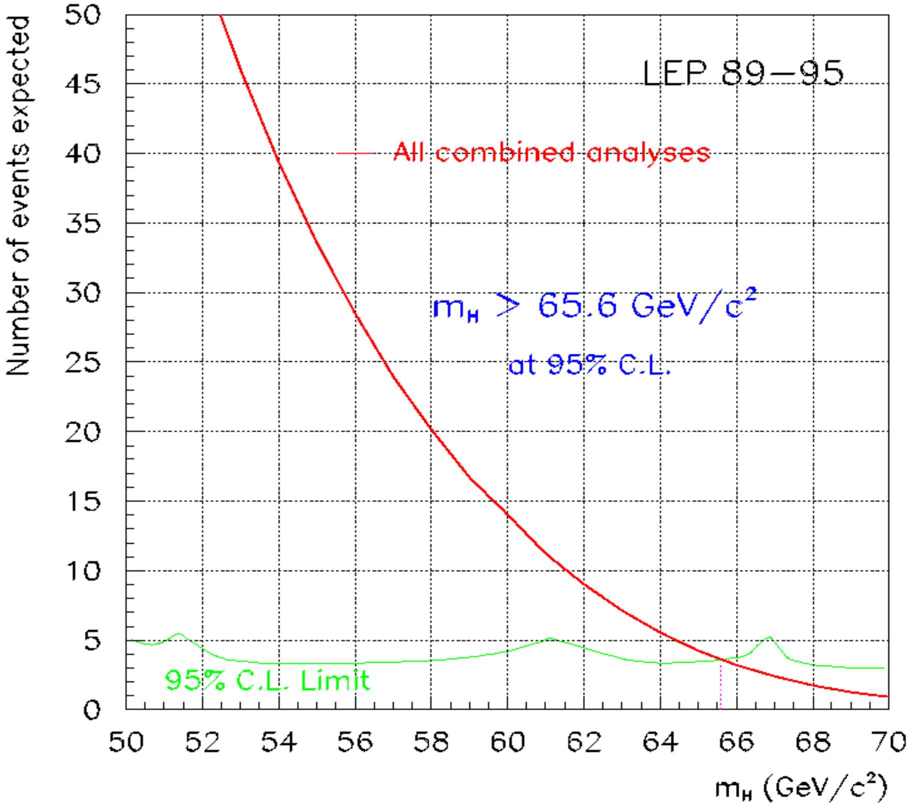


$S \leq 342$ degrees

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

Higgs Boson Searches at LEP 1: Result

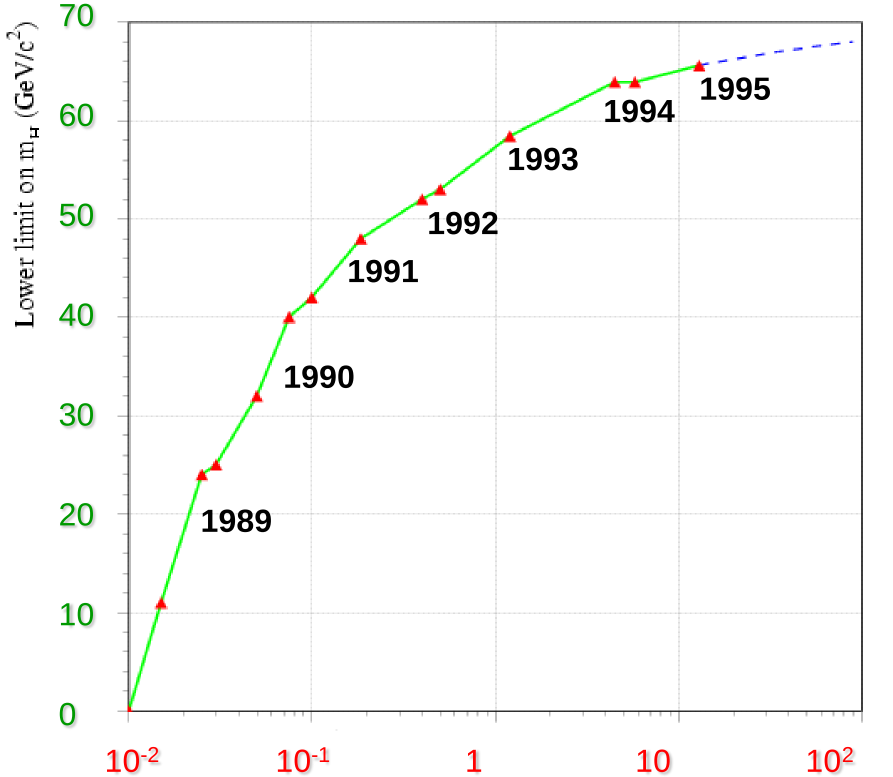
With the 4 LEP expts combined, 4.0 signal events were expected. None were observed.



$0.0 < m_H < 65.6$ GeV/c^2

Excluded at 95% C.L.

Saturation was being reached:



GO FOR LEP 2 !

Search for the SM Higgs at LEP 200

- LEP: e+e- collider at CERN
  four experiments: ALEPH, DELPHI, L3, OPAL
- LEP1: 1989-1995, $\sqrt{s}$=91 GeV,
  precision measurement of Z boson parameters
- LEP2: 1995-2000, $\sqrt{s}$ =130-208 GeV

year	‘95	‘96	‘97	‘98	‘99	2000
$\sqrt{s}$	130-136	161-172	183	189	192 196 200 202	204 205 207 208
Lum (pb^{-1})	3 3	11 11	55	160	25 80 80 40	9 72 130 8
Lum x4 exp	24	88	220	640	900	875

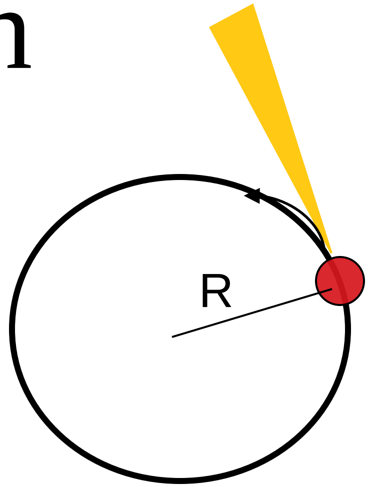
>2.5 fb^{-1} @ E_{cm}>180 GeV

Synchrotron Radiation

- Energy loss per revolution

$$\Delta E = \frac{e^2}{3\varepsilon_0} \frac{\beta^3 \gamma^4}{2\pi R} \qquad \beta = \frac{\mathrm{v}}{c} \qquad \gamma = \frac{\mathrm{E}}{m} \qquad R = \text{orbit radius}$$

$$\Delta E[GeV] = 5.7 \times 10^{-7} \frac{E^4[GeV]}{R[km]}$$



- Example : LEP, $2\pi R$=27km, E=100 GeV (in 2000)
  - **ΔE = 2 GeV!!**
  - LEP at limit, need more and more energy just to compensate energy loss

- Note : for ultrarelativistic protons/electrons ($\beta \simeq 1$)

$$\Delta E[p] / \Delta E[e] = (m_e/m_p)^4 = \mathbf{10^{-13}\ !!}$$

Beam Energy increases in LEP

Energy Loss per Turn $\propto E^4/\rho$ (Synchrotron Radiation)

Maximum Beam Energy $\propto$ [RF Voltage $\times$ Bending Radius]$^{1/4}$

- Increase RF Voltage;

  (130 MV for E = 45.6 GeV;

  $\geq$ 3 GV for E = 100 GeV;

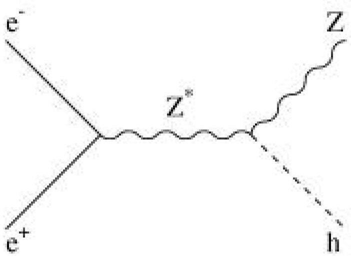
  $\rightarrow$ Go for SC RF Cavities)

- Increase Bending Radius!
- Or increase both.

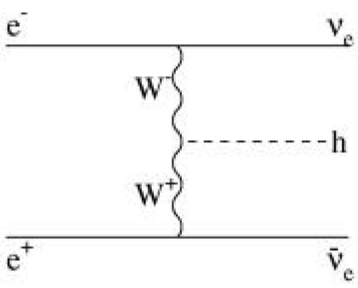
Year	√s (GeV)	# Cu Cavities	# SC Cavities	RF (MV)
1989-95	m_Z	128	None	180
1996	161 172	128	144 176	1600 2000
1997	183	52	240	2500
1998	189	52	272	2850
1999	192 196 200 202	48	288	3000 ↓ ↓ 3550
2000	205 ↓ 209.2	56	288	3650

Higgs searches at LEP 200

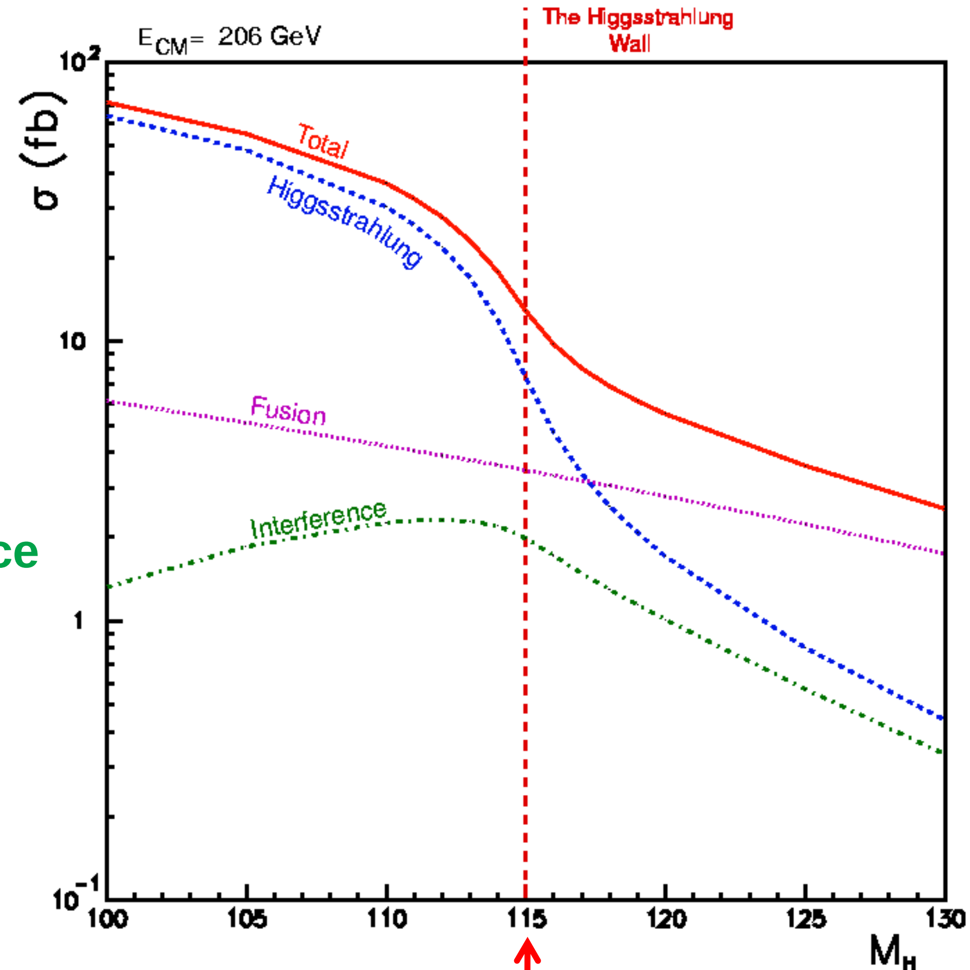
Higgsstrahlung
(dominant mode)



WW fusion



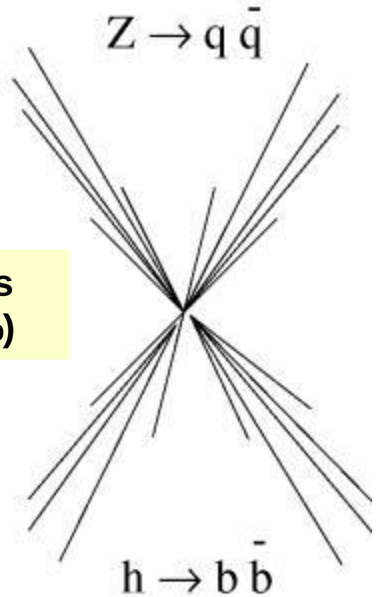
+ positive interference

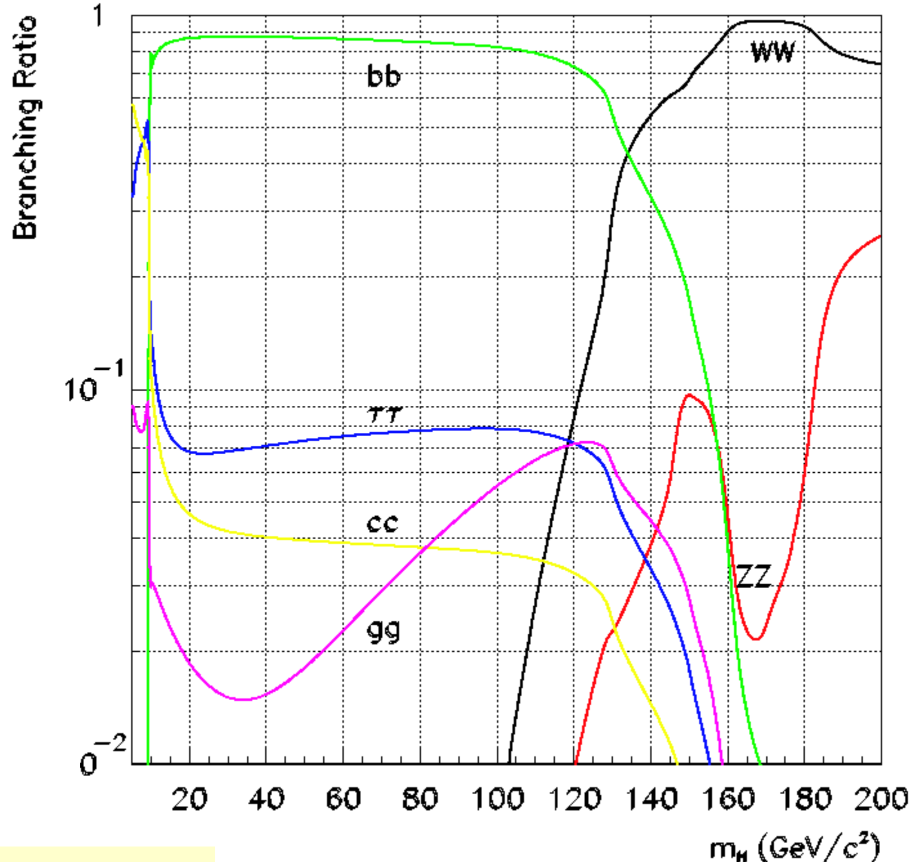


$M_H \leq \sqrt{s} - M_Z$

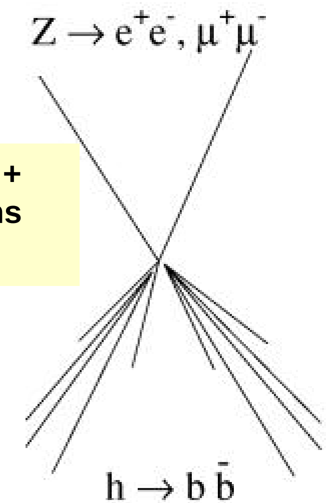
Higgs searches at LEP 200

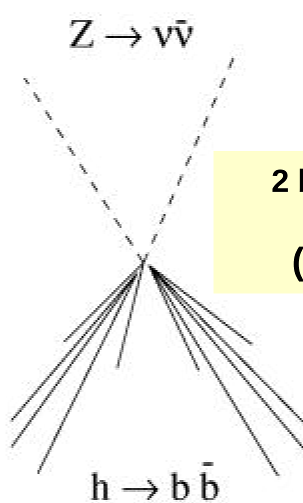
4 jets
(60%)





2 b-jets +
2 leptons
(6%)



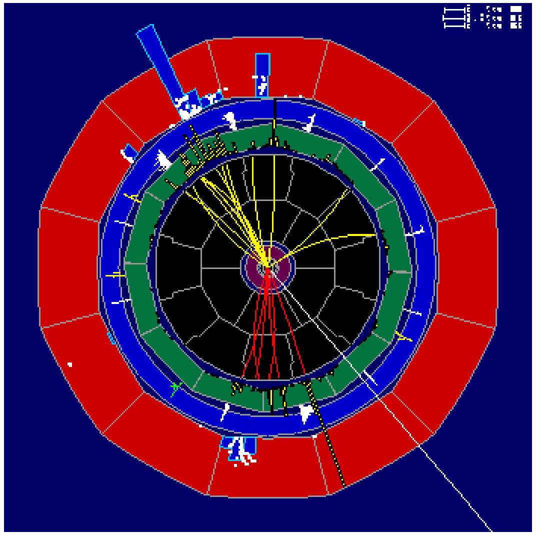


2 b-jets +
MET
(19%)

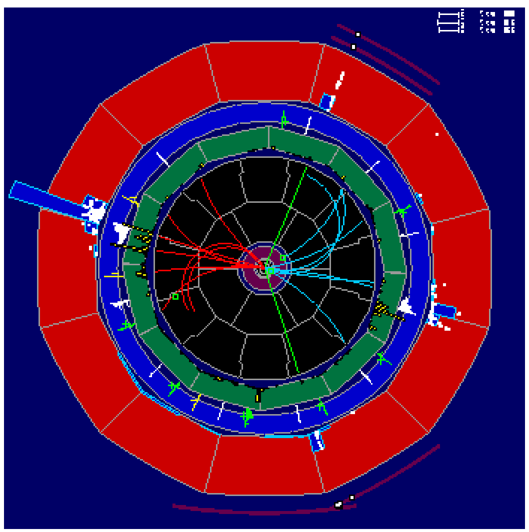
+ a contribution (7%) h → $\tau\tau$ (also WW*, gg)

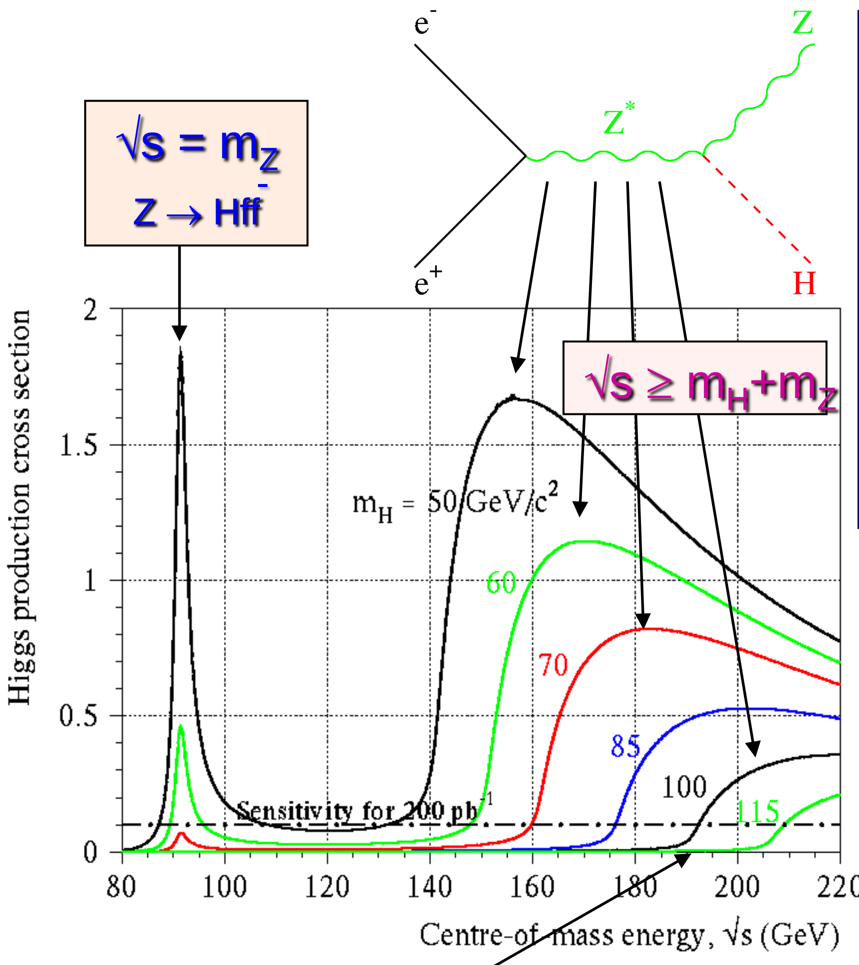
Direct Searches at LEP 2

$H\nu\bar{\nu}$

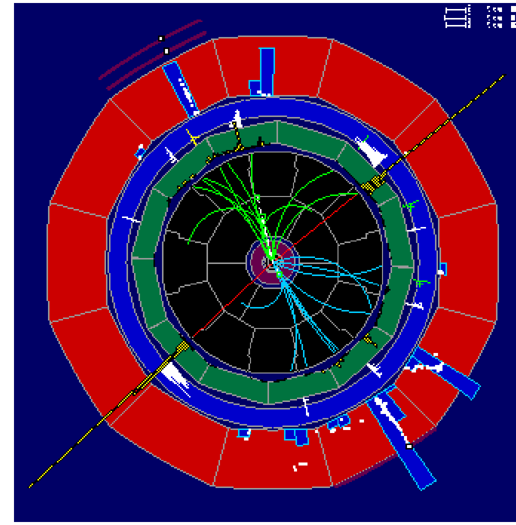


$H\mu^+\mu^-$

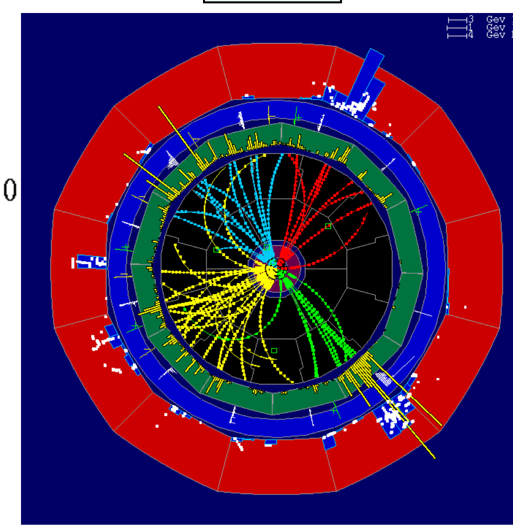




He^+e^-



$Hq\bar{q}$



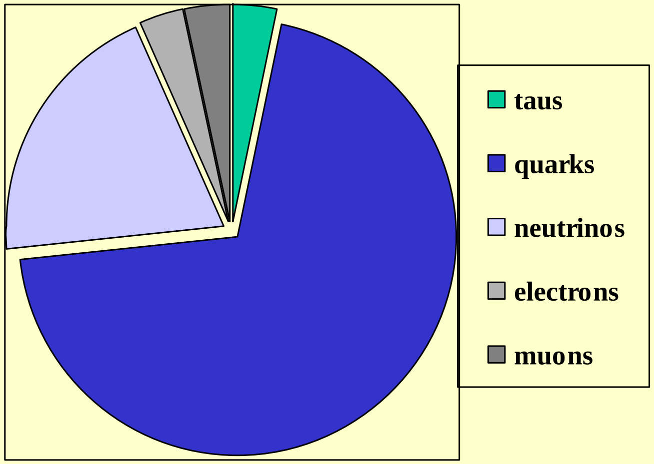
5σ sensitivity for 200 pb^{-1}:

- $\sqrt{s}$ = 192 GeV for m_H = 100 GeV/c^2;
- $\sqrt{s}$ = 210 GeV for m_H = 115 GeV/c^2;

Event Signatures

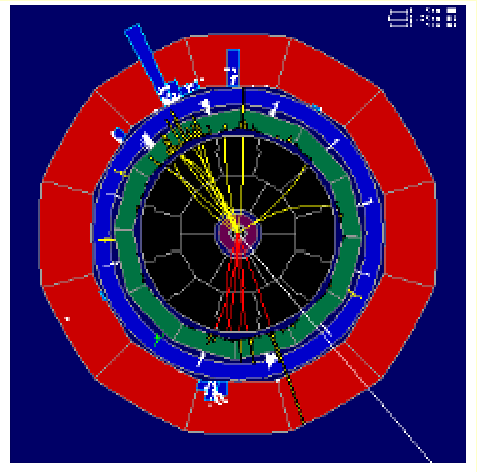
Defined by the Z decay mode:

Higgs	*Z*	*Fraction*
bb	*qq*	**51.5%**
bb	$\nu\nu$	**14.7%**
Any	*ll*	**6.7%**
bb	$\tau\tau$	**2.5%**
$\tau\tau$	*qq*	**5.0%**
Total		**80.9%**



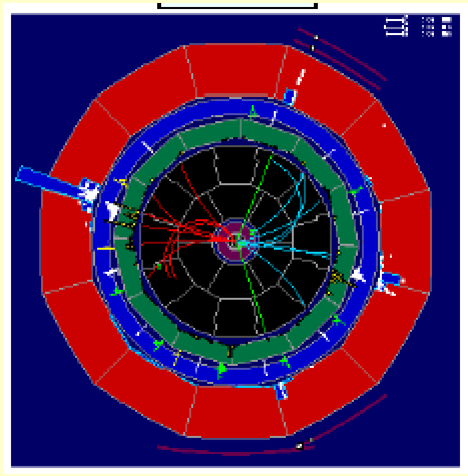
"missing E"

$H\nu\overline{\nu}$

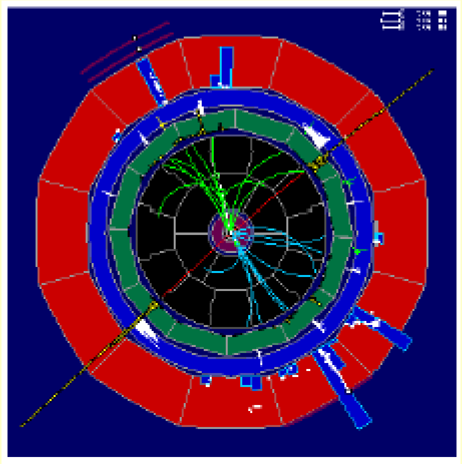


"leptons"

$H\mu^+\mu^-$

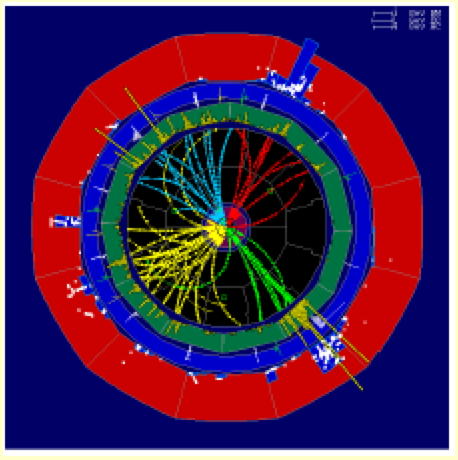


He^+e^-



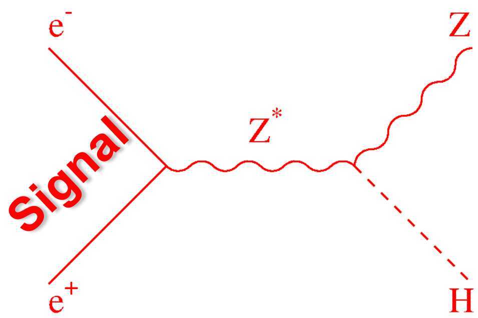
"4-jets"

$Hb\overline{b}$



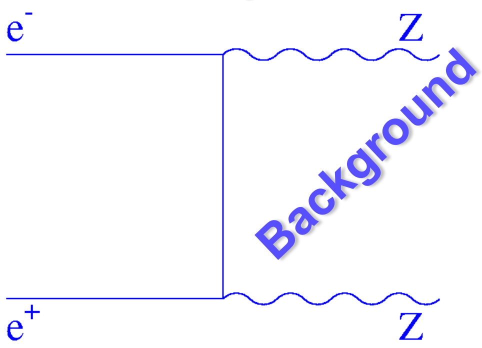
Signal vs Background (I)

$e^+e^- \to HZ$
$\sigma = 0.1$ pb



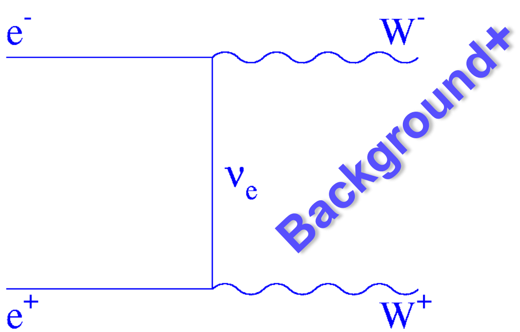
Must evaluate the "signal-ness", s/b, of the candidate events

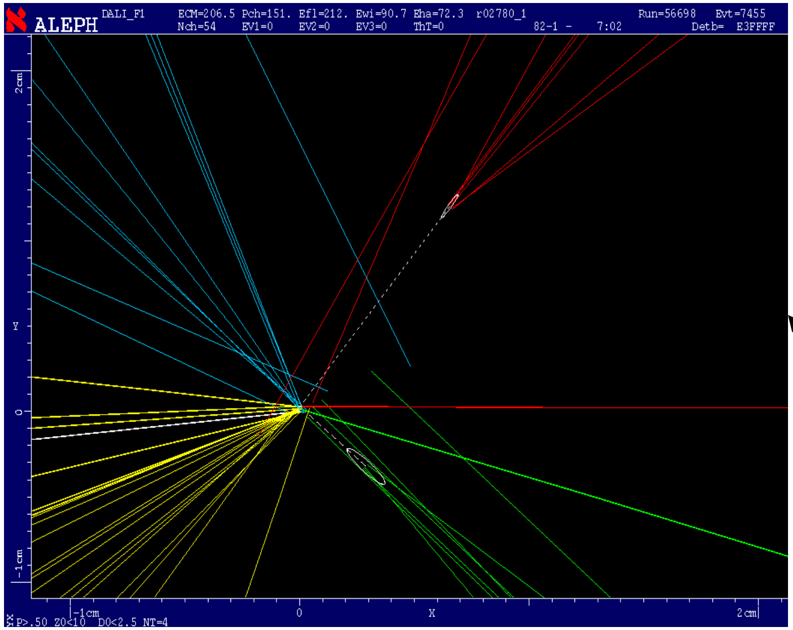
$e^+e^- \to ZZ$
$\sigma \sim 2$ pb



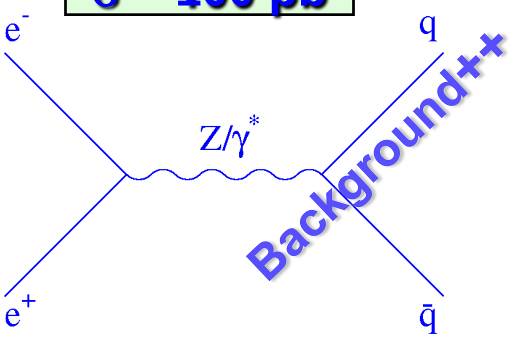
- Reconstructed Higgs boson mass;
- Other kinematic variables;
- b-tagging (lifetime, leptons, …);

$e^+e^- \to W^+W^-$
$\sigma \sim 20$ pb





$e^+e^- \to q\bar{q}$
$\sigma \sim 100$ pb



Zoom of ±1cm around the interaction point

Higgs searches at LEP

$e^+e^- \rightarrow H\,Z$
Very small cross section
+
huge background

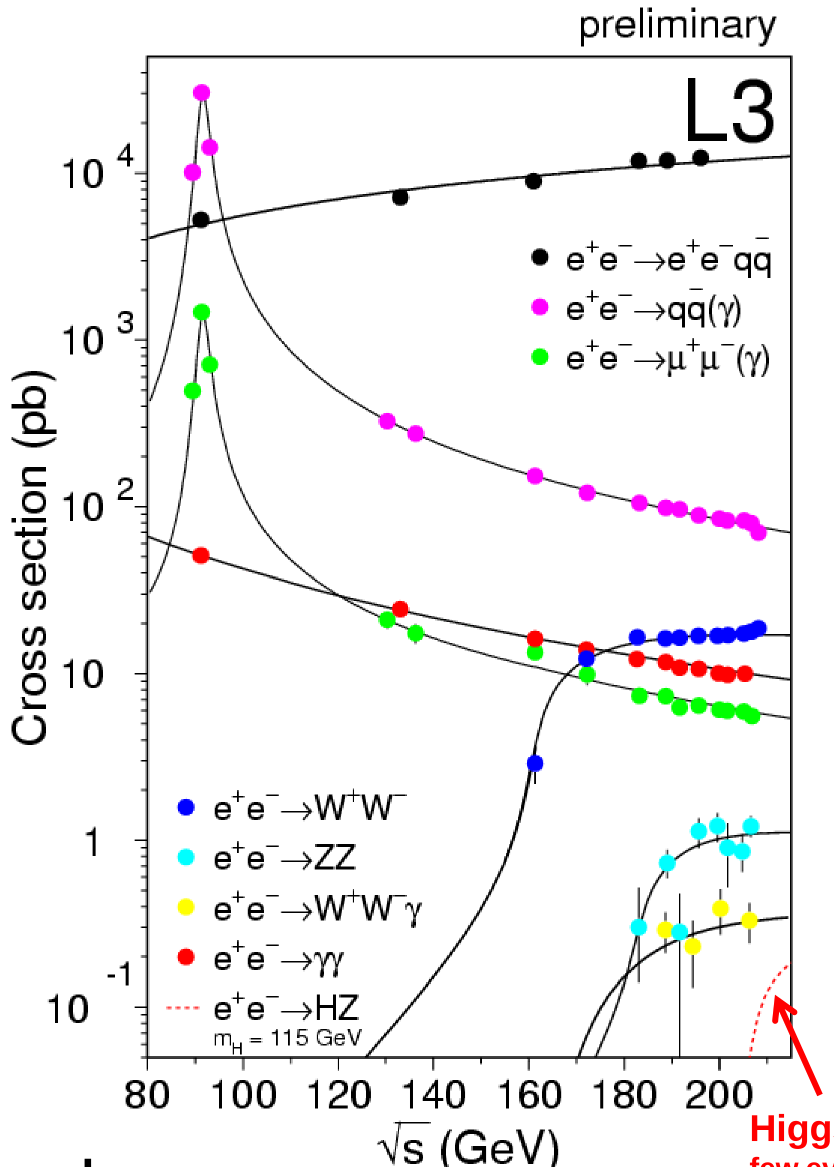
$H \rightarrow b\,b^{bar}$
$\rightarrow$ b tagging crucial
$\rightarrow$ microvertex detector needed

$Z \rightarrow qq^{bar}$ 4 jets
pairing of the jets is a problem:
two jets forced to the Z mass

$Z \rightarrow \nu\nu^{bar}$ missing energy
$\rightarrow$ detector hermeticity
$\rightarrow$ energy flow

$Z \rightarrow \ell^+\,\ell^-$
very clean but low rate

$e^+e^- \rightarrow$ WW: dominant in 4 jets
$e^+e^- \rightarrow$ Z Z : irreducible background



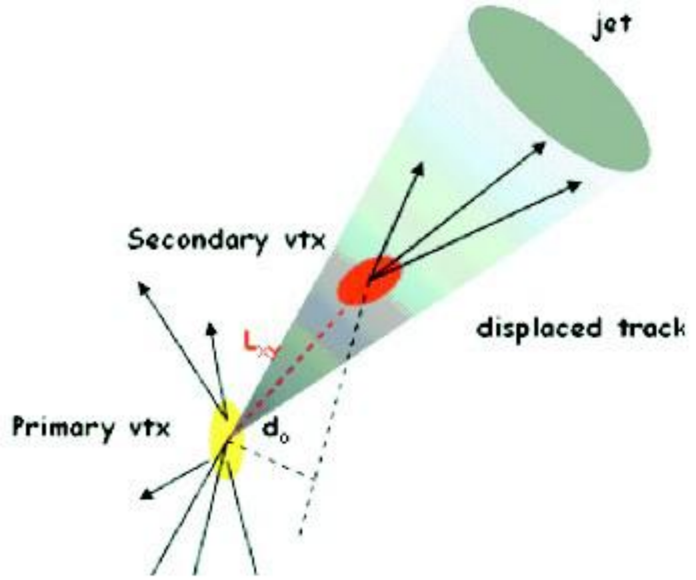
Higgs of 115 GeV/c^2
few events expected
with the 2.5 fb^{-1} integrated Lumi

b tagging

- b-tagging is crucial for Higgs searches at LEP

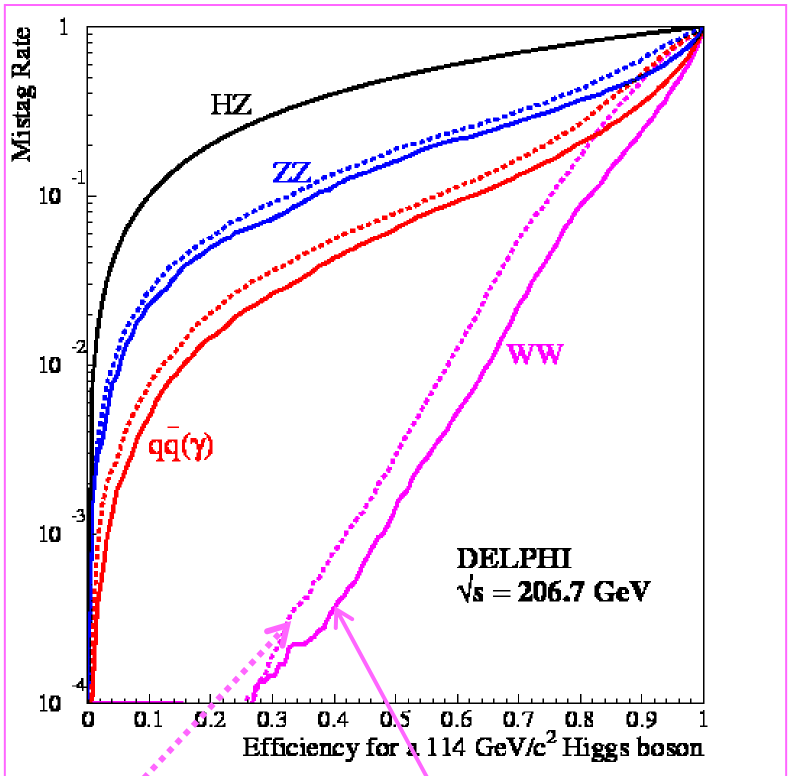
  B hadron properties can be exploited to tag b-jets:

- long B lifetime (1.57±0.01 ps)
  - Can travel few millimeters before the decay
  - Secondary vertex displaced few millimeters from the interaction vertex
- high mass (~ 5.2 GeV/c^2)
- high charged decay multiplicity (4.97 ± 0.06)



b-jet tagging at LEP2

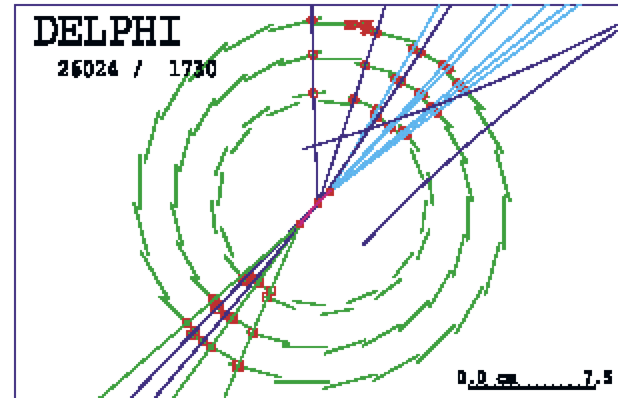
4-jets events

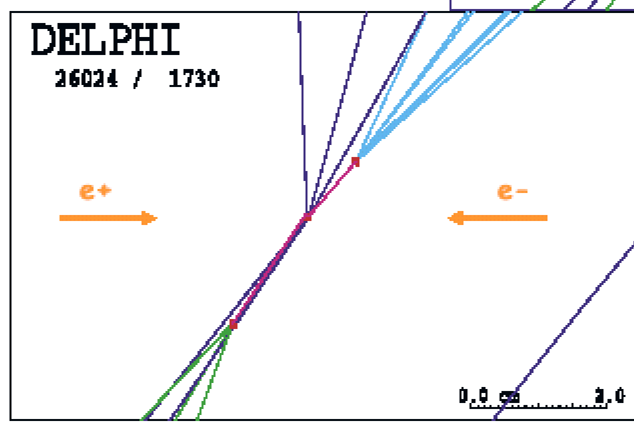


b-tag < 1998 **b-tag > 1999**

Silicon Microvertex detectors !

ee -> Z -> bb





Beam spot size≈120X10 μm
Resolutions on:
Primary vertex ≈ 20X10 μm
Impact Par ≈ 28 μm in Rφ
≈ 35 μm in z

Signal topologies & background...

Four-jet channel:

$Z \to qq$ $H \to bb$

70% x 80% > 50%

Kinematics & b-tag

→

ZZ "irreducible background"

$Z \to qq/\nu\nu/ll$ $Z \to bb$

σ ~1 pb (x 30% if bb)

"The Reference"

Missing energy channel:

$Z \to \nu\nu$ $H \to bb$

20% x 80% **> 15%**

Energy flow & b-tag

→

WW background

$WW \to qqqq$ $WW \to qq\tau\nu$

σ ~18 pb

"No b-tag (except Vcb)"

Leptonic channels:

$Z \to ll(e/\mu/\tau)$ $H \to bb$

$Z \to qq$ $H \to \tau\tau$ (70% x 7% **~ 5%**)

Lepton id (& b-tag)

→

Two fermion (Z/γ) background

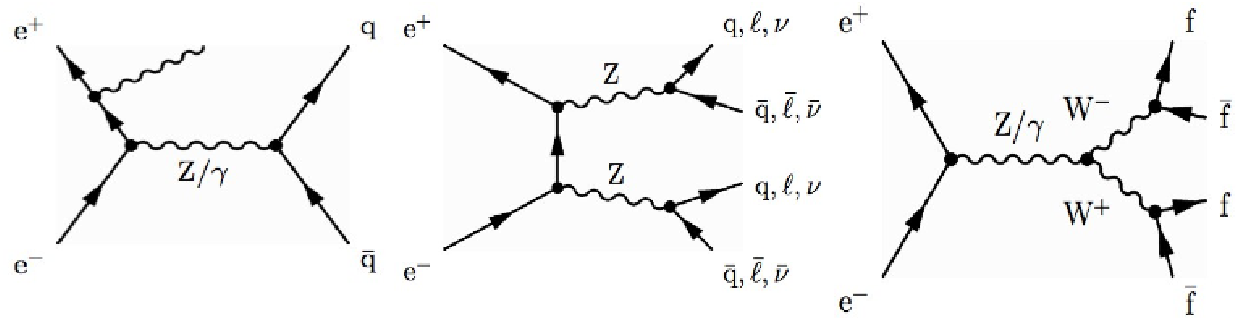
ISR (single/double)

QCD: qq (g)(g)

$$HZ \to b\bar{b}q\bar{q}$$

The 4-jets channel

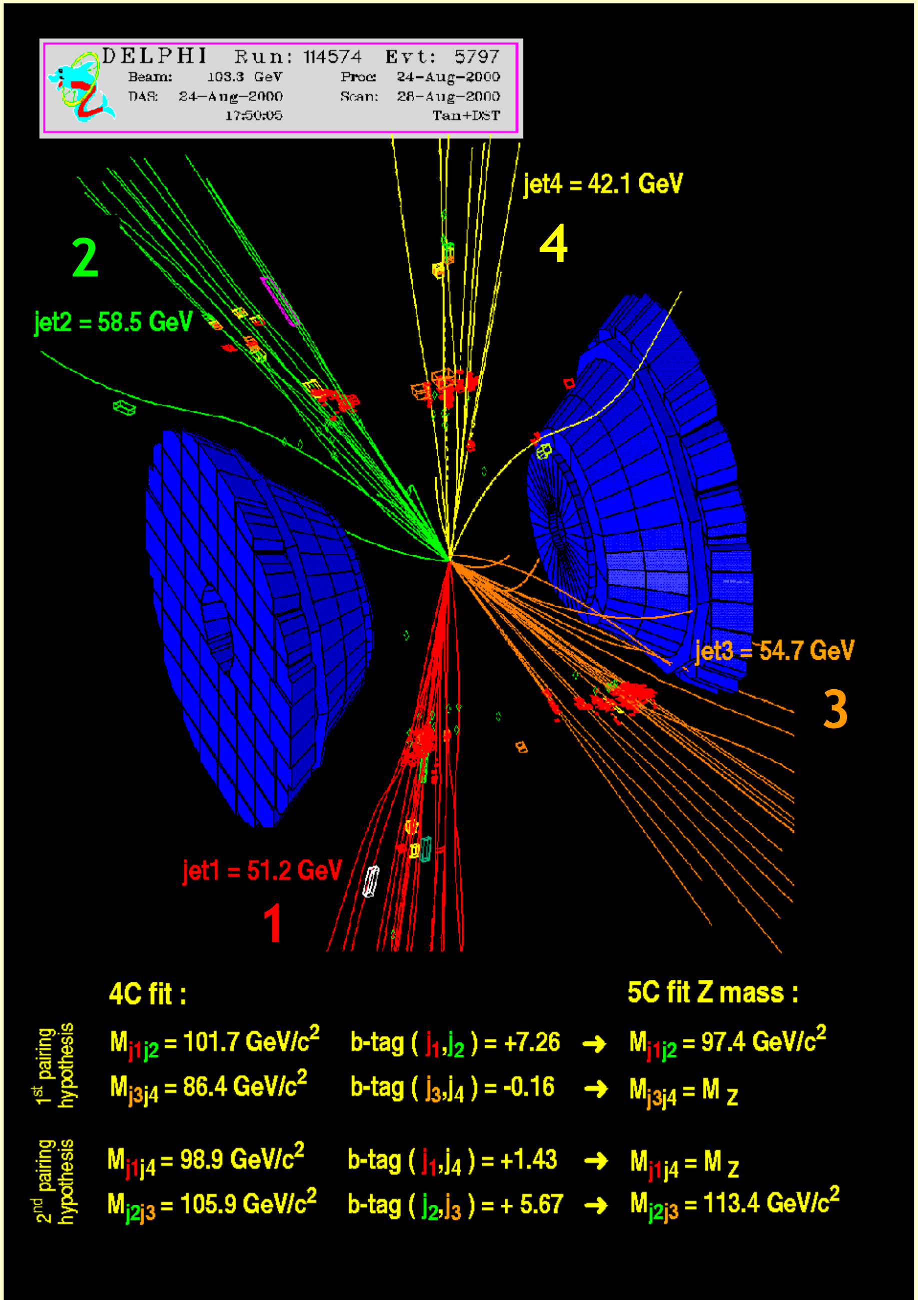
Background from QCD, ZZ, WW



- Problem: 4 jets give 3 mass combinations... L

  Different solutions:
  - asking for a Z recoiling (5Cfit) D,O
  - asking for jet-b-tagging
  - checking the spin of the boson A
  - the best fit with WW,ZZ or HZ hypo: all

But in general, mass ambiguities



from Jesus Marco, Budapest

pairing & mass reconstruction

six possible pairings:

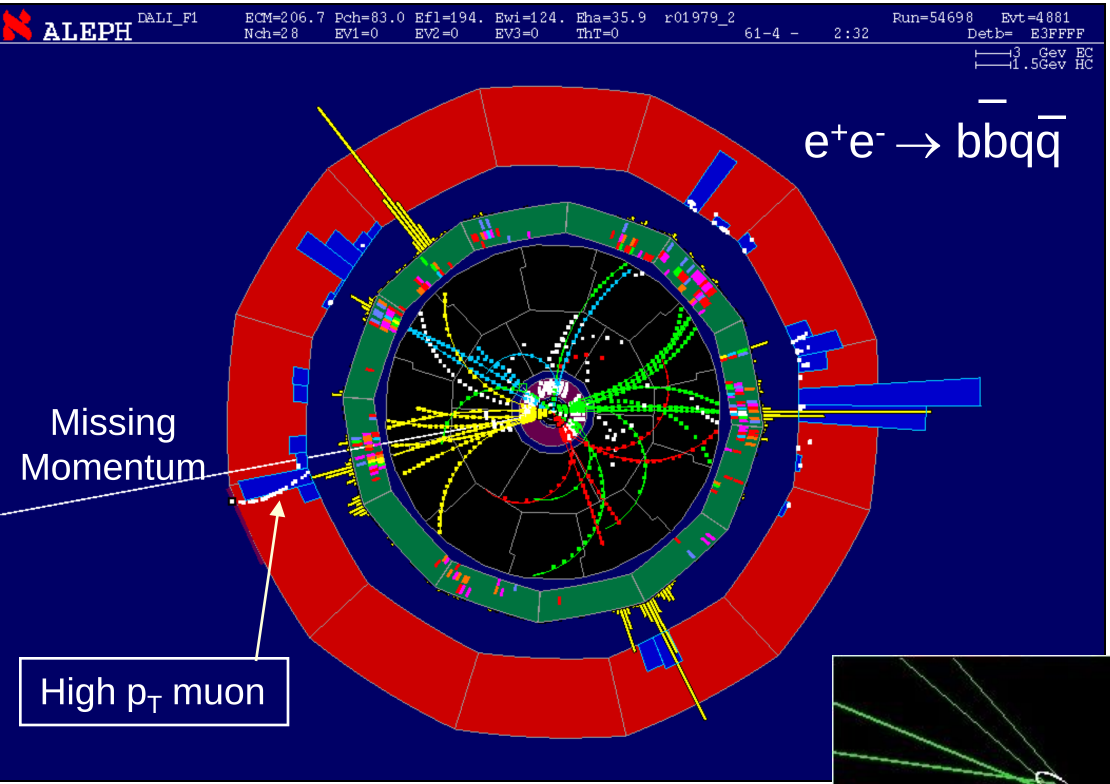
H dijet	(1,2) M=97 B=5.7	(1,3)	(1,4)	(2,3) M=113 B=3.4	(2,4)	(3,4)
Z dijet	(3,4) M=M_Z B=-0.5	(2,4)	(2,3)	(1,4) M=M_Z B=2.0	(1,3)	(1,2)

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

Most likely combination is selected!

A unique mass value is defined

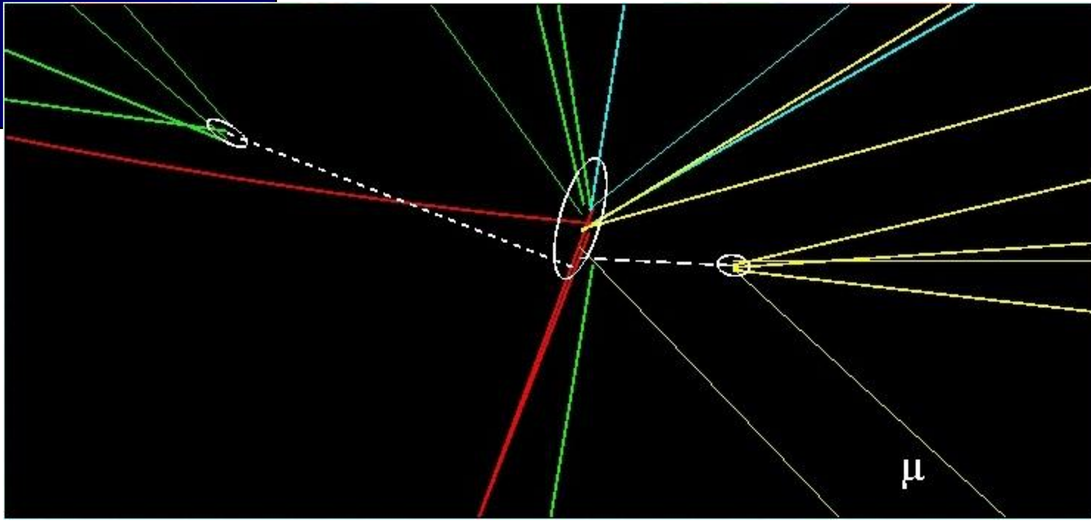
First pb^{-1}'s above 206 GeV: First thrills at 115 GeV/c^2



First Candidate Event (14-Jun-2000, 206.7 GeV)

- Mass 114.3 GeV/c2;
- Good HZ fit;
- Poor WW and ZZ fits;
- P(Background) : 2%
- s/b(115) = 4.7

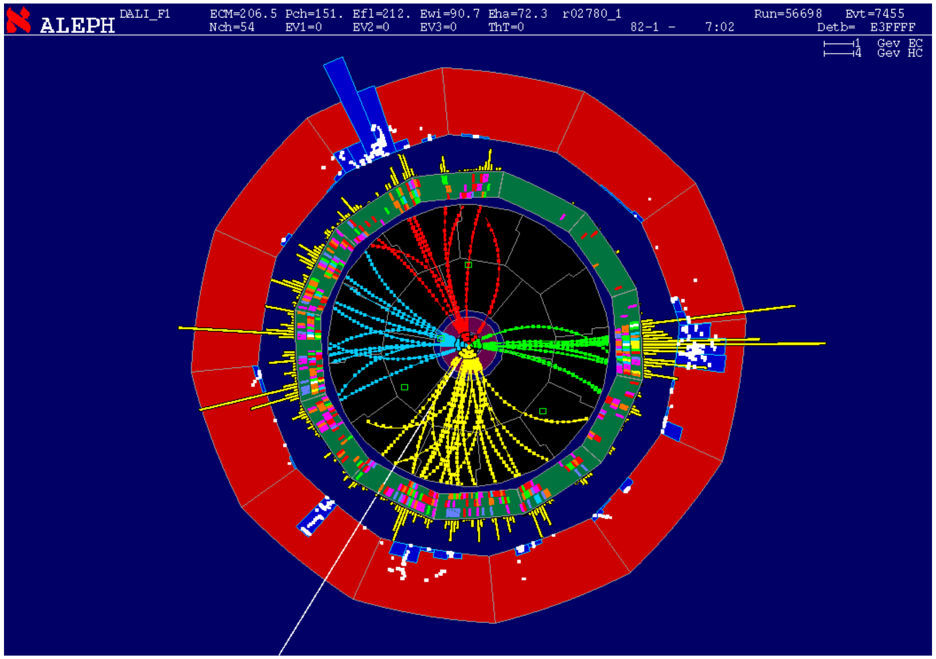
The purest candidate event ever!

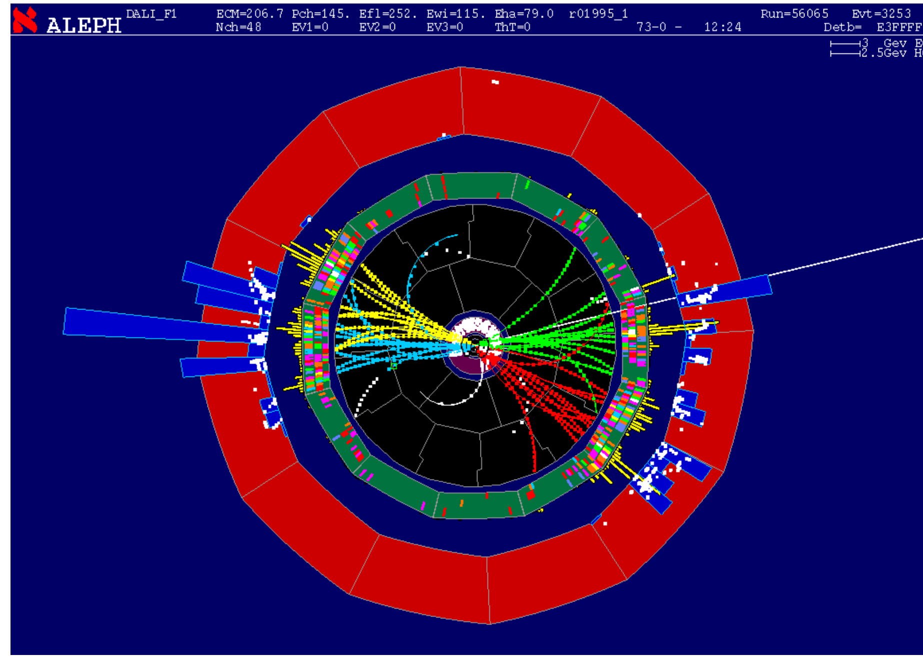


b-tagging
(0 = light quarks, 1 = b quarks)

- Higgs jets: 0.99 and 0.99;
- Z jets: 0.14 and 0.01.

ALEPH: four-jet bbbb candidates





Two strong candidates, m=113, 110 GeV/c^2

"Only" possible background: ZZ (+wrong pairing/undetected ISR)

$H\nu\nu$: an irreducible background $e^+e^- \rightarrow bb^{bar}$

The signal is not collinear:

due to the Z width, even in the Higgstrahlung close to the kinematical limit, the H is not usually produced at rest

but

for acollinearity $< 5^o$

5% of Higgs $\sigma \sim 0.015$ pb

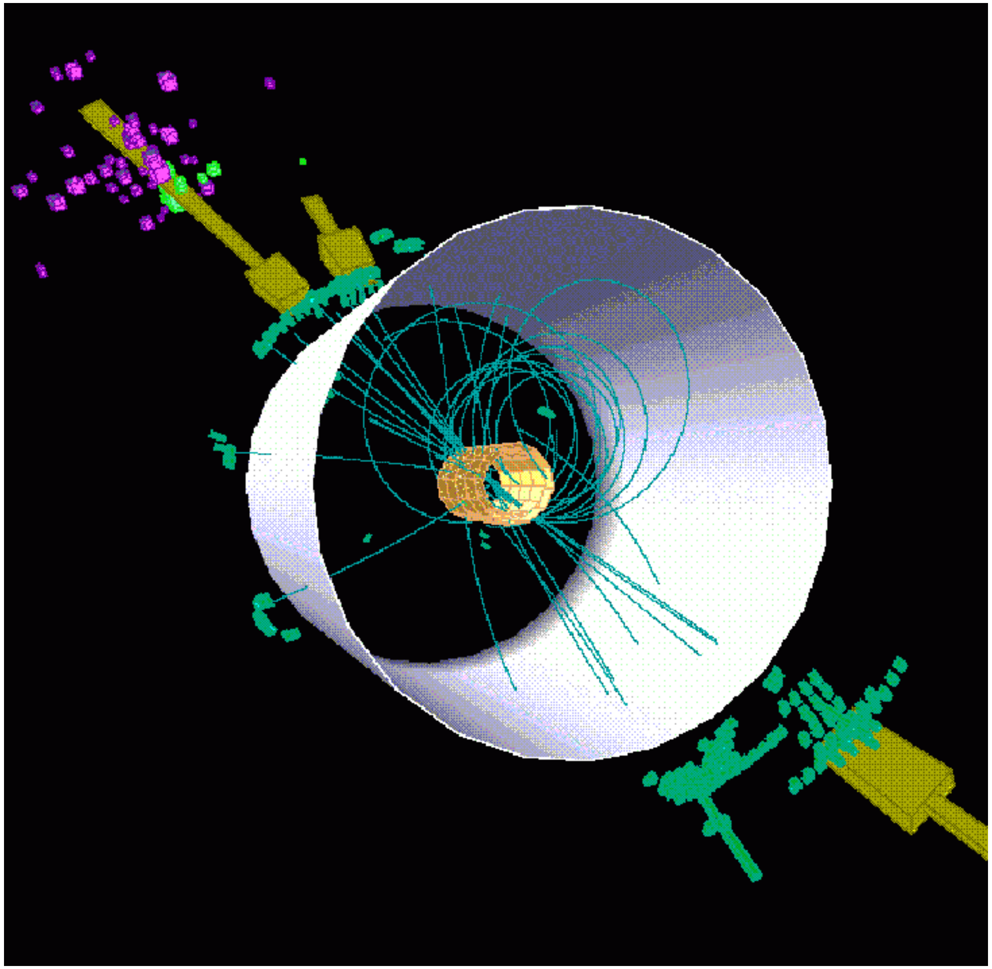
30% of qq(g) $\sigma \sim 80$ pb

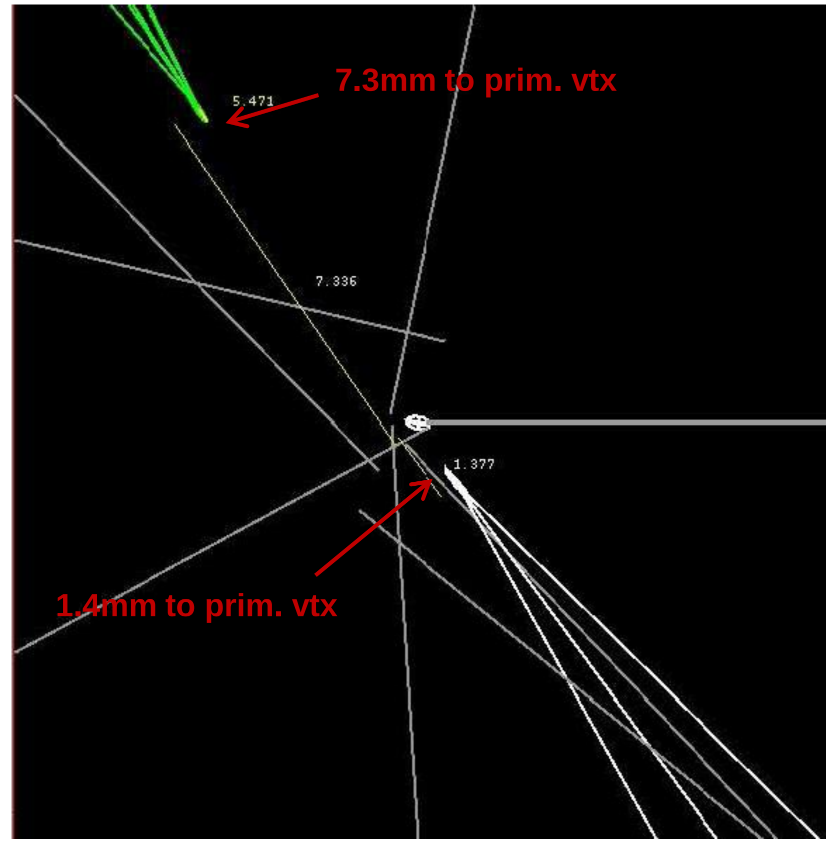
The collinear events are:

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

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

L3 H$\nu\nu$ candidate





Two well b-tagged jets

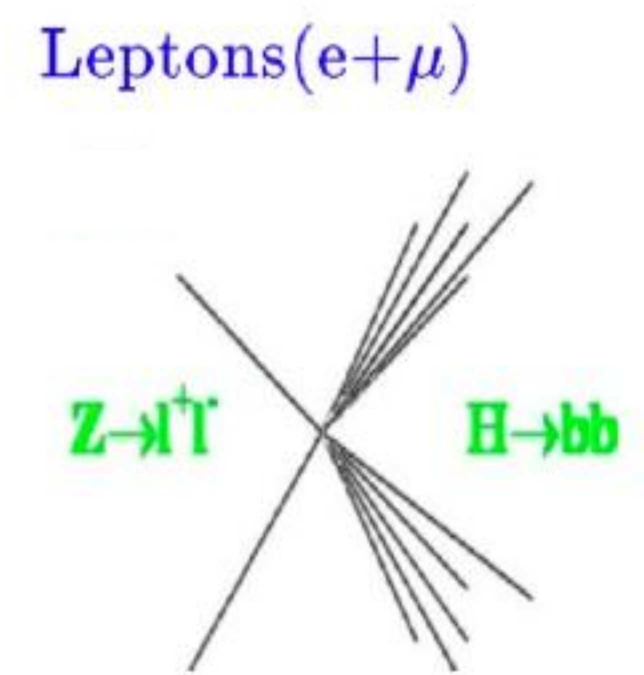
m_H~114.4 GeV/c^2 (σ~3 GeV/c^2)

The lepton channel

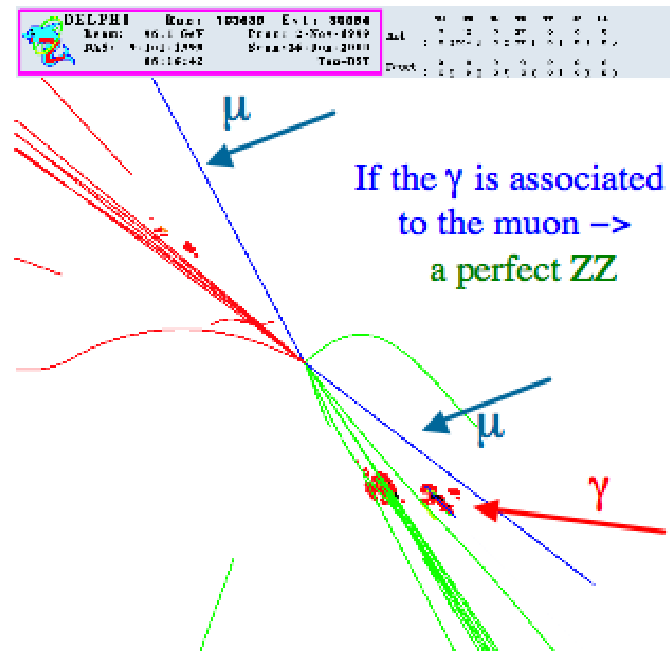
Very clean

but

BR ≈ 3% for each flavour…



b-tagging of jets crucial



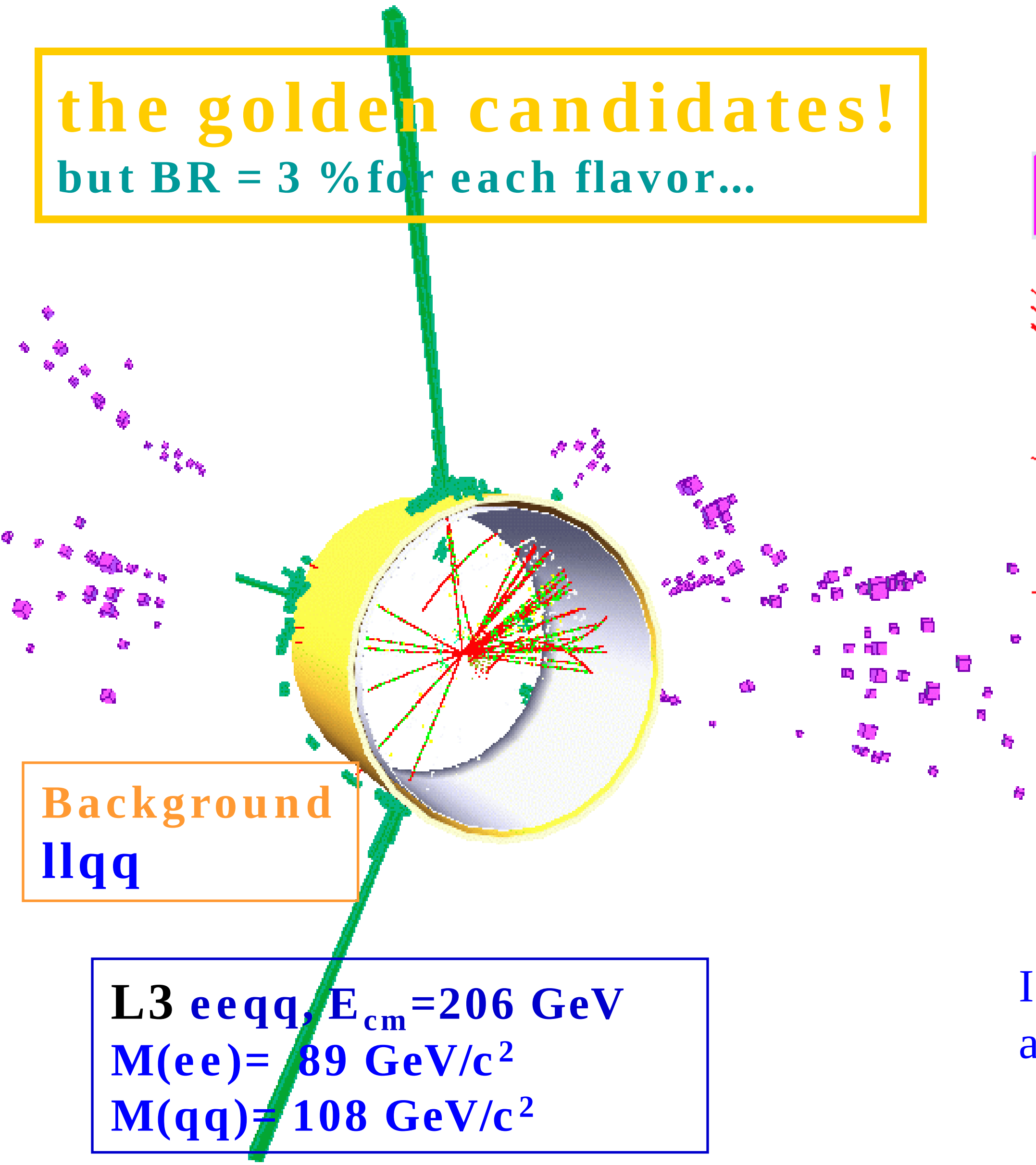
If the γ is included in the jet:
a very high di-jet mass ->
good high mass Higgs candidate !

Danger: radiated photons !

The lepton channel

the golden candidates!

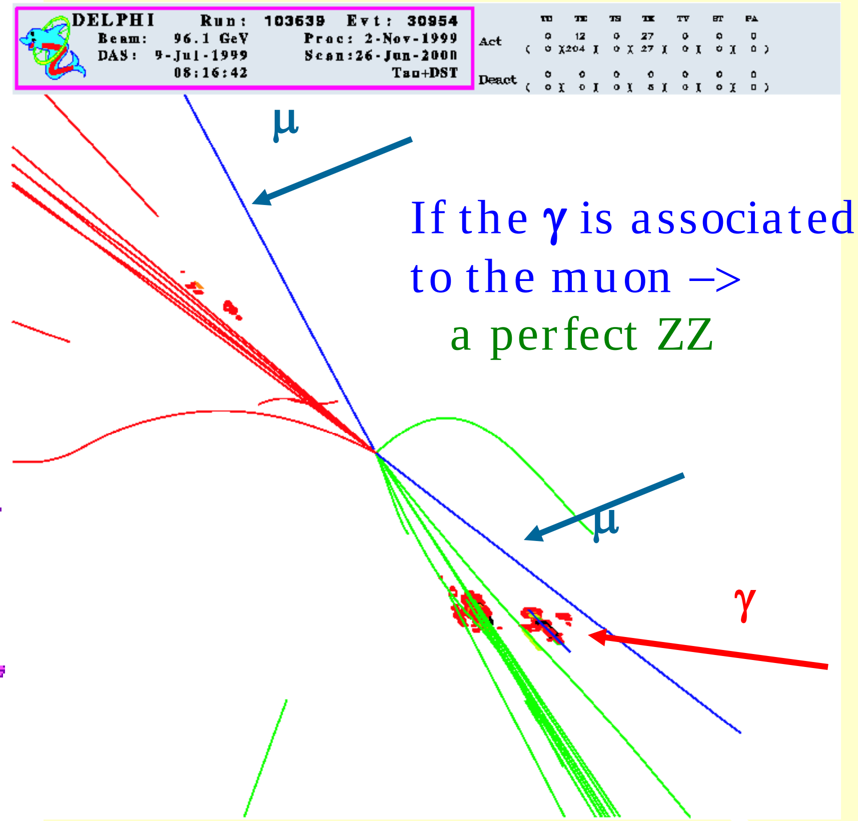
but BR = 3 % for each flavor...



Background
llqq

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

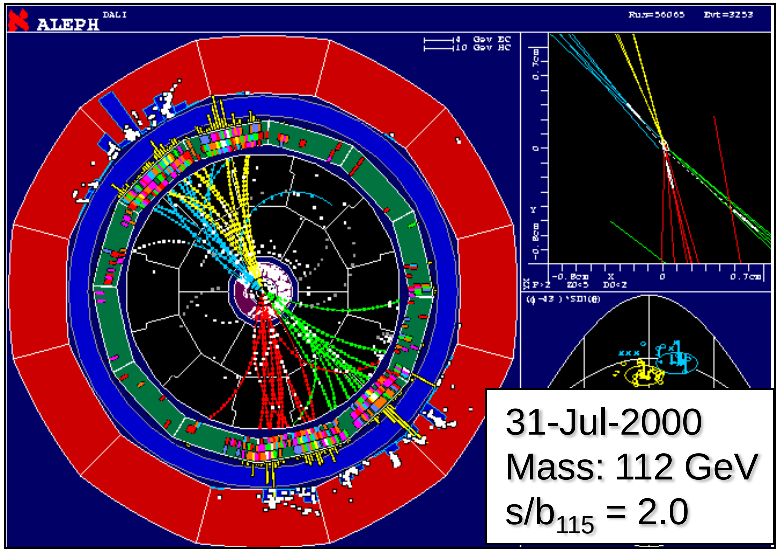
but...radiated photons



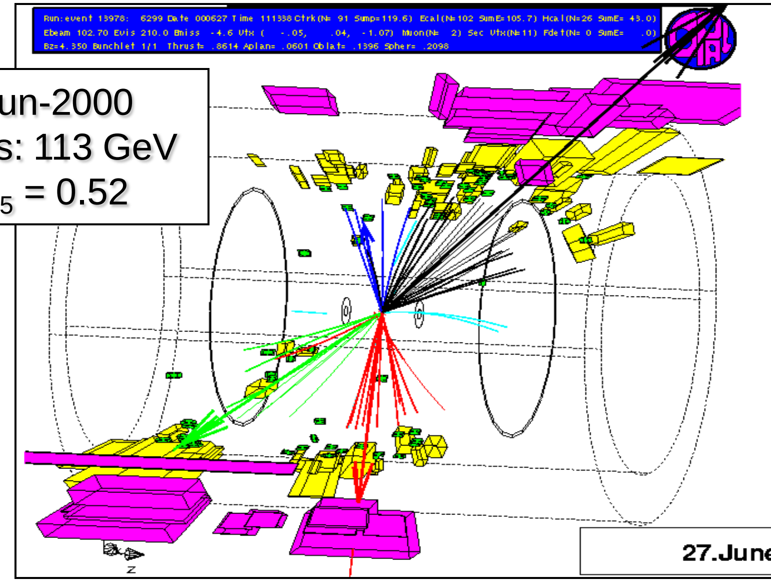
If the γ is associated to the muon –> a perfect ZZ

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

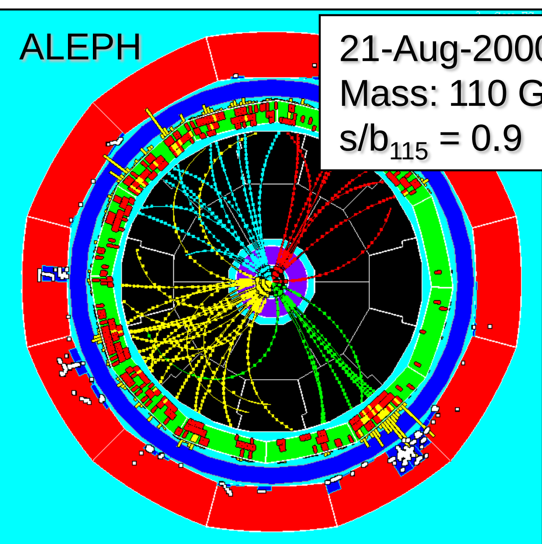
A few candidate events at 115 GeV/c^2



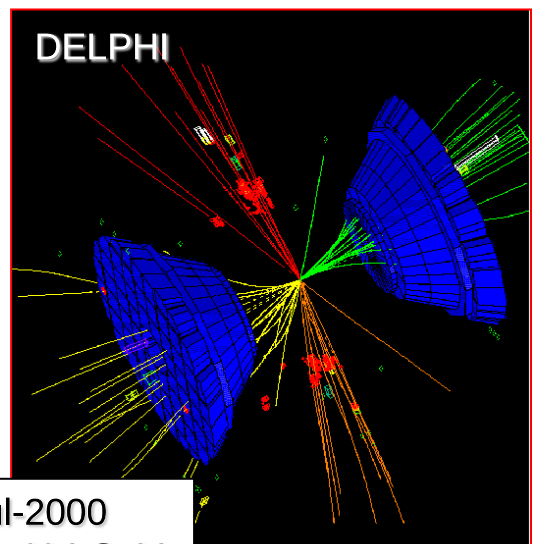
31-Jul-2000
Mass: 112 GeV
$s/b_{115} = 2.0$



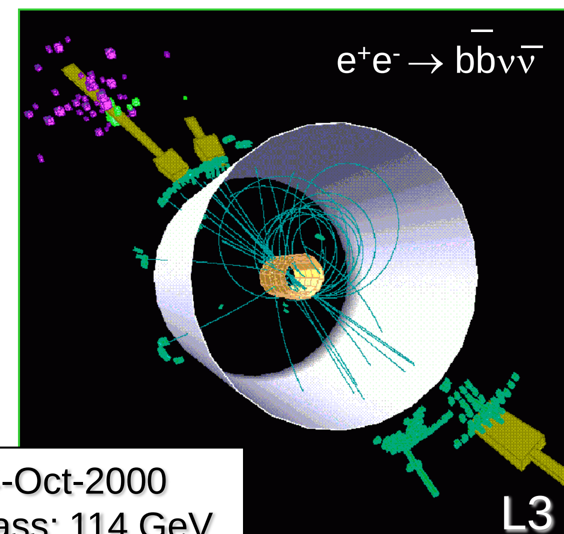
27-Jun-2000
Mass: 113 GeV
$s/b_{115} = 0.52$



21-Aug-2000
Mass: 110 GeV
$s/b_{115} = 0.9$



21-Jul-2000
Mass: 114 GeV
$s/b_{115} = 0.4$



14-Oct-2000
Mass: 114 GeV
$s/b_{115} = 2.0$

The 14 Most Significant Events

s/b > 0.3: Expected signal-to-noise ratio of ~1

Expected: 7
Observed: 14

Number of events compatible with s+b

Number of events in each experiment compatible with being democratic (~1.6 bkg expected)

In ALEPH: 6
In L3: 3
In OPAL: 3
In DELPHI: 2

In Hq$\bar{q}$: 9 (70%)
In H$\nu\bar{\nu}$: 3 (20%)
In Hl$^+$l$^-$: 2 (10%)

Number of events in each Z decay compatible with HZ predictions

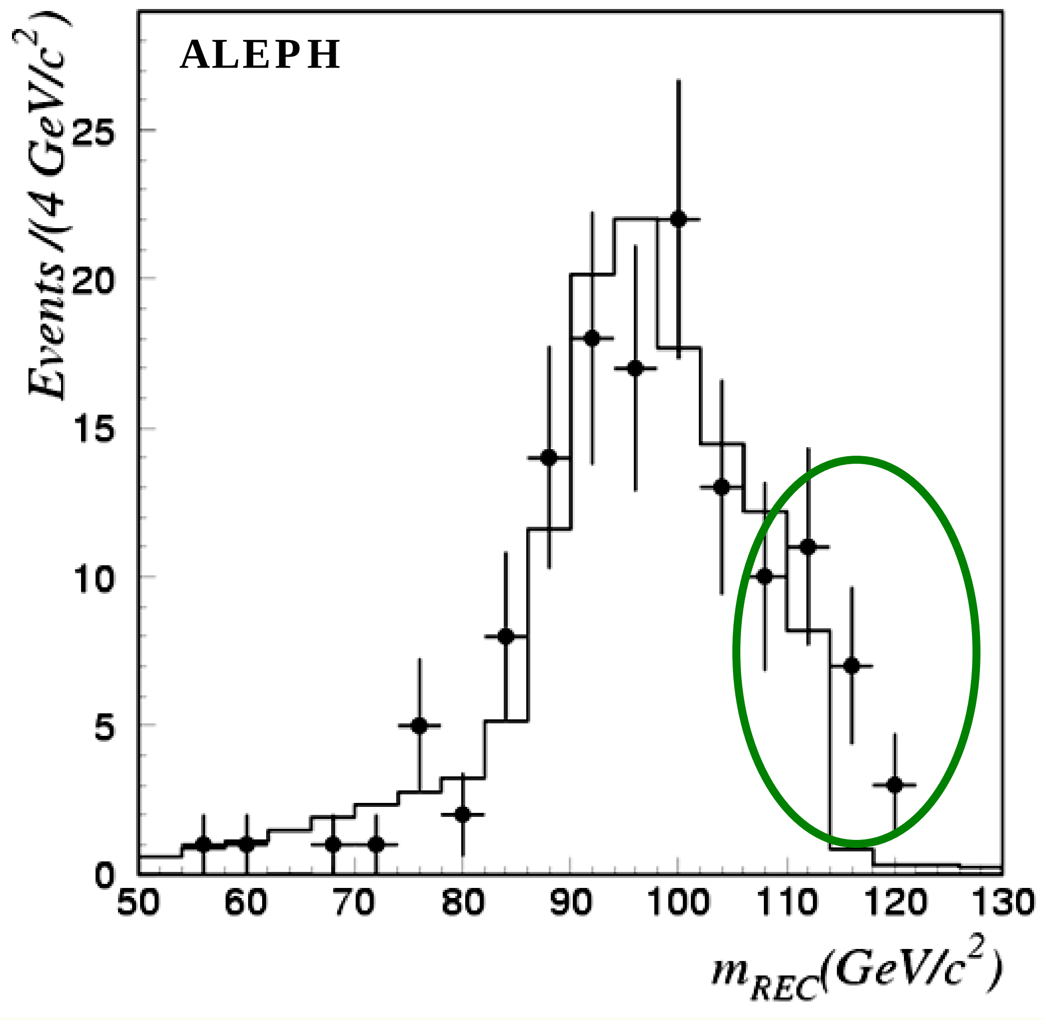
s/b	Rec. mass (GeV/c^2)	Channel	Expt
4.7	114	Hqq	ALEPH
2.3	112	Hqq	ALEPH
~~2.0~~ 0.7	~~114~~ 115	H$\nu\nu$	L3
0.90	110	Hqq	ALEPH
0.60	118	Hee	ALEPH
~~0.52~~ 0.7	113	Hqq	OPAL
0.50	111	Hqq	OPAL
0.50	115	H$\tau\tau$	ALEPH
0.50	115	Hqq	ALEPH
0.49	114	H$\nu\nu$	L3
0.47	115	Hqq	L3
0.45	97	Hqq	DELPHI
0.40	114	Hqq	DELPHI
0.32	104	H$\nu\nu$	OPAL

Values as of Nov 5th, 2000

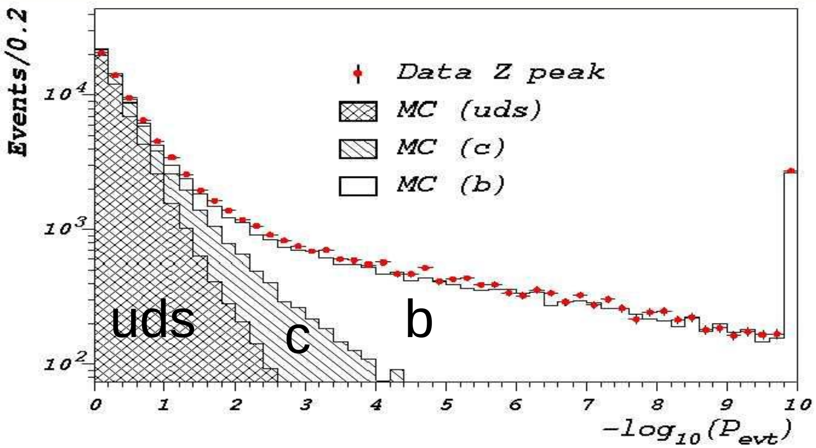
Mass Reconstruction

Distribution tails have to be well under control

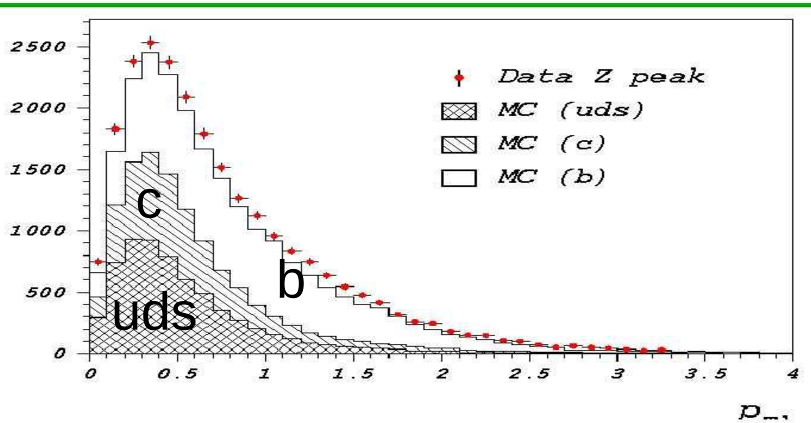
Pre-selection level



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



Impact Parameter with resp
to Primary Vertex

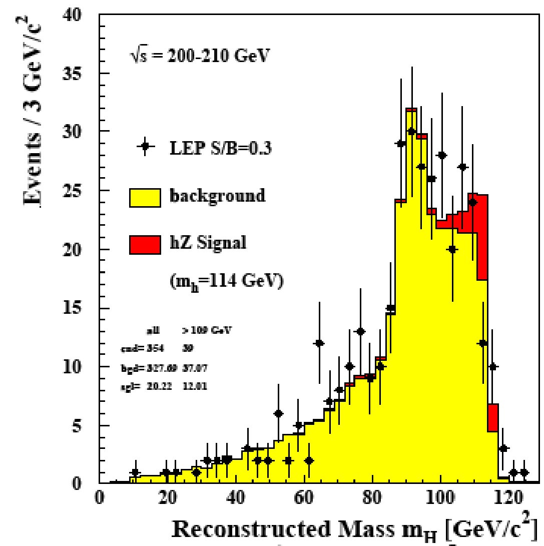


Lepton Transverse Mom p_T^{lept}
with respect tgeb axis

Reconstructed m_H of selected candidates

Have to cut somewhere. For illustration only.

Cut on mass independent variables (like b-tags)
so that $\frac{s_{expected}}{b_{expected}} \approx 0.3$ For m_{rec}>109 GeV
for a 114 GeV Higgs

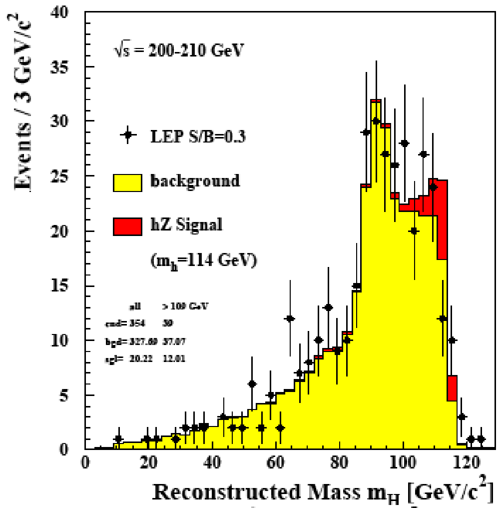


All 2000 Data

	Data	Backg	Signal
All m_{rec}	354	328	20.2
m_{rec}>109 GeV	39	37.1	12.0

Reconstructed m_H of selected candidates

Have to cut somewhere. For illustration only.
Cut on mass independent variables (like b-tags) so that $\frac{s_{\text{expected}}}{b_{\text{expected}}} \approx 0.3$ For m_{rec}>109 GeV for a 114 GeV Higgs



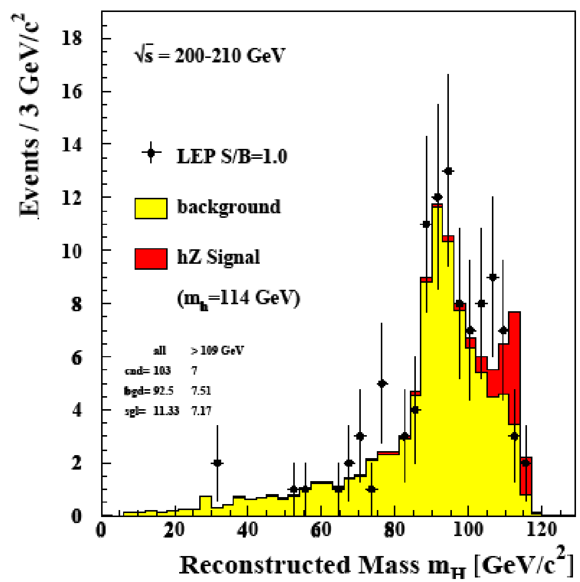
All 2000 Data

	Data	Backg	Signal
All m_{rec}	354	328	20.2
m_{rec}>109 GeV	39	37.1	12.0

Cutting a Little Harder

This time, adjust cuts so that

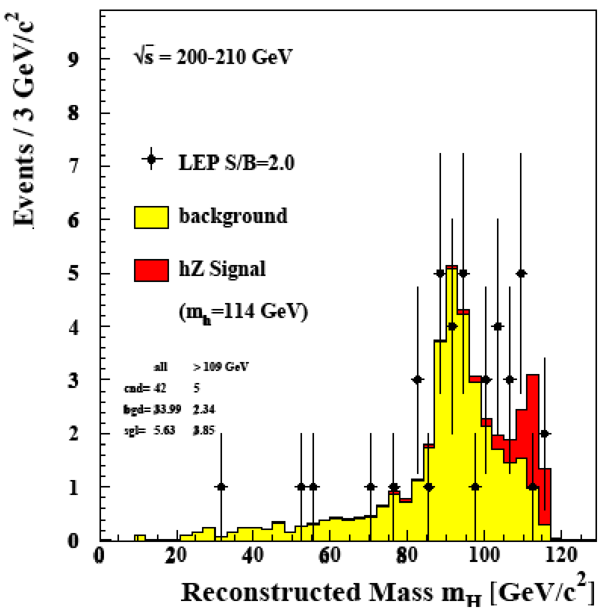
$\frac{s_{\text{expected}}}{b_{\text{expected}}} \approx 1.0$ For m_{rec}>109 GeV for a 114 GeV Higgs



	Data	Backg	Signal
All m_{rec}	103	92.5	11.3
m_{rec}>109 GeV	7	7.5	7.2

Very Hard Cuts

$\frac{s_{\text{expected}}}{b_{\text{expected}}} \approx 2.0$ For m_{rec}>109 GeV for a 114 GeV Higgs



Losing Efficiency -- but “really good” events kept

	Data	Backg	Signal
All m_{rec}	42	34.0	5.6
m_{rec}>109 GeV	5	2.3	3.9

Why Cut at All?

- Need to separate the expected signal from the expected background

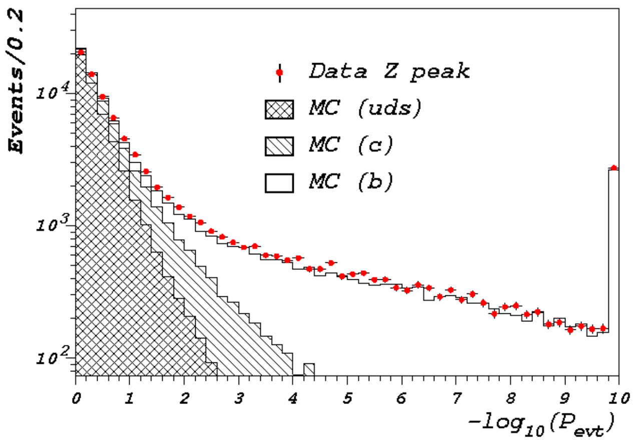
- **Pick good variables to optimize separation**
  - reconstructed m_H
  - b-tags
  - kinematic variables

- **Express in bins**
  - Experimental Data
  - Monte Carlo Signal Expectation
  - Monte Carlo Background Expectation

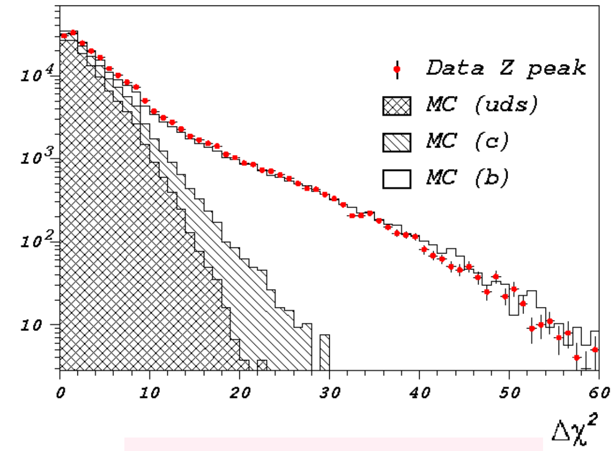
- **Systematic Uncertainties**
  - By search channel, on signal and background
  - Signed errors, labeled by source name
  - Correlated errors properly treated

Need a language: classical confidence levels

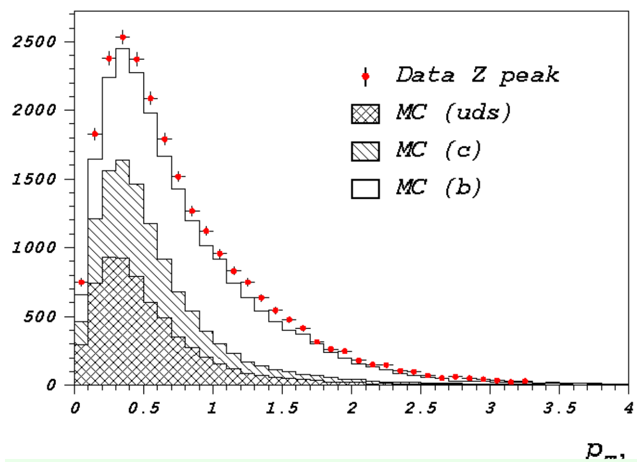
Elements of b tagging



Impact Parameter with respect to Primary Vertex



χ^2 decrease with a Secondary vertex



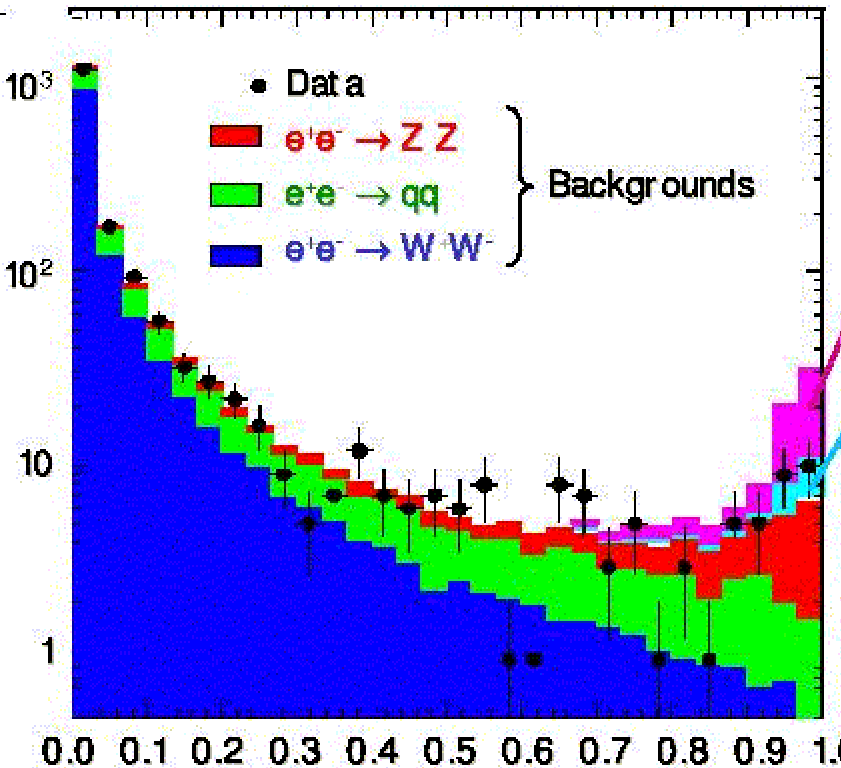
Lepton Transverse Momentum with respect to b-jet axis

Combine with Neural Networks Likelihood's, …

Other jet-shape variables (multiplicity, mass, sphericity)

Multivariate Techniques

Multivariate techniques are more powerful than simple cut method



Discriminating variable G ranging

from 0 (background like events) to 1 (signal like events)

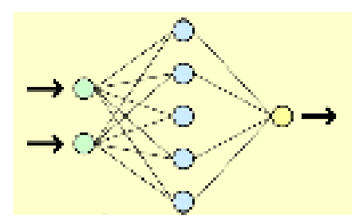
Consider simultaneously kinematic variables to optimize separation of the expected signal from the expected background :

- **Impact parameter distribution with respect to the primary vertex**
- **Lepton transverse momentum distribution with respect to the b-jet axis**
- **Other discriminating variables (rapidity distribution, multiplicities of jet..)**

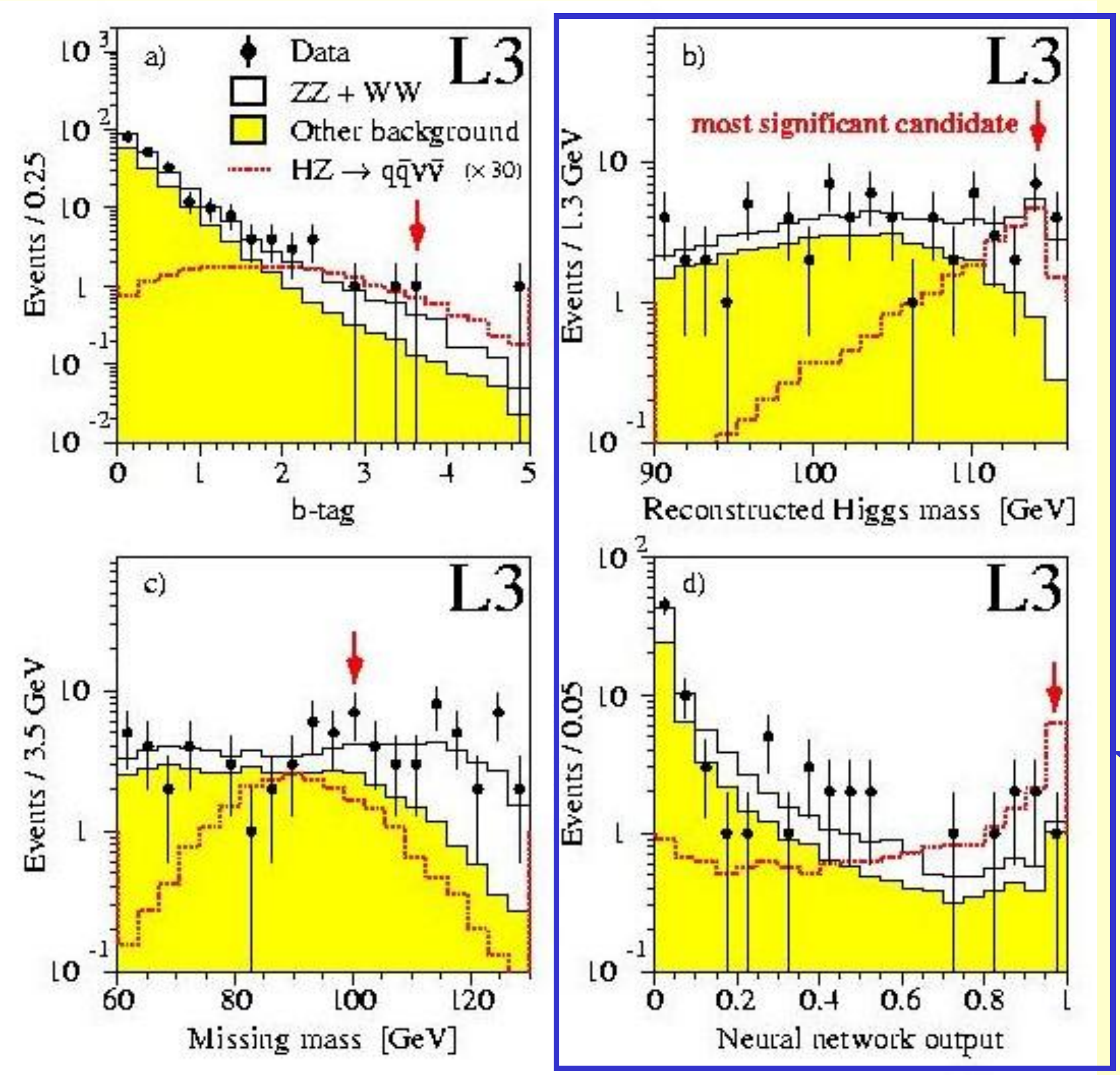
Signal for m_H=100 GeV

Signal for m_H=115 GeV

Build a discriminating variable G(0,1) output of a Neural Network trained on a set of discriminating variables for signal and background:



L3 Hνν characteristics



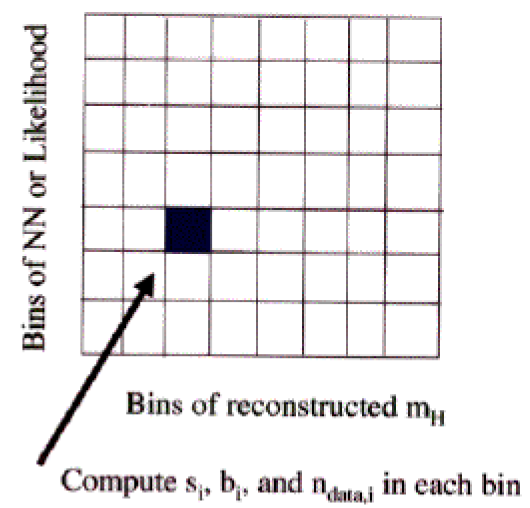
Mass and neural network output both at signal peak

Used for discriminator

Interpreting the Results

LEP HIGGS WG

- Combine all channels in a 2-D space:
  - reconstructed Higgs mass $\mathbf{M}_{\mathbf{Hrec}}$
  - discriminant variable **G** (b-tag, kinematical info..)
- In each bin of M_{Hrec} and G:
  - Background (MC) b_i
  - Signal (MC) s_i
  - Num. of candidates N_i
- For each "test mass" m_H



Construct a parameter Q to order experimental outcomes:

Does the experiment look signal like or background like?

$$Q = \frac{P_{poiss}(data|signal+background)}{P_{poiss}(data|background)}$$

$$lnQ = -s_{tot} + \Sigma_{bins} n_i^{data} ln\left(1 + \frac{s_i}{b_i}\right)$$

The statistical procedure

LEP HIGGS WG

The data from all channels (**Hqq, Hνν, Hll, qqττ**) 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 $\mathbf{N_i}$

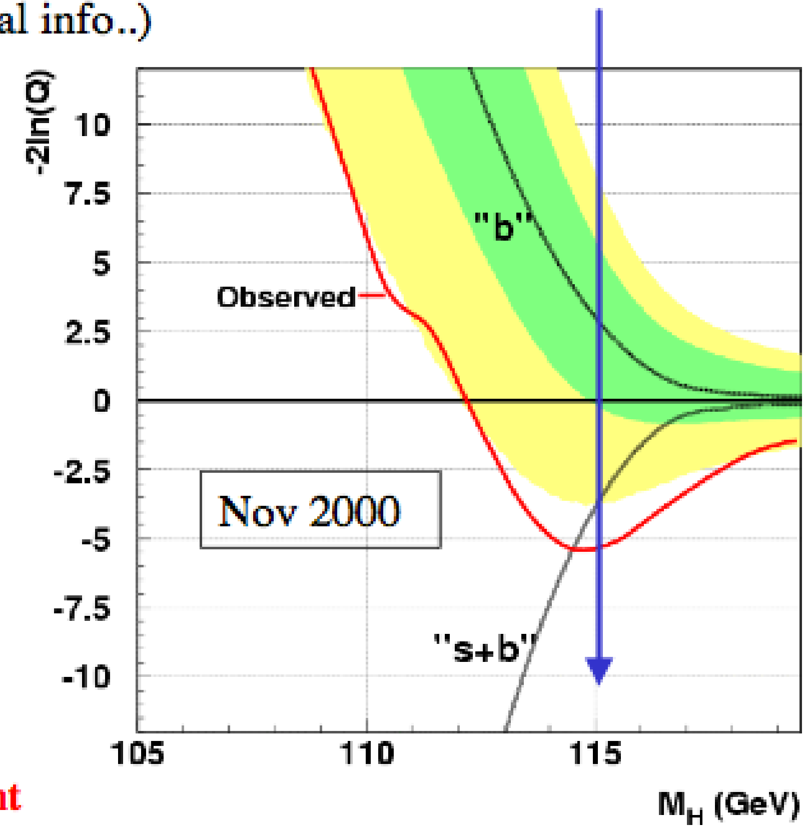
For each "test mass" m(H)

LIKELIHOOD TEST :

"sig+bkgr " ⇔ 'bkgr"

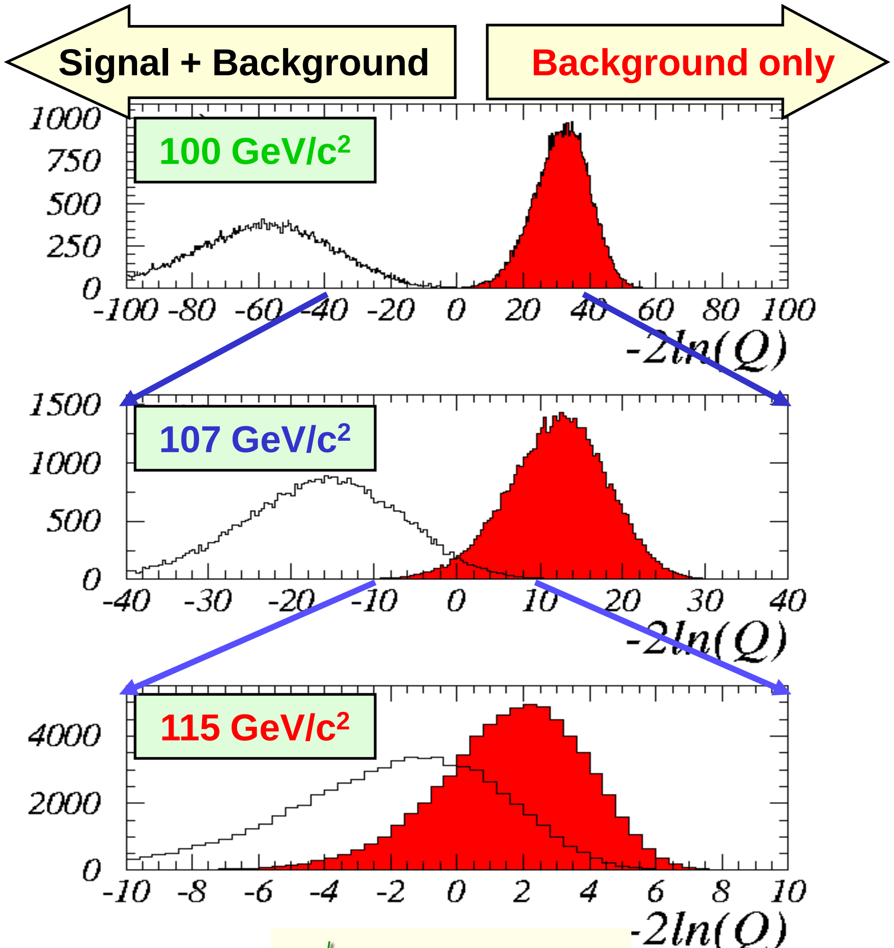
$$\ln Q(m(H)) = -S_{tot} + \sum N_i \ln[\underbrace{1+s_i(m(H)) / b_i}_{W_i \text{ of the event}}]$$

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



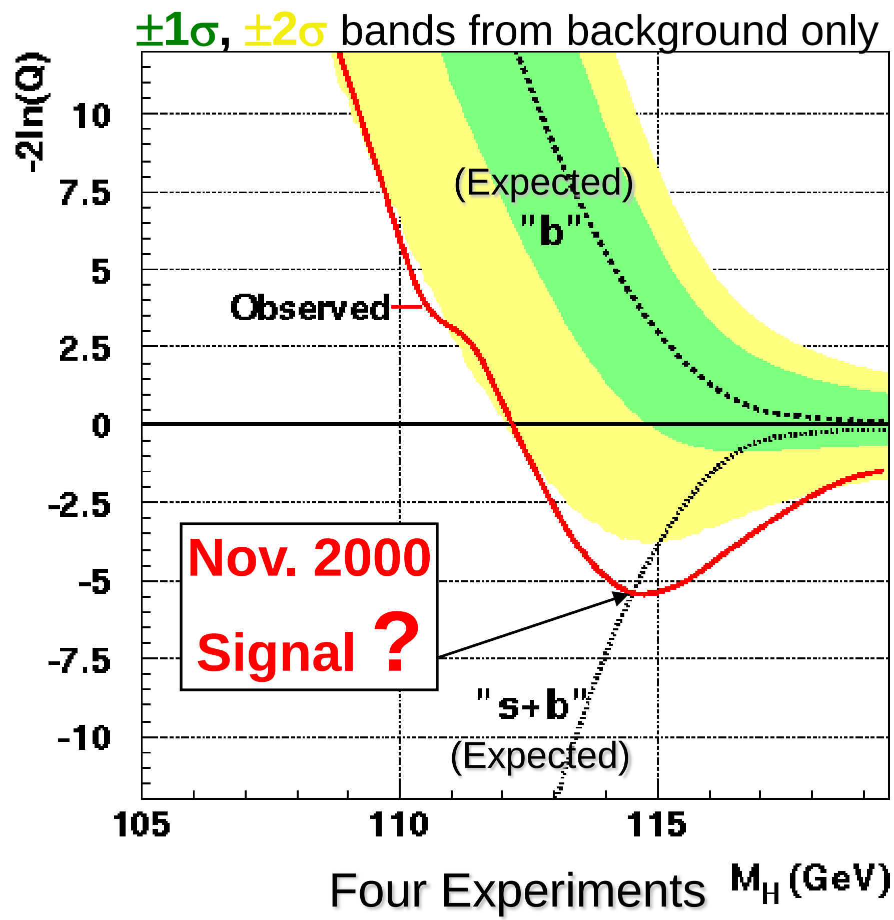
Signal vs Background

- Overall Likelihood of a given event sample: $Q = \prod_{i=1}^{N} (s_i+b_i)/b_i$;
- Larger in presence of signal;
- Negative Log-Likelihood L = -2 Log Q (Smaller in presence of signal).

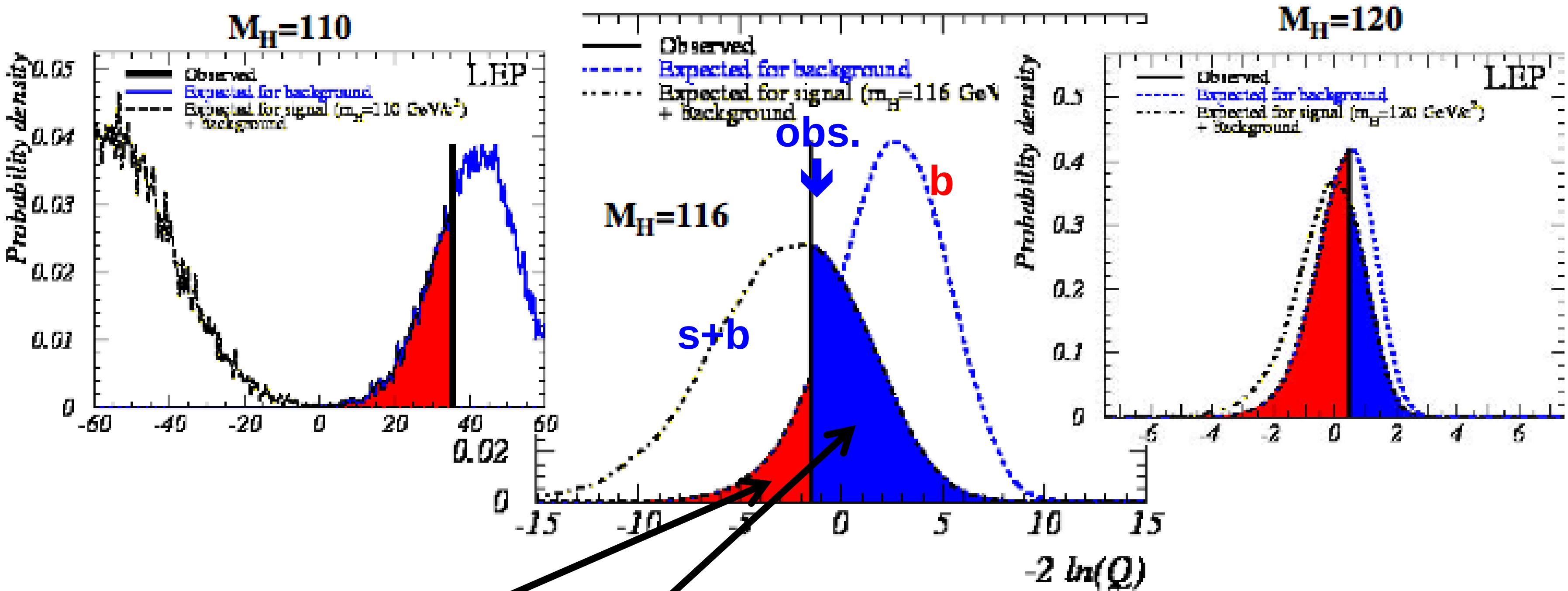


√s = 206 GeV
One Experiment

What if $m_H \approx 115$ GeV/c²?



How significant is it ?➔Confidence Level



$1 - CL_b$: a measure of incompatibility with "b"

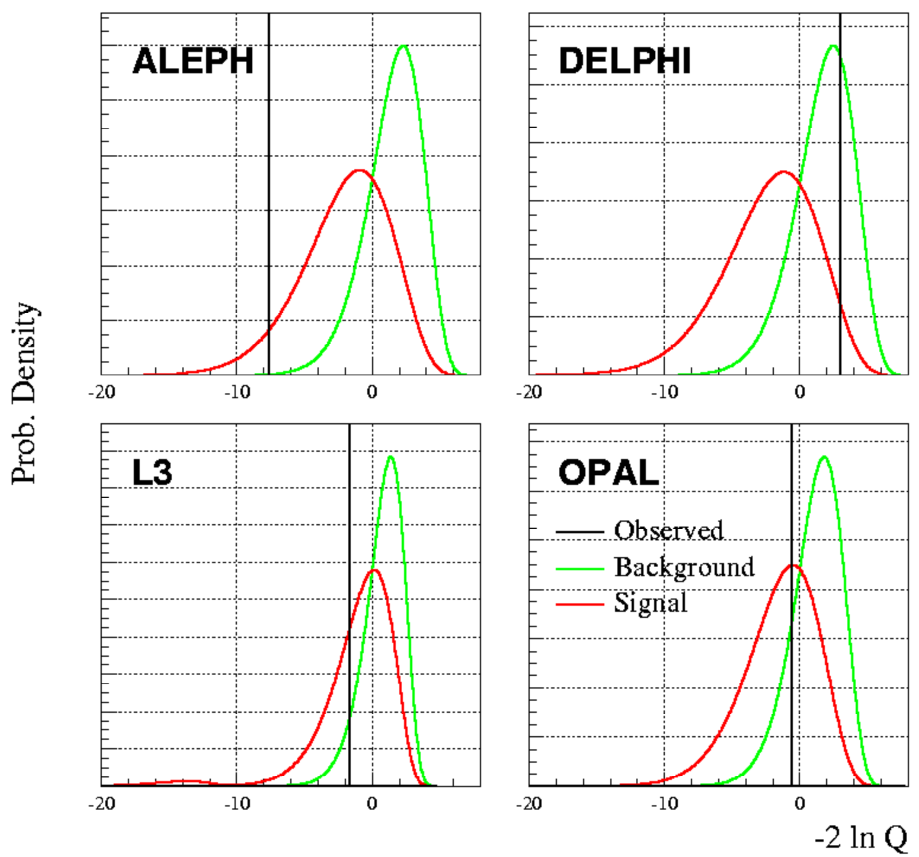
$1 - CL_b$	0.32	0.064	2.7×10^{-3}	6.3×10^{-5}	5.7×10^{-7}
	1σ	2σ	3σ	4σ	5σ

CL_{s+b} : a measure of compatibility with "s+b"

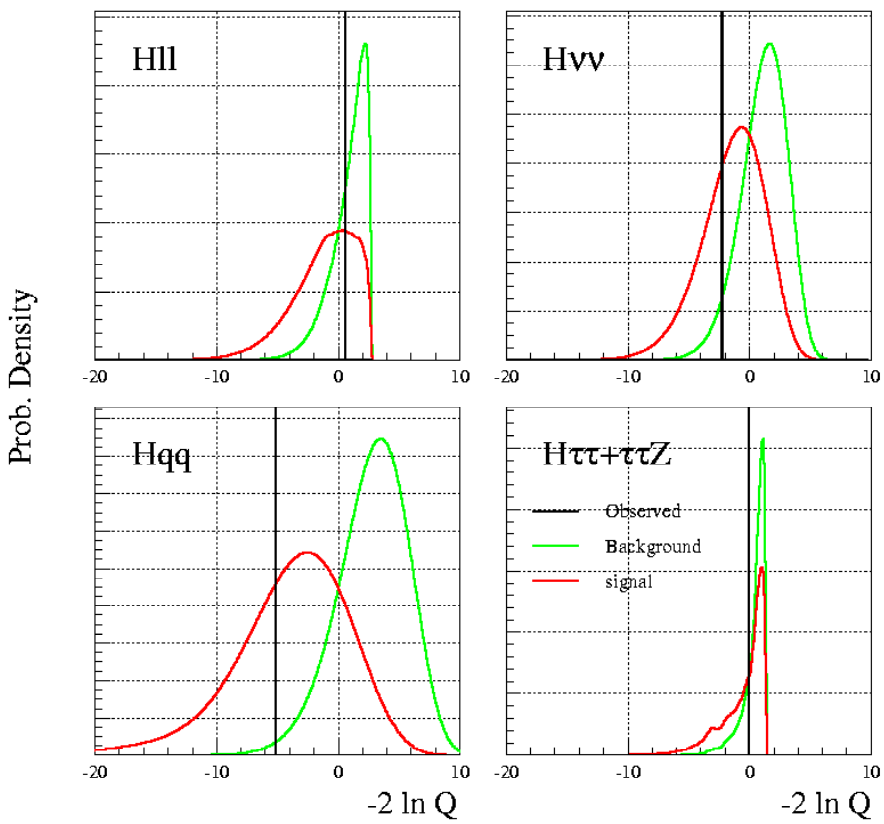
$CL_s = CL_{s+b} / CL_b$ gives the lower bound on Higgs mass

Estimators for m_H=115 GeV/c^2

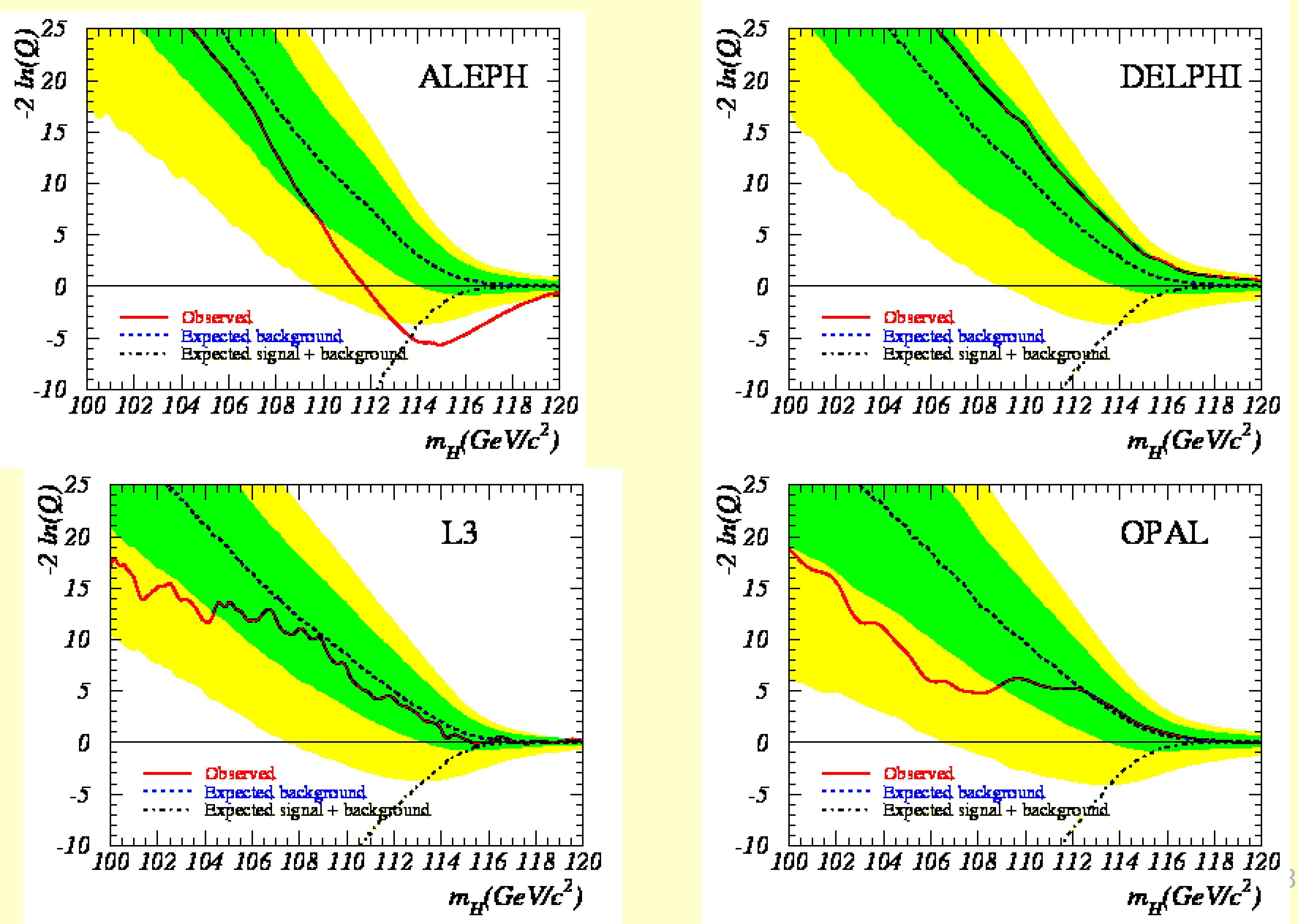
By experiment



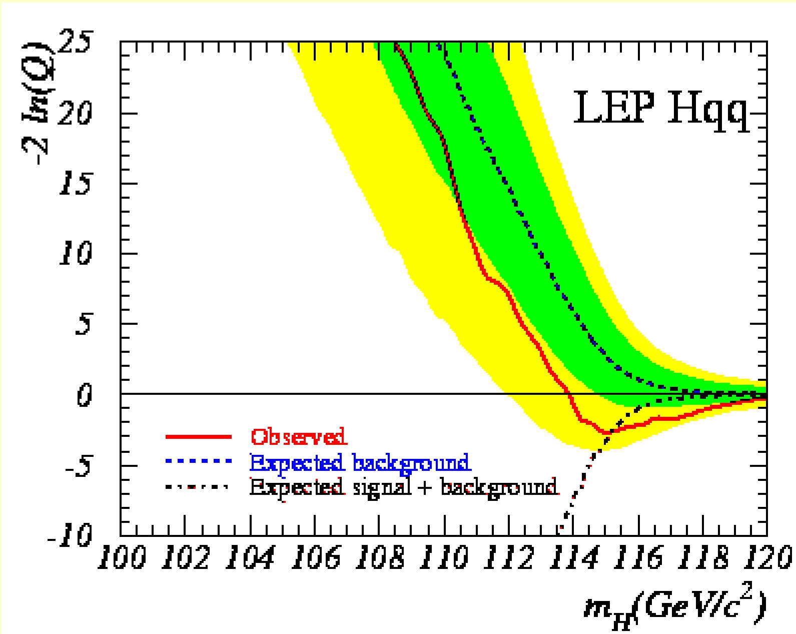
By channel

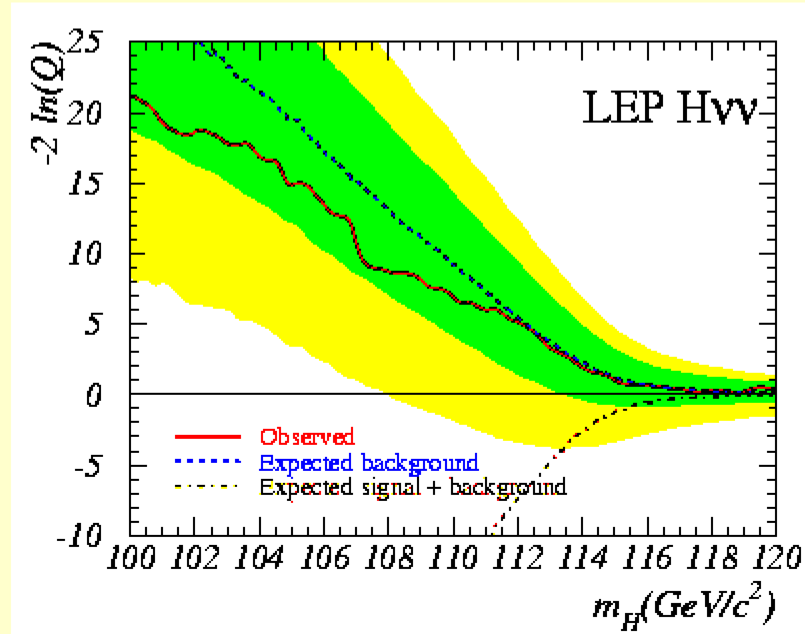


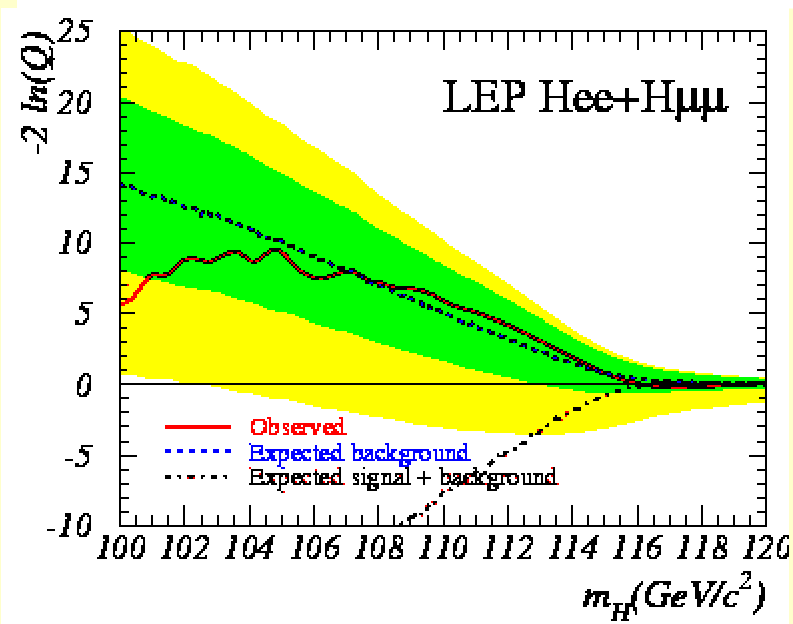
The results of each experiment

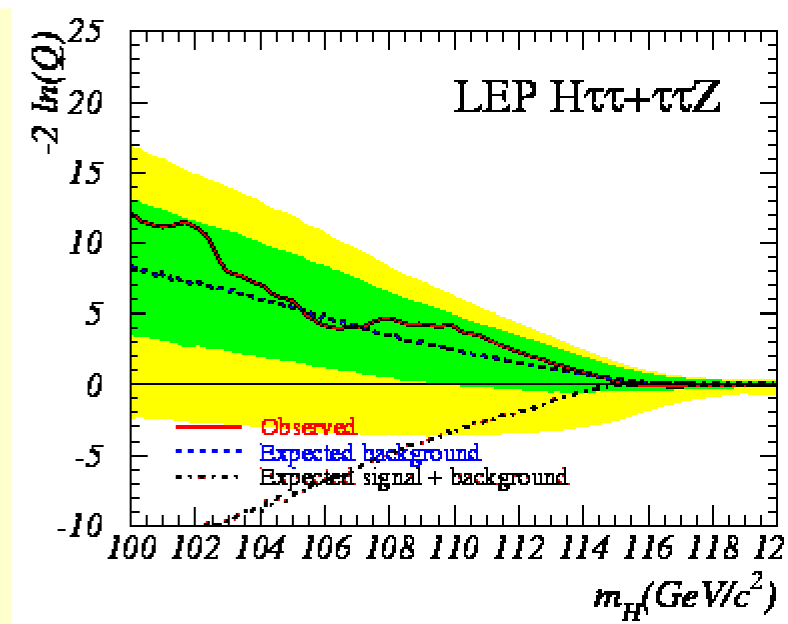


The results per channel

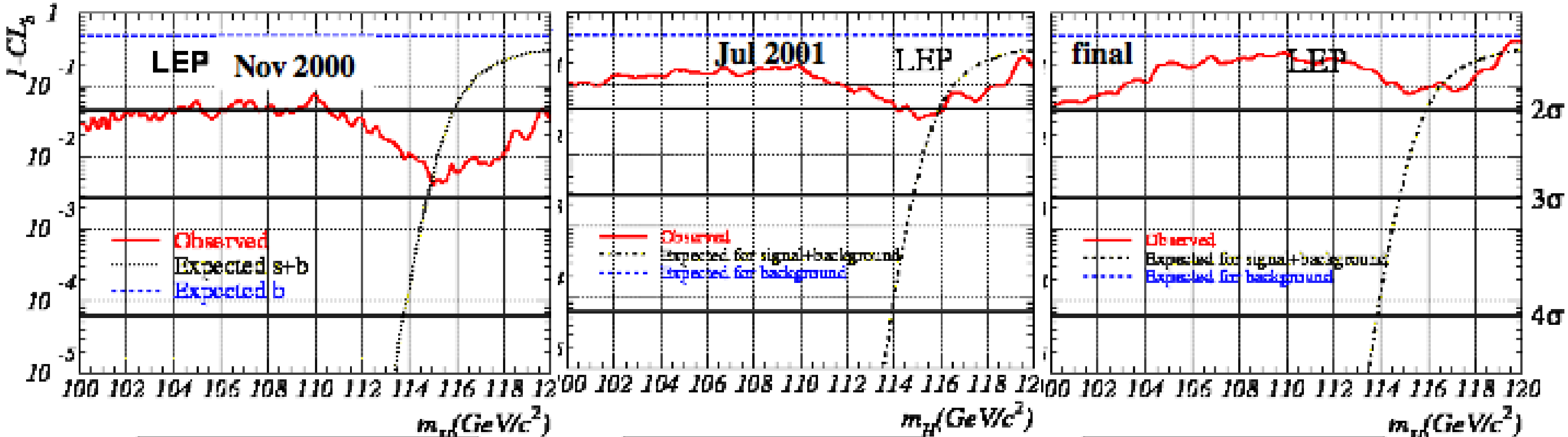








Higgs discovery?
from end of 2000 to the final results…



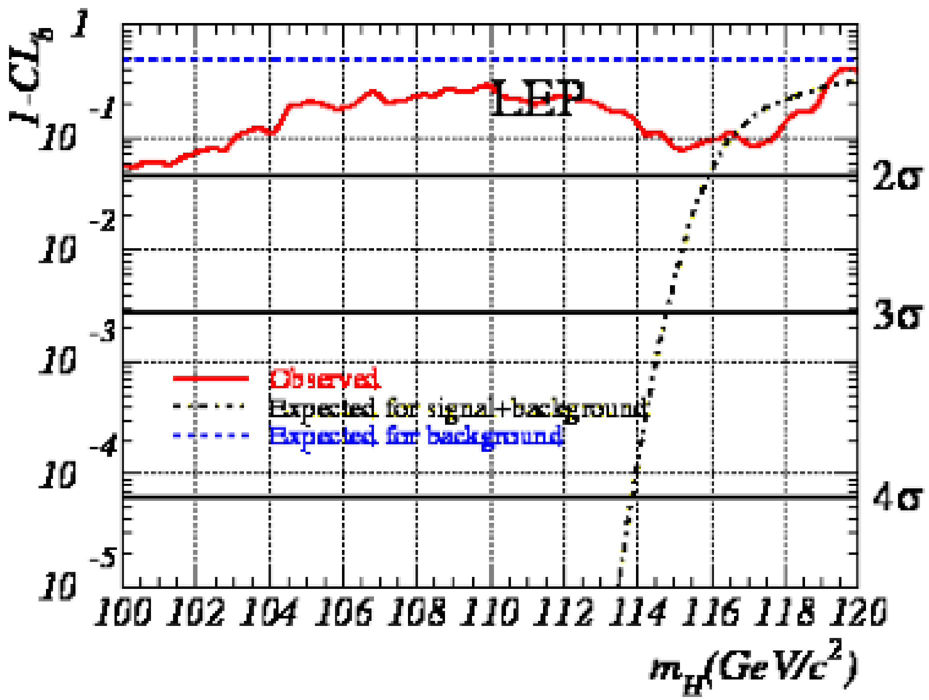
Nov 2000	Jul 2001	final
4.2×10^{-3}	~0.03	~ 0.09
$m_H > 113.5$	$m_H > 114.1$	$m_H > 114.4$
(115.3 expected)	(115.4 expected)	(115.3 expected)

$1-CL_b$ confidence for background hypo. (if $< 5.7 * 10^{-7}$ is a 5σ discovery)

CL_{s+b} confidence for signal+backg. hypo. (exclusion at 95% C.L. if < 0.05)

$CL_s < 0.05$ signal hypothesis ruled out at 95% C.L.

Compatibility with the background



$1-CL_b$ @ 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+ν+τ	0.368

Neutrinos	0.474
Leptons	0.275
Taus	0.255

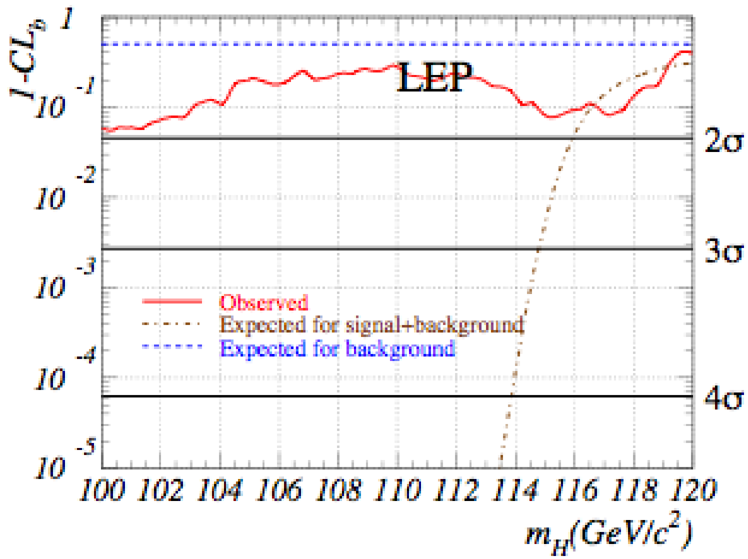
CL_{s+b} (Mh=116) = 0.37

$1-CL_b$ confidence for background hypo. (if < $5.7*10^{-7}$ is a 5σ discovery)

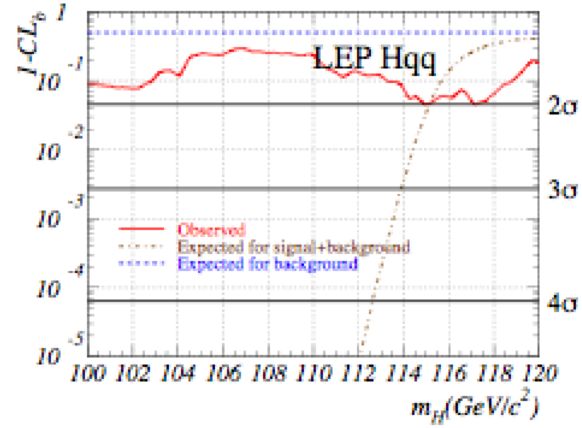
CL_{s+b} confidence for signal+backg. hypo. (exclusion at 95% C.L. if < 0.05)

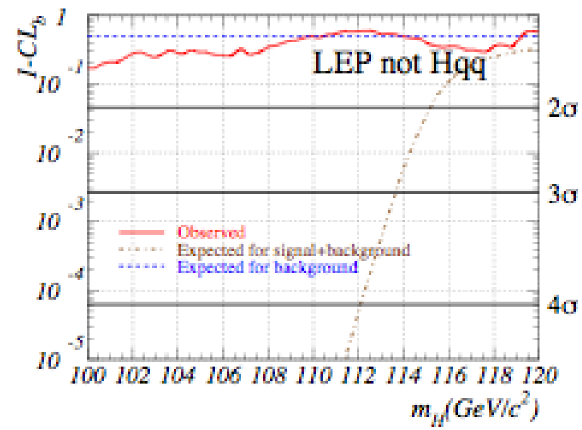
CL_s < 0.05 signal hypothesis ruled out at 95% C.L.

Discovery ?



$1\text{-CL}_b = 0.08$
$\text{CL}_{s+b} = 0.37$





1-CL_b confidence for background hypo. (if < $5.7 \ast 10^{-7}$ is a 5σ discovery)

CL_{s+b} confidence for signal+backg. hypo. (exclusion at 95% C.L. if < 0.05)

CL_s < 0.05 signal hypothesis ruled out at 95% C.L.

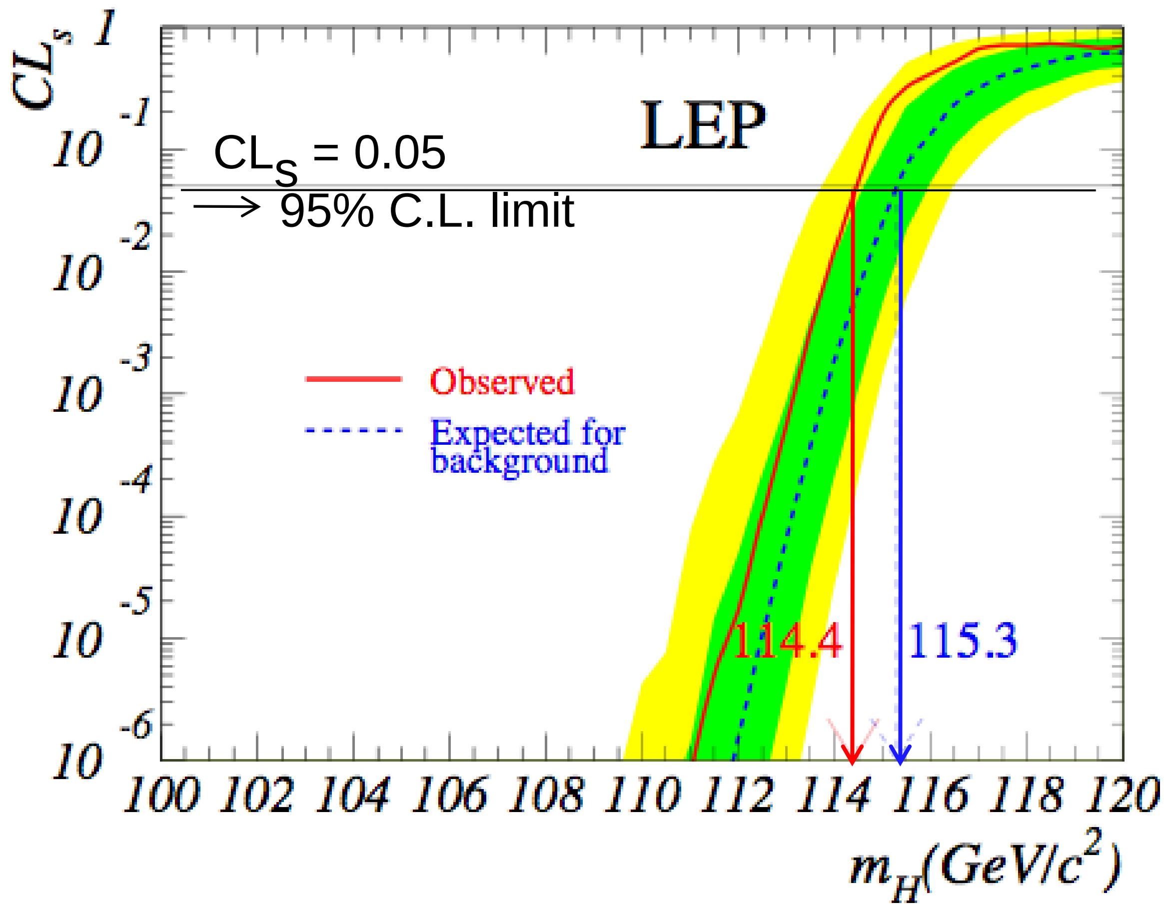
Higgs Mass Lower Bound

$CL_s = CL_{sb}/CL_b < 0.05$ for 95% C.L.

$m_{Higgs} > 114.4 GeV/c^2$

LEP excludes a 114.4 GeV Higgs boson @ 95% CL. (expected 115.3 GeV)

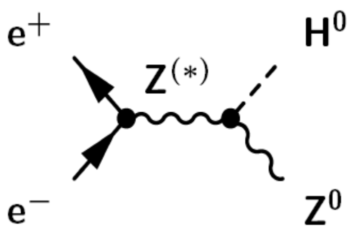
	Exp.	Obs.
ALEPH	113.5	111.4
DELPHI	113.3	114.1
L3	112.4	112.0
OPAL	112.7	112.7



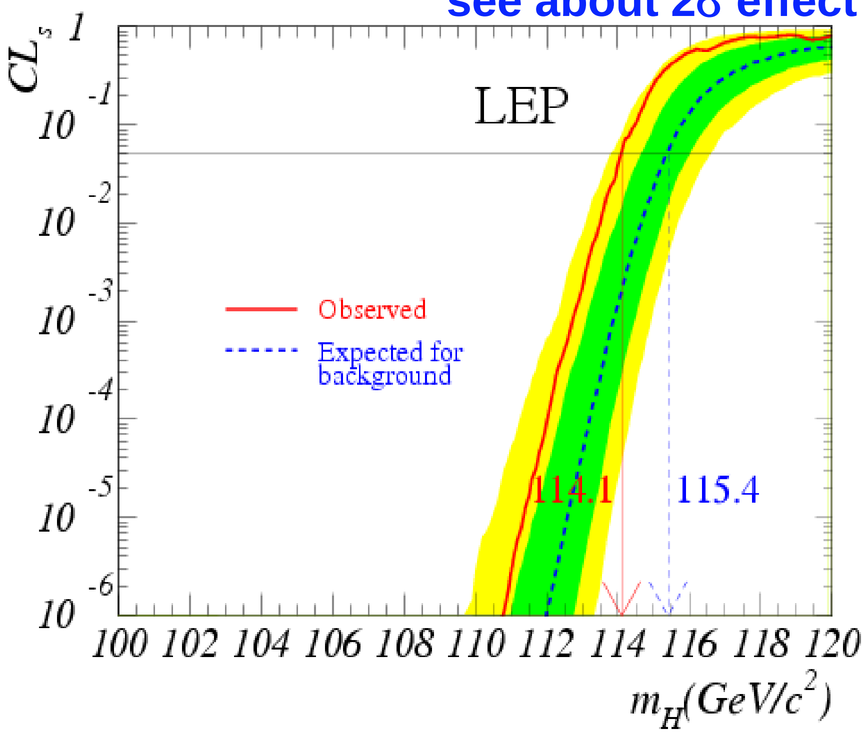
- Final combination for SM Higgs boson

LEP set the 95% CL mass limit = **114.4 GeV**, very close to the kinematic limit. Above, modest indication for a possible signal **1-CL**$_b = 0.08$ **vs CL**$_{s+b} = 0.37$ **@ 116-118 GeV**
LEP excludes also a SM-like Higgs boson with cross-section **20 times lower than the SM one from 12 to 80 GeV.**

Direct searches at LEP, e^+e^- collisions, (1989-2000)

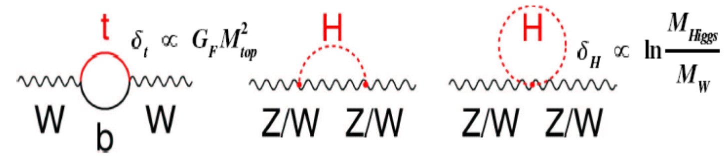


First Hint of Higgs boson with mass 115 GeV observed by ALEPH. LEP experiments together see about 2σ effect

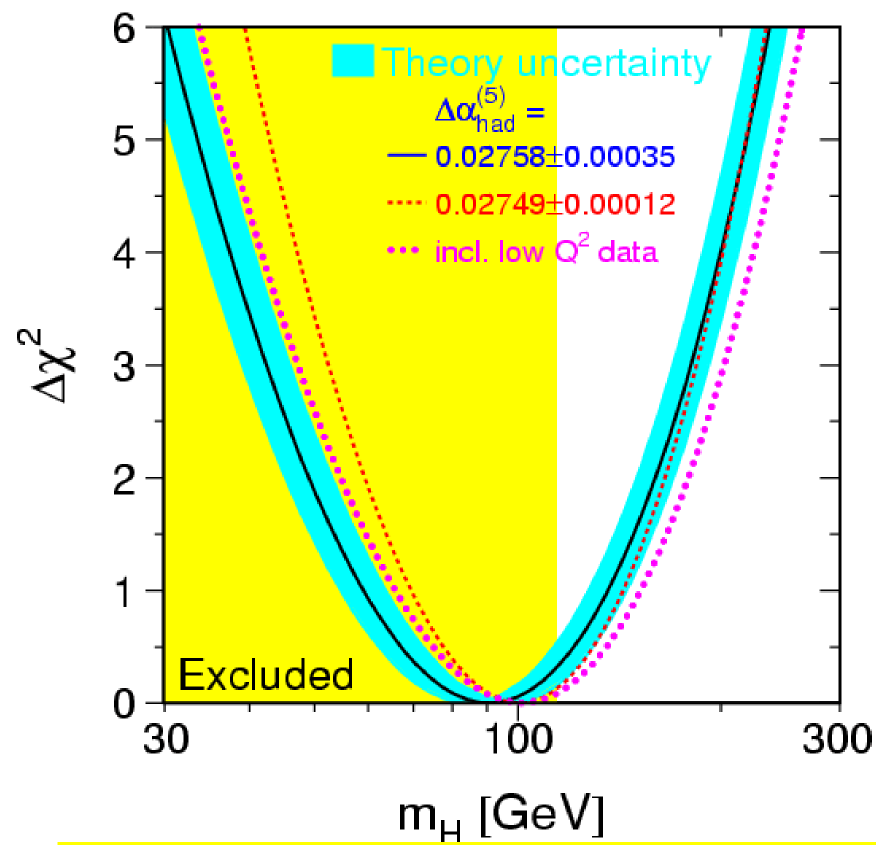


M_H>114.1 GeV @ 95% C.L.

Indirect evidence is driven by radiative corrections



CDF+D0 Top Quark Mass = 172.7 ± 2.9 GeV



$M_H=91^{+45}_{-32}$ <186 GeV @ 95% C.L.

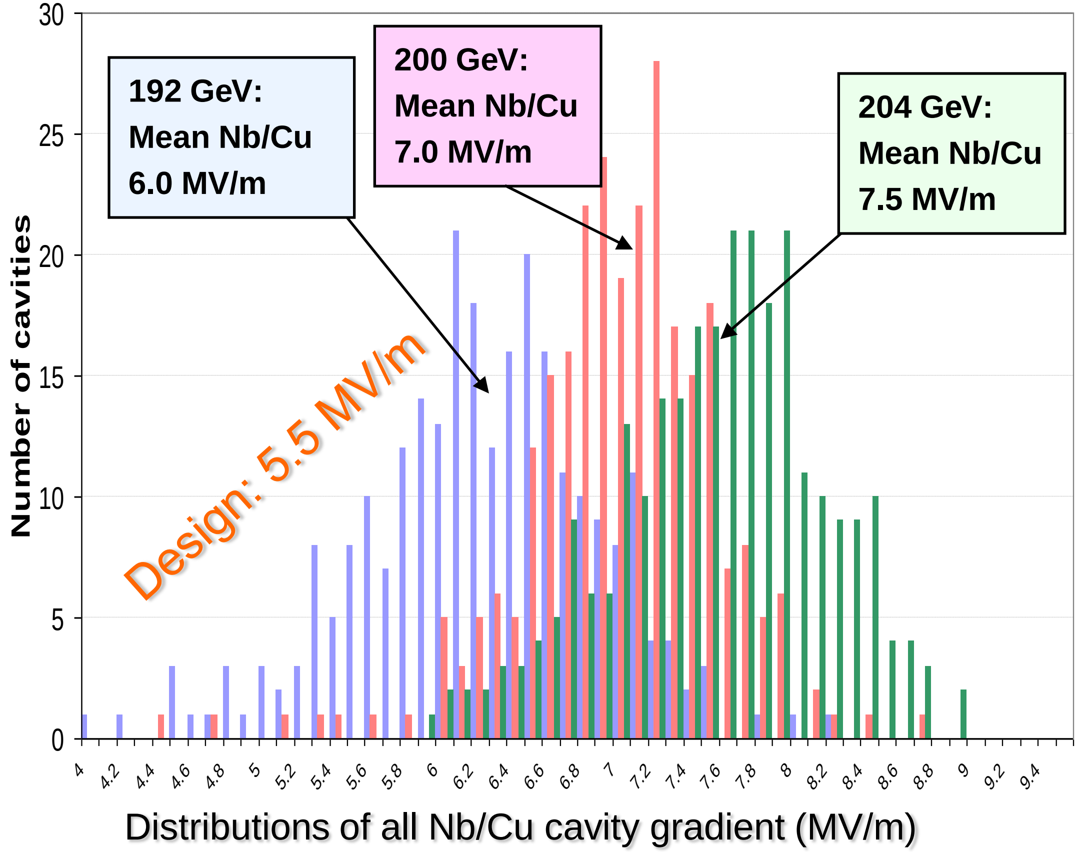
At the end of the year 2000 the glorious LEP was closed and dismounted to allow the construction of LHC the Large Hadron Collider

Meanwhile, in US, the TEVATRON.......but this story is for tomorrow

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)



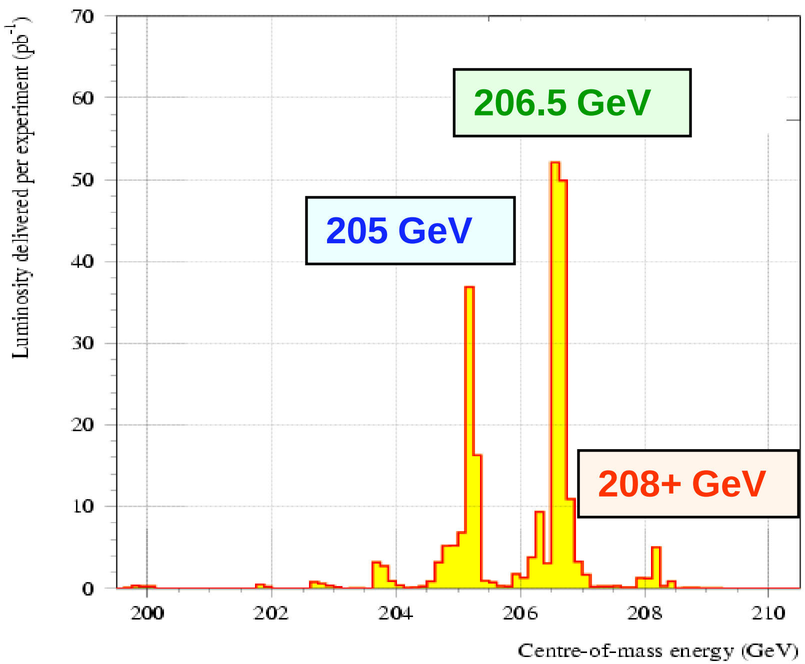
E: 192 $\rightarrow$ 200 $\rightarrow$ 204 GeV;

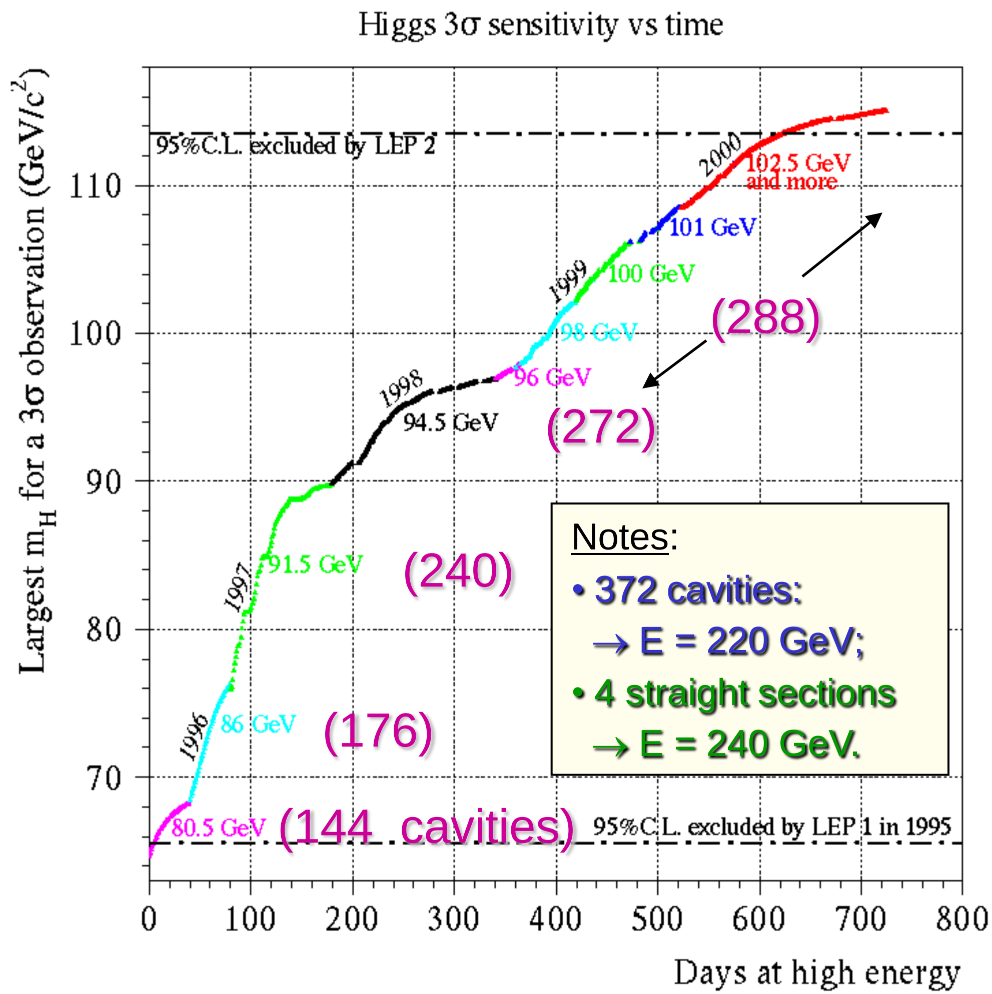
m_H: 100 $\rightarrow$ 108 $\rightarrow$ 112 GeV/c^2

Improvements in 1999/2000: Results

$220\ pb^{-1}$ delivered in 2000:

- starting at 204-205 GeV (April-May)
- Regularly above 206 GeV (from June onwards)
- Only above 206.5 GeV (September to November)





$m_H < 114.1\ GeV/c^2$

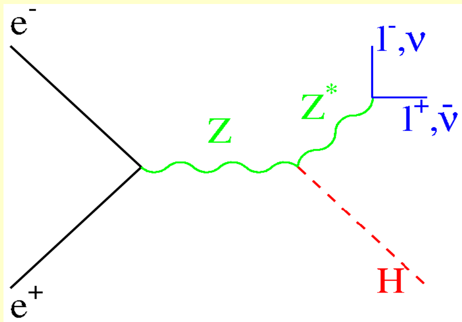
excluded at 95% C.L.

Higgs Production at LEP

- Dominant Production Process:

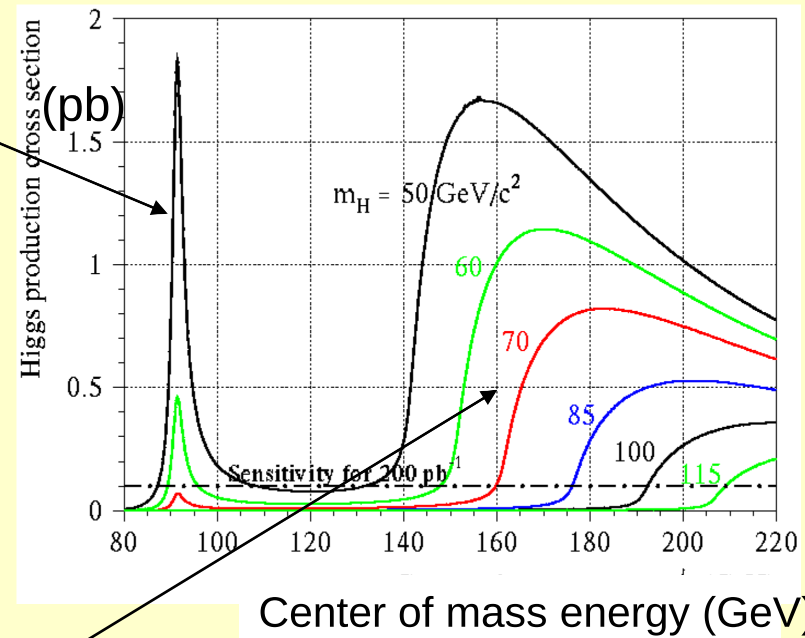
Bjorken Process

LEP1



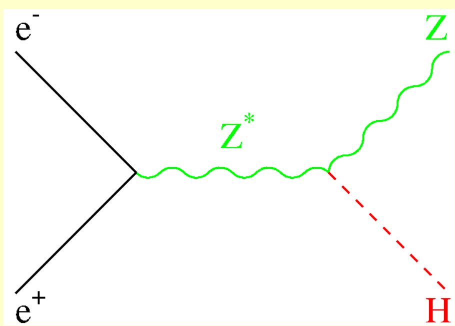
$\sqrt{s} = m_Z$

Higgs Production Cross Section



``Higgsstrahlung''

LEP2



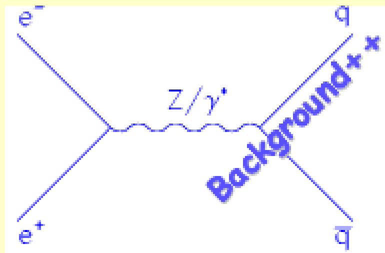
$\sqrt{s} \geq m_H + m_Z$

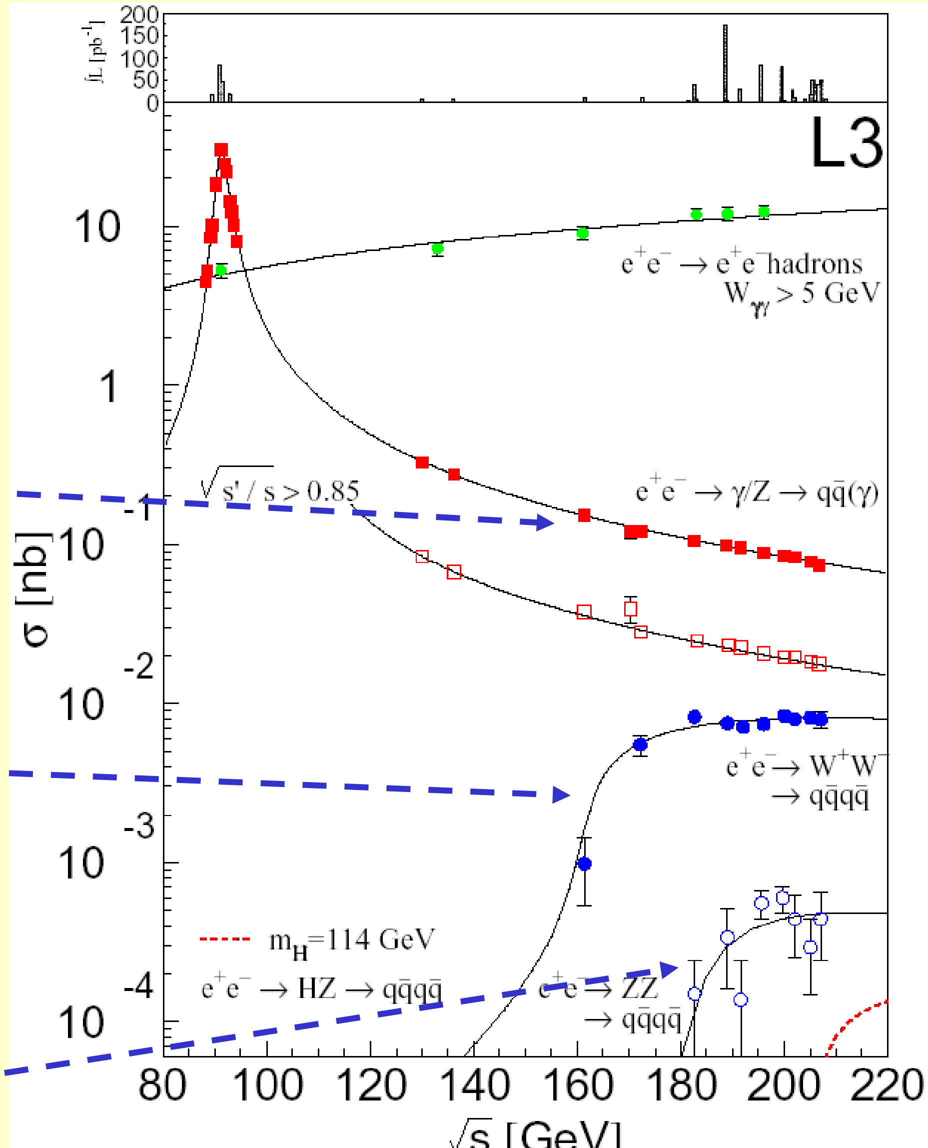
SM background processes

At LEP SM processes well understood and measured.

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

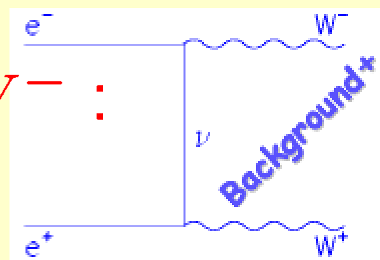
$\sigma \sim 200\text{pb}$





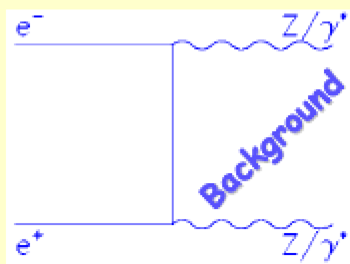
$e^+e^- \to W^+W^-$:

$\sigma \sim 20\text{pb}$



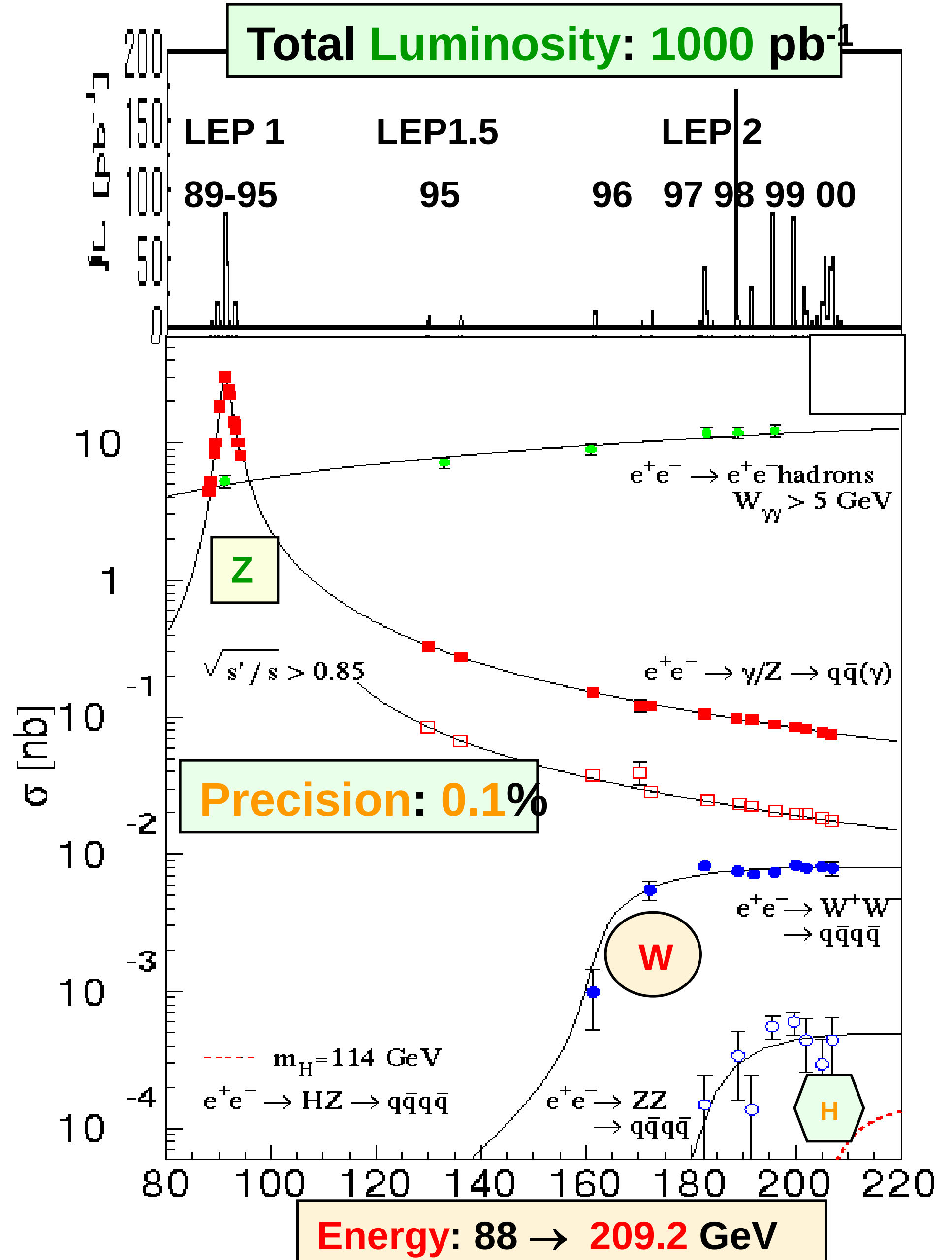
$e^+e^- \to ZZ$:

$\sigma \sim 2\text{pb}$



LEP Overview

- Conventional collider e^+e^- ring;
- Energy upgradeable;
- Energy measurable;
- Four detectors (A,L,D,O);
- Large luminosity;
- 20 Million Z events.



SM Four Jet Channel

- Topologies:

4b: H→bb/Z→bb and
2b: H→bb/Z→qq (where q= [u,d,s,c])
Different backgrounds and hence performance

- Backgrounds:
  - ZZ: Dominant for m_H ~ 90 GeV/c^2 when Z→ bb
    - Most important for 4b channel at all masses
  - WW:A priori reducible (no b-quark jets, apart from Vub).
    - Tedious if jets are mistagged.
  - Quark pair production (QCD processes):
    - Important near threshold production for m_H>m_Z
    - b's and gluons back-to-back,

⇒reconstructed mass = maximum possible