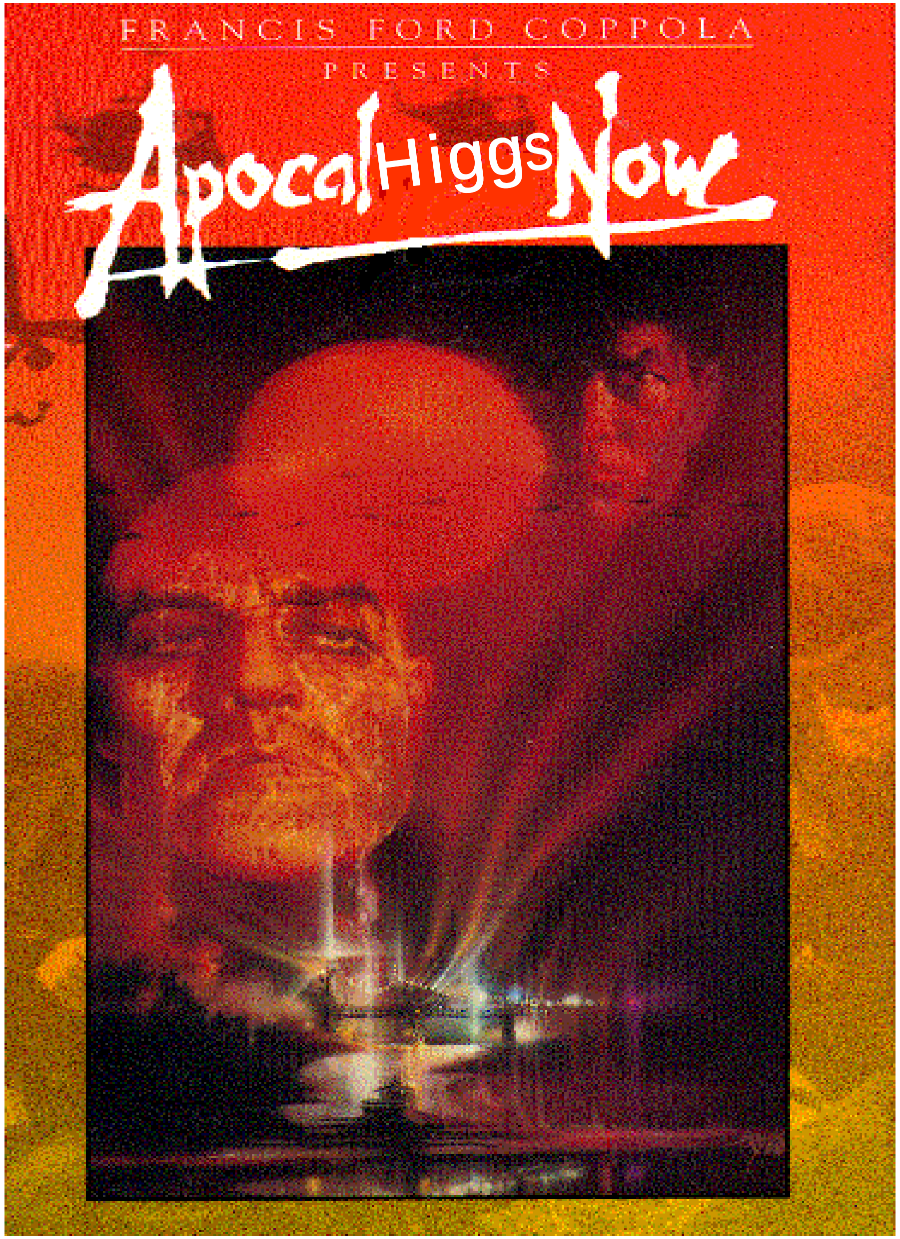
The Standard Model Higgs Searches at LEP



Second Lecture Outline:

1. Brief Theory Reminder:
   Mass, Decays, Production

2. The Situation before LEP

3. Higgs Boson Searches at LEP 1

4. Higgs Boson Searches at LEP 2

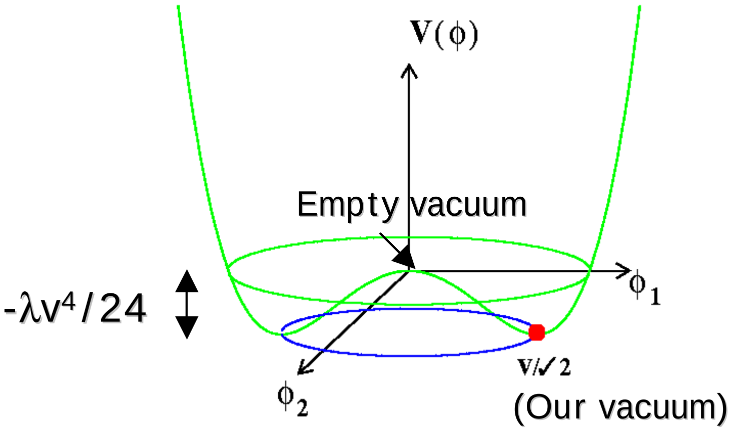
5. 2001, A Spoilt Odyssey

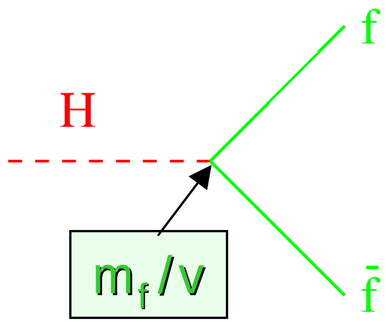
"Theory": SM Higgs Boson Mass and Couplings

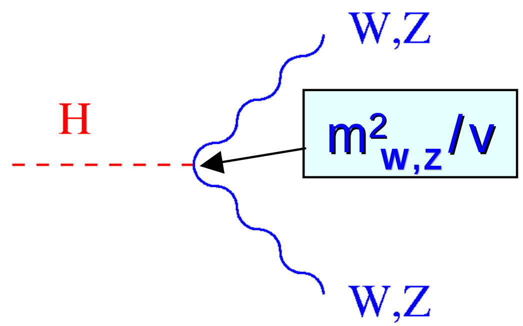
From the Higgs Mechanism ... and from Gauge Invariance :

$m_Z = m_W / \cos\vartheta_W$; $m_W = gv/2$; ($\rightarrow$ v ~ 250 GeV).

vacuum expectation value







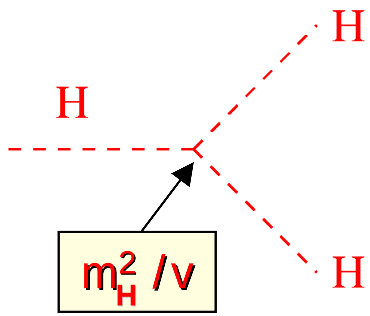
All couplings predicted

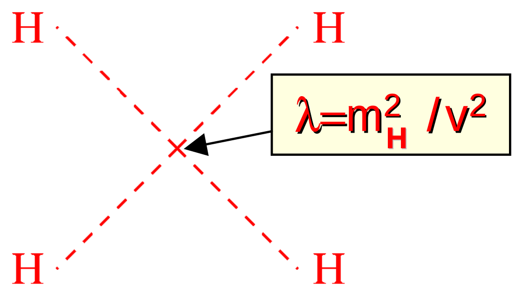
$$V(\phi) = \frac{\lambda}{3!}\left\{\bar{\phi}\phi - \mathrm{v}^2/2\right\}^2$$
$$= \frac{1}{2}\frac{\lambda \mathrm{v}^2}{3} H^2 + \frac{\lambda \mathrm{v}}{3!} H^3 + \frac{\lambda}{4!} H^4$$

(unknown)

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

Mass unknown



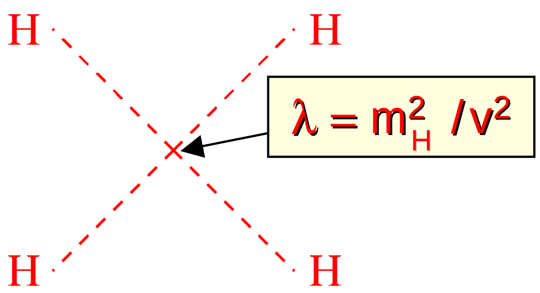


"Theory": SM Higgs Boson Mass

The mass m_H is mostly unknown, but ...

$$m_{\mathrm{Higgs}}^{\mathrm{EW}} = 108^{+57}_{-38}\ \mathrm{GeV}/c^2$$

(In the Standard Model)

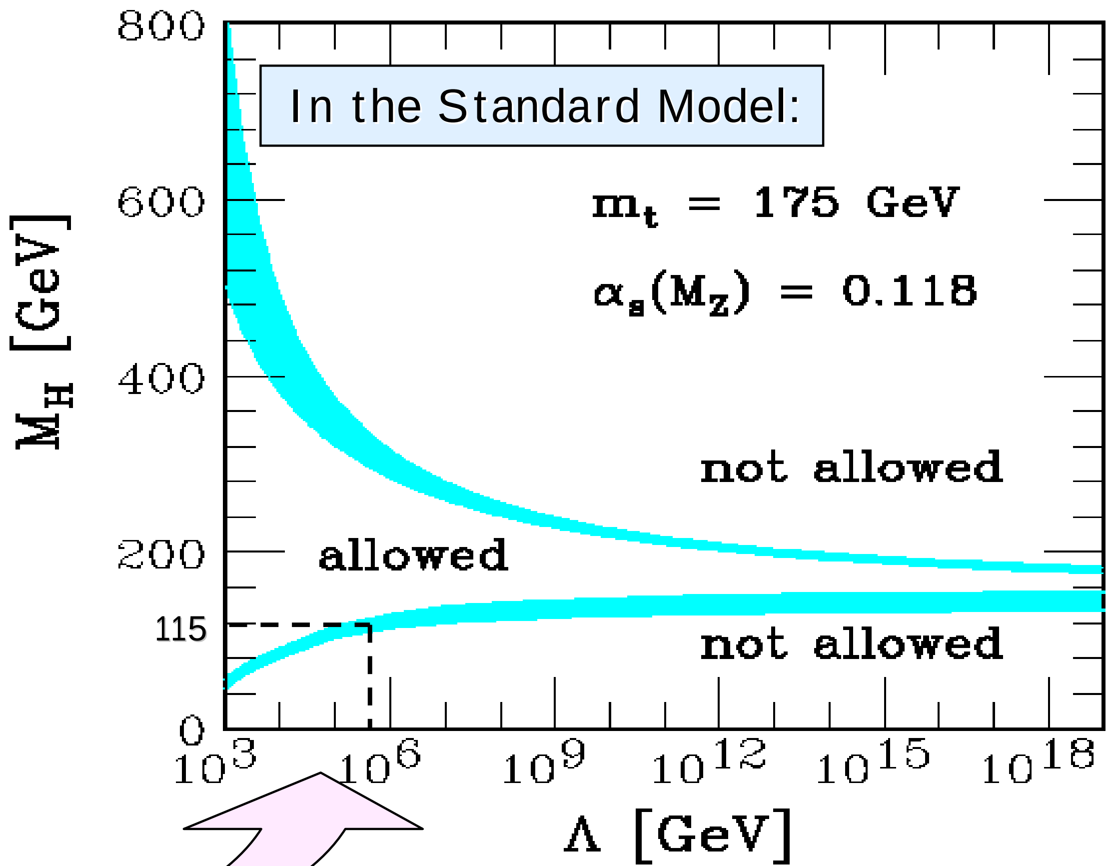


As for any other coupling constant, the particle content of the standard model determines the running of λ up to a scale Λ, at which the model is no longer valid.

The following conditions must be realized:

$$\boxed{0 \le \lambda(\Lambda) \le \infty}$$

Vacuum Stability   Triviality

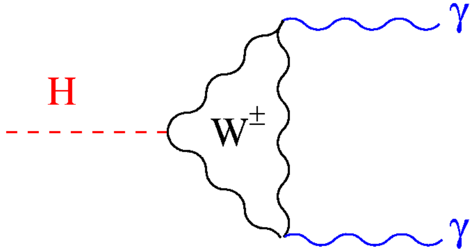


R.G.E.

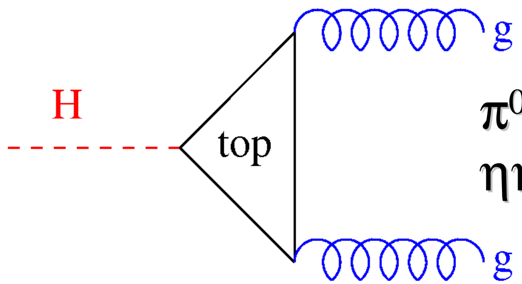
"Theory": SM Higgs Boson Decays

The decay branching ratios depend only on m_H:

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



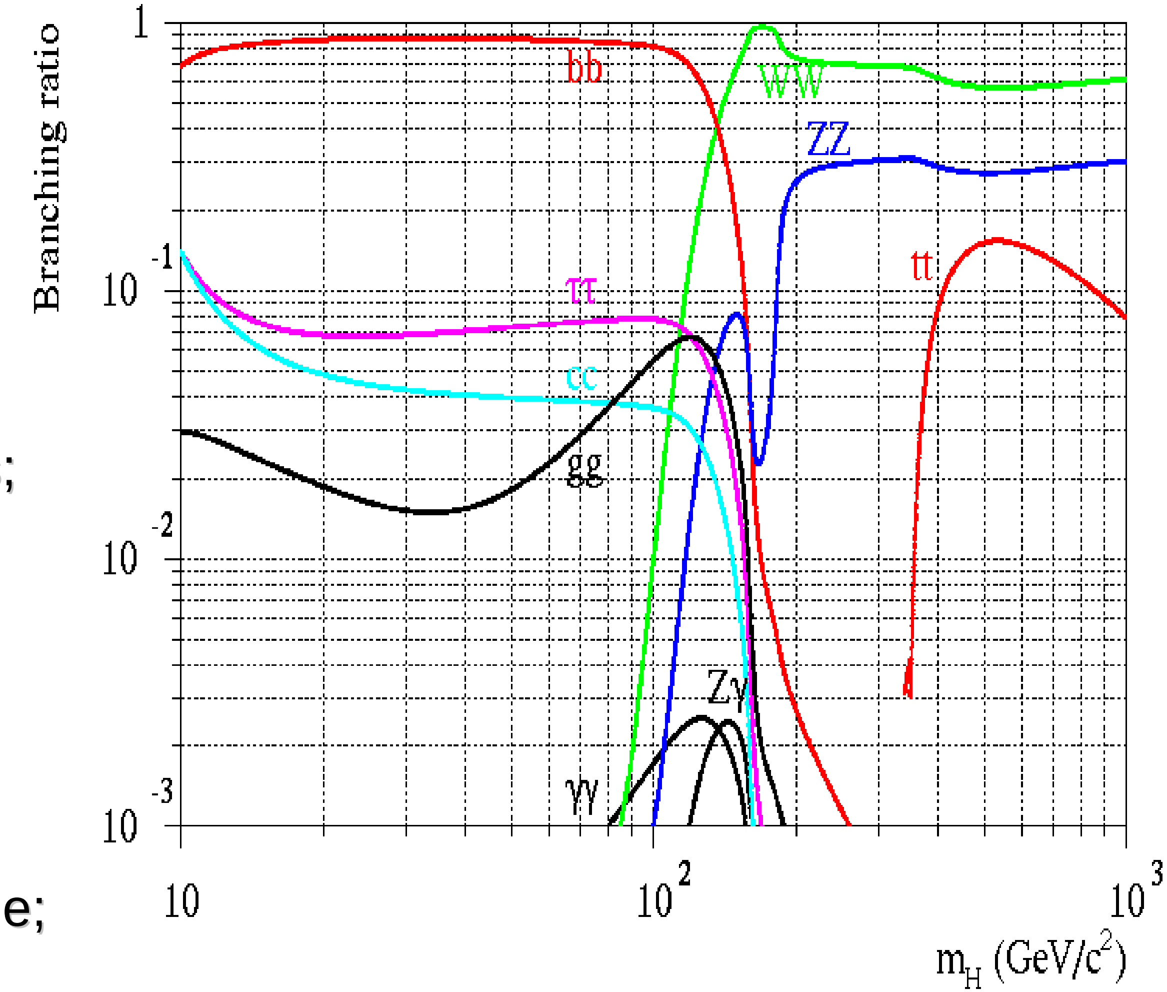
- $m_H < 2m_\mu$: $H \to e^+e^-$ dominates;
- $m_H < 2m_\pi$: $H \to \mu^+\mu^-$ dominates;
- $m_H <$ 3 - 4 GeV: $H \to gg$ dominates;



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

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

- $m_H > 2m_b$ up to 1000 GeV/c²:

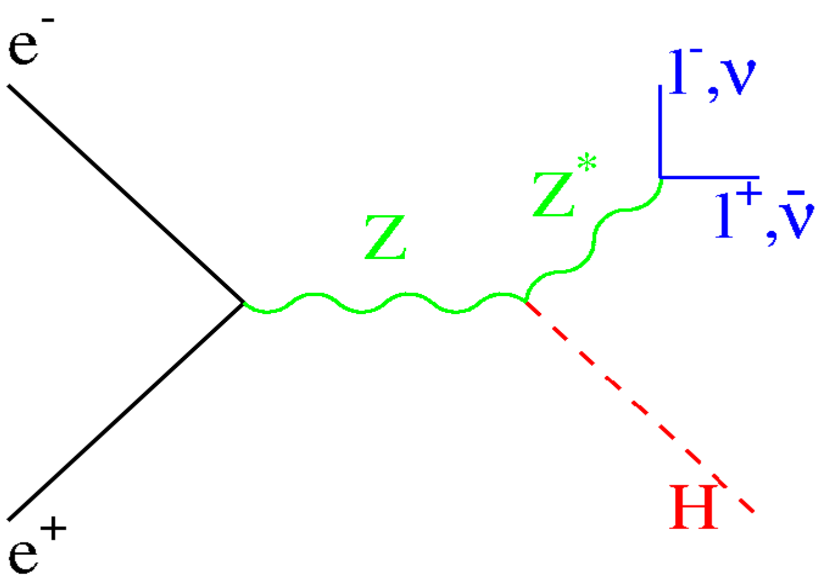


"Theory": SM Higgs Boson Production at LEP

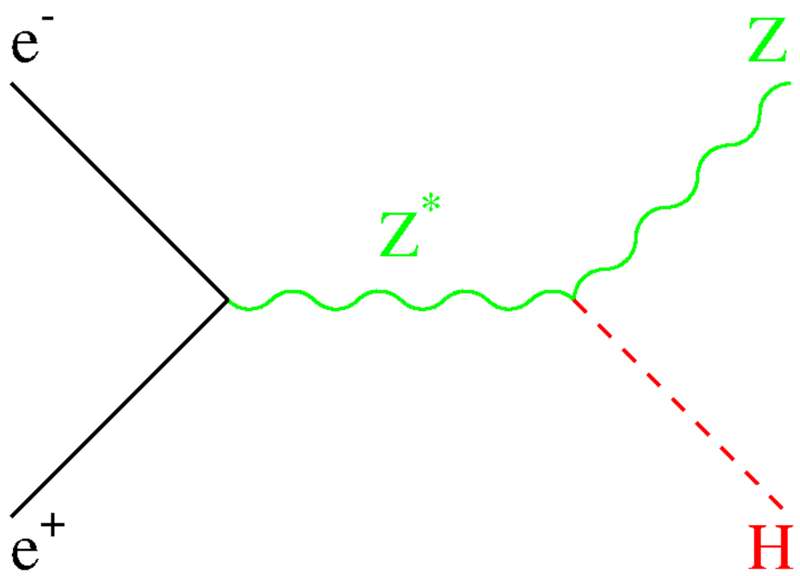
Dominant at LEP: The Higgs-strahlung process

(The production cross section depends only on m_H)

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



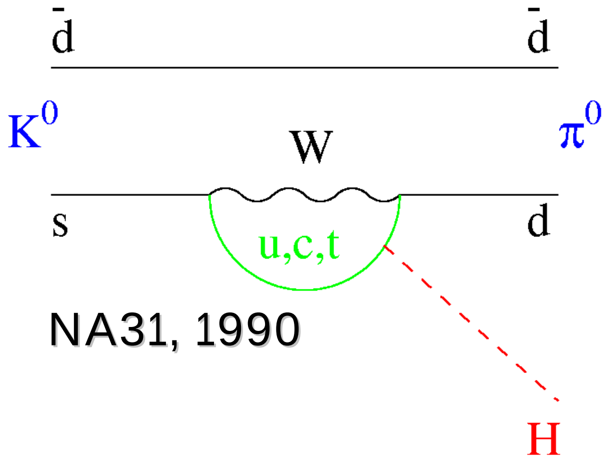
LEP 2: $\sqrt{s} \geq m_Z + m_H$



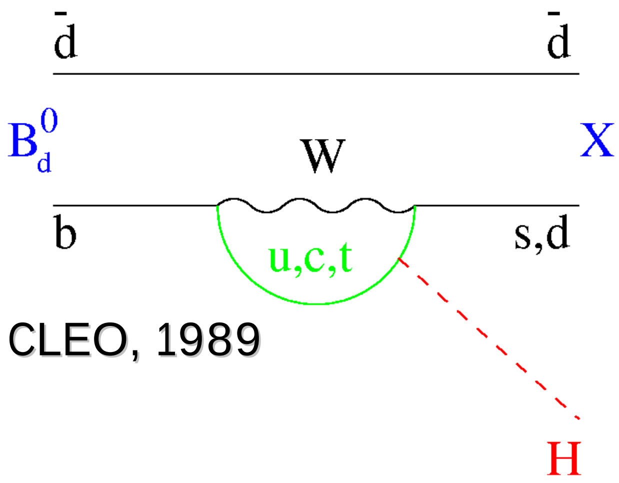
(Large coupling to the Z $\Rightarrow$ Only sizeable cross section)

The situation before LEP (I)

Quite a few searches in hadron decays:



NA31, 1990

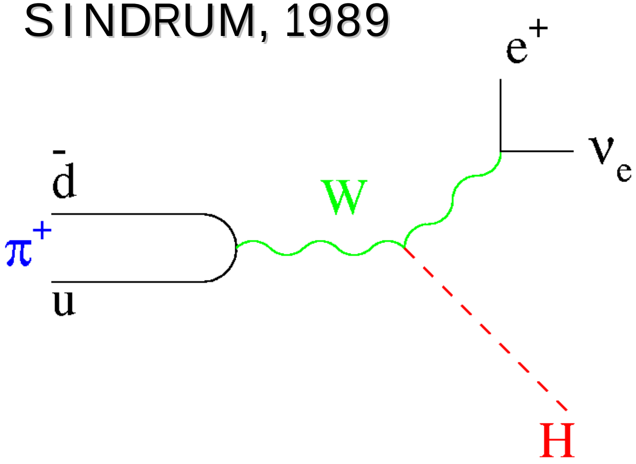


CLEO, 1989

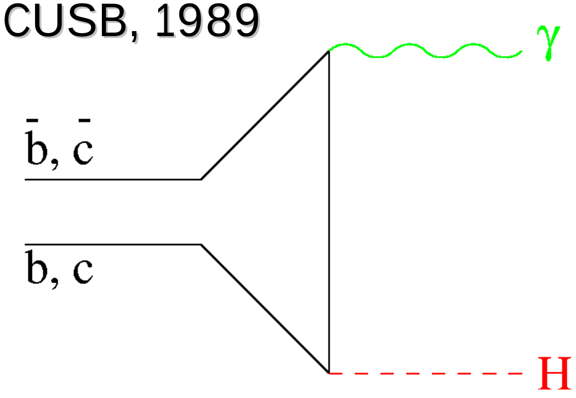
No excess seen, but...

No unambiguous limit set

SINDRUM, 1989



CUSB, 1989



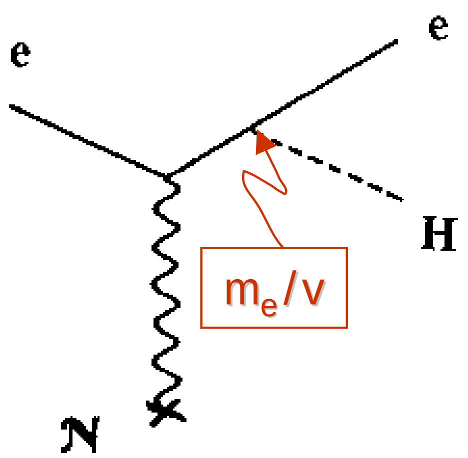
(Large theoretical uncertainties
on the predicted decay rates.)

The situation before LEP (II)

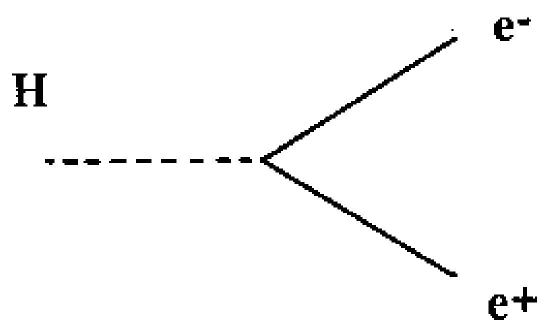
Only one unambiguous limit:

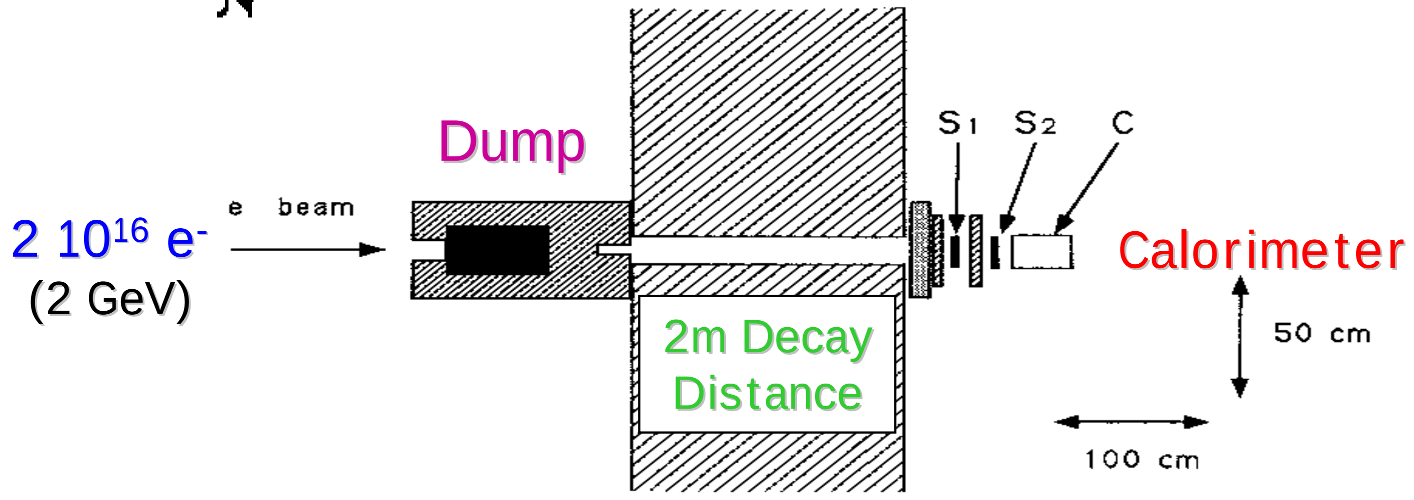
M. Davier and H. Nguyen Ngoc, 1990

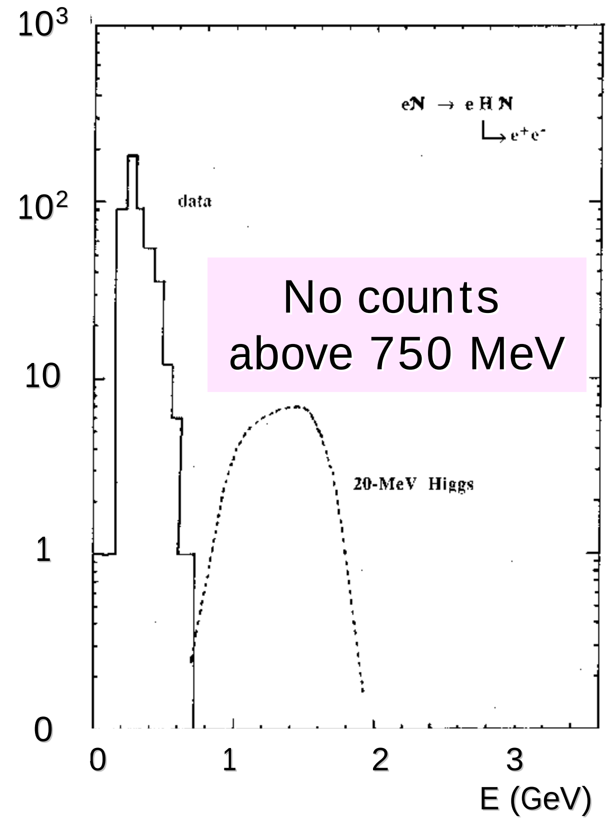
1) Production:



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



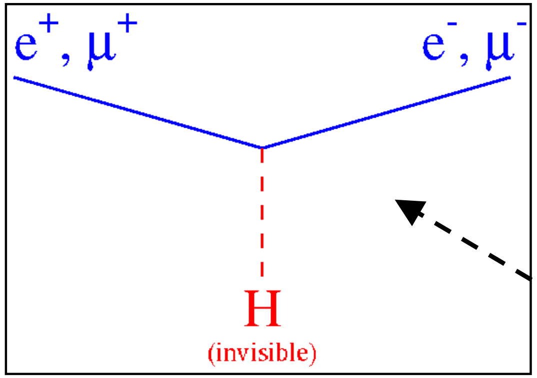




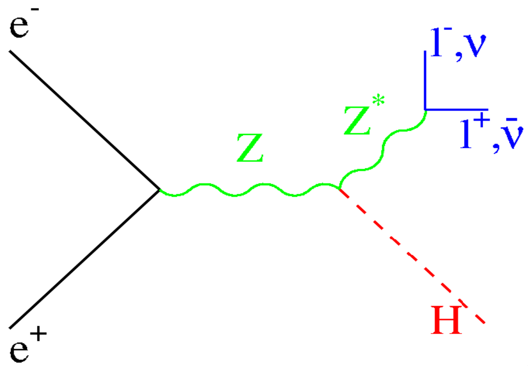
$$1.2\ \mathrm{MeV}/c^2 < m_H < 52\ \mathrm{MeV}/c^2$$

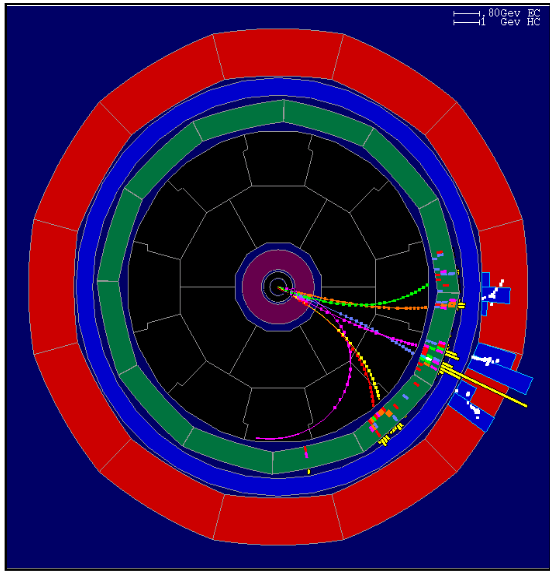
Excluded at 95% C.L.

Direct Searches at LEP 1



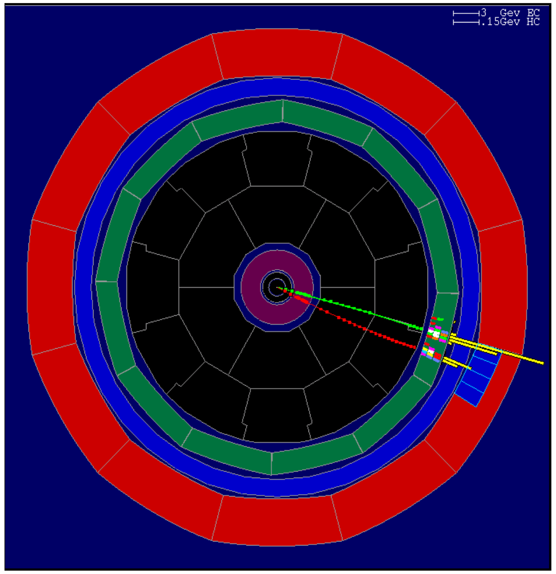
Acoplanar lepton pairs

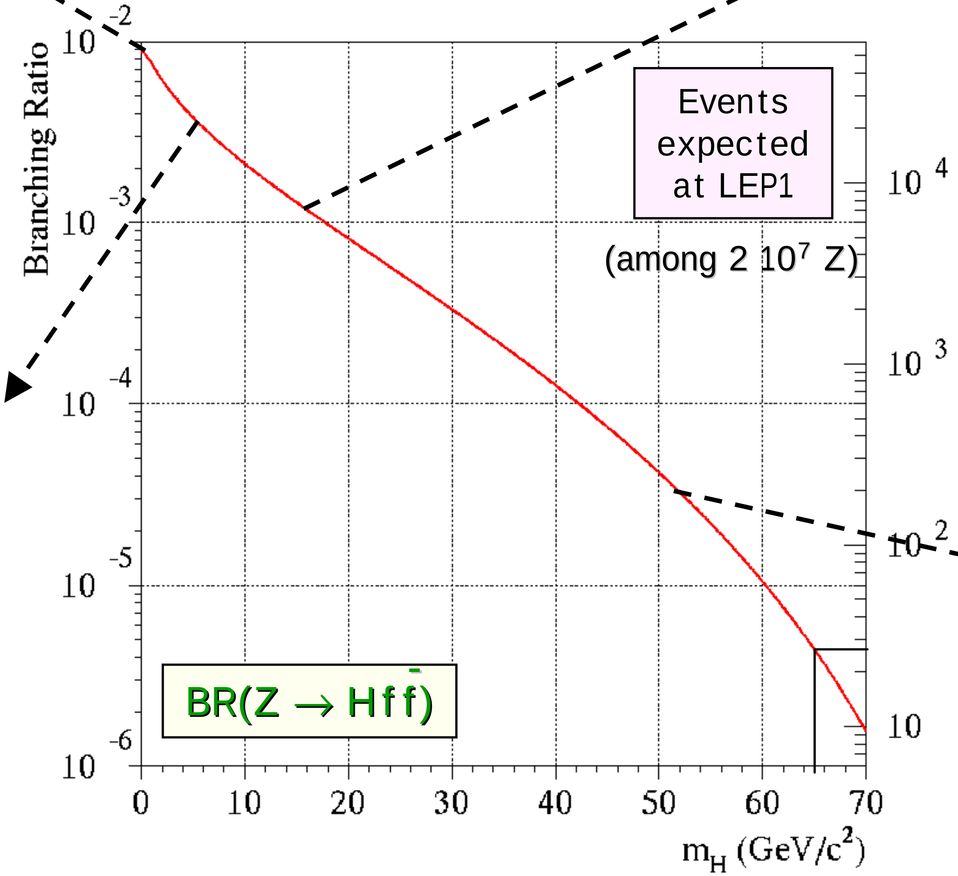




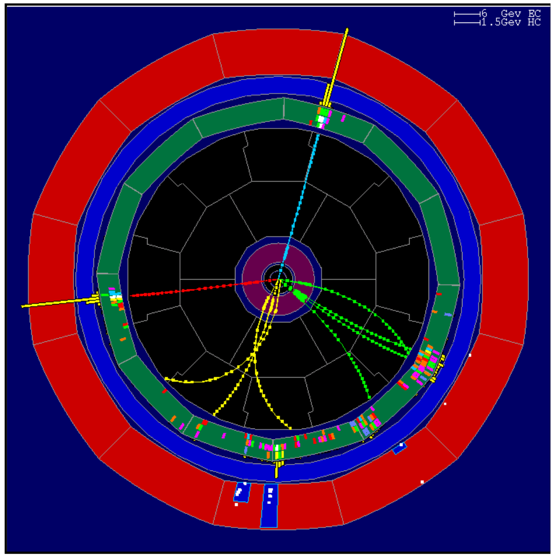
Monojets

Acoplanar pairs





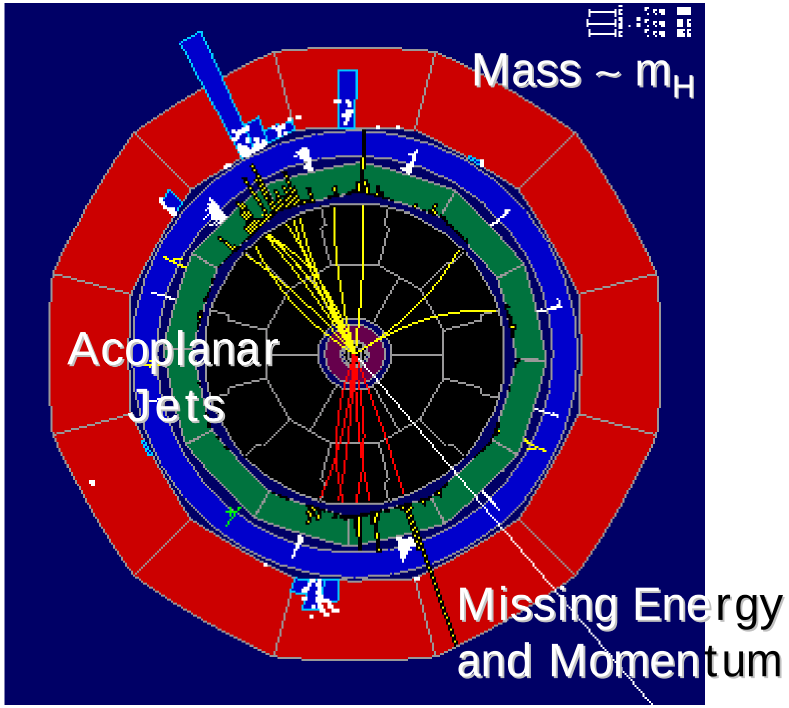
Acoplanar jets

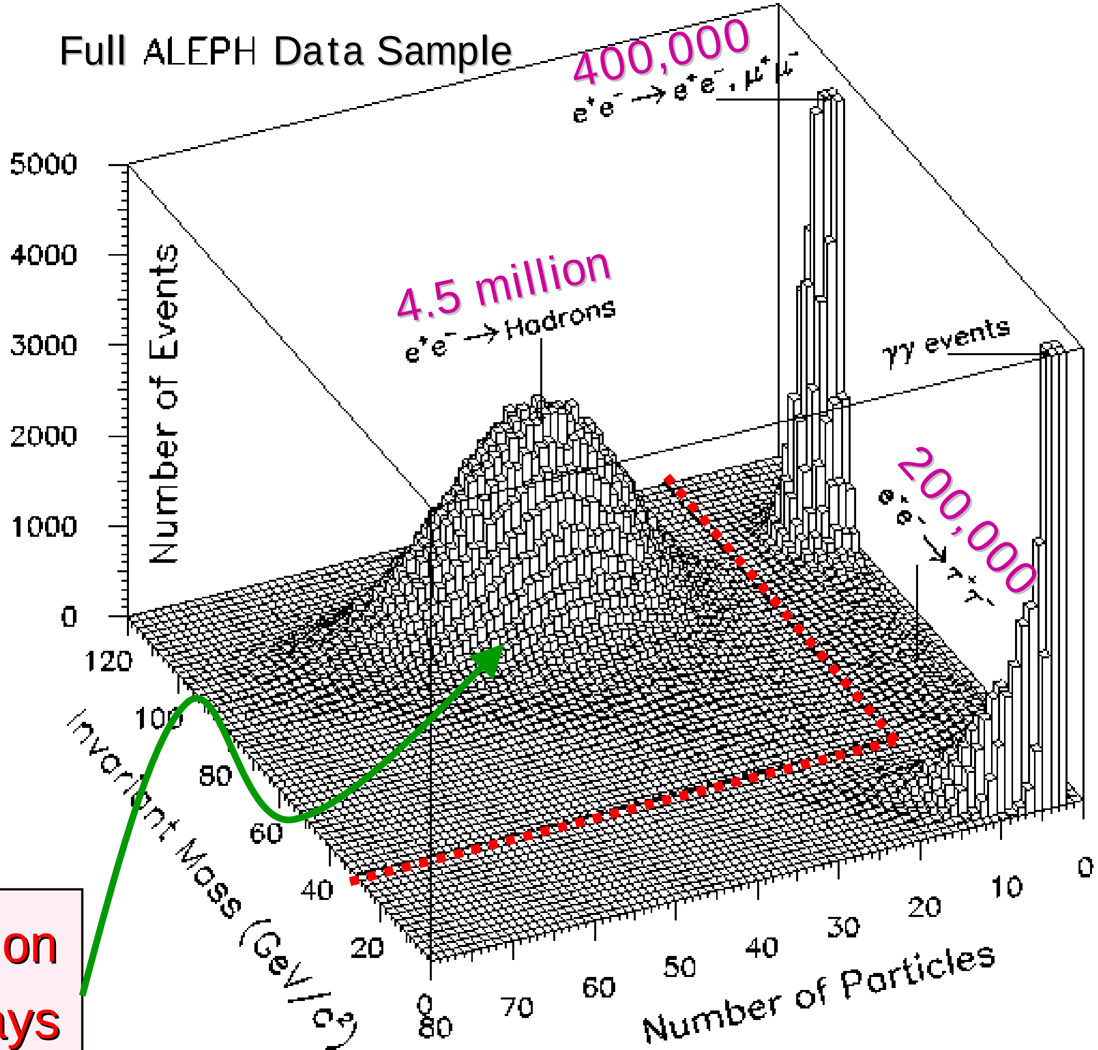


Very little background expected

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

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



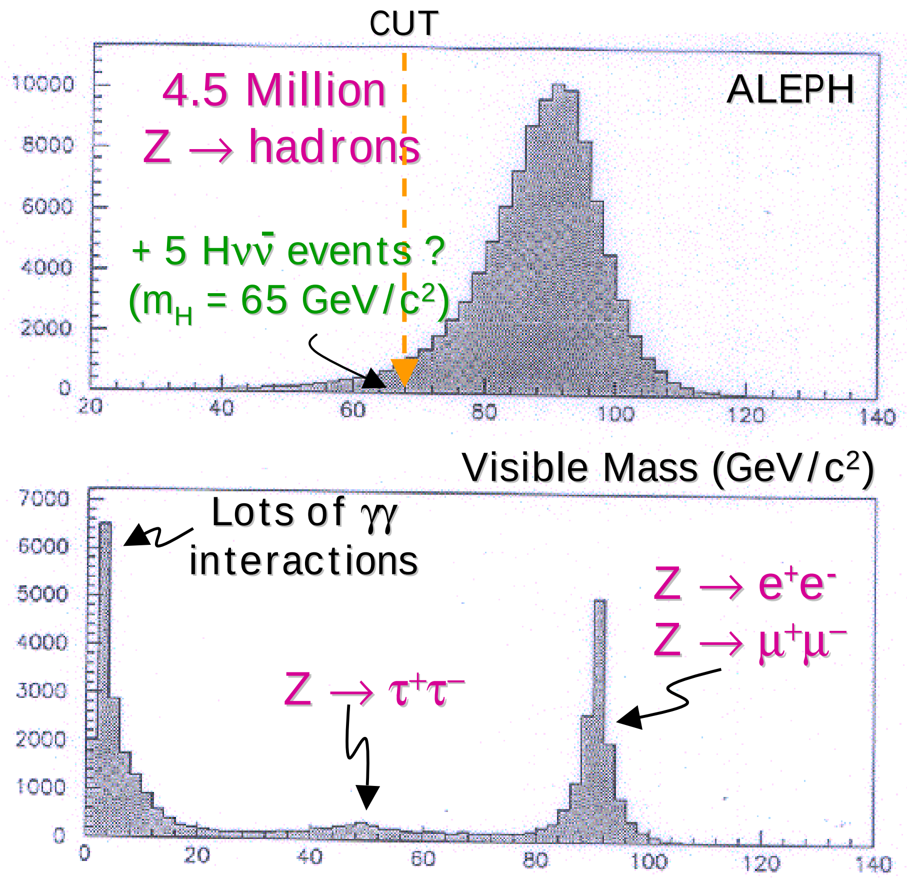


Within more than 20 million other events from Z decays (or from other processes)

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

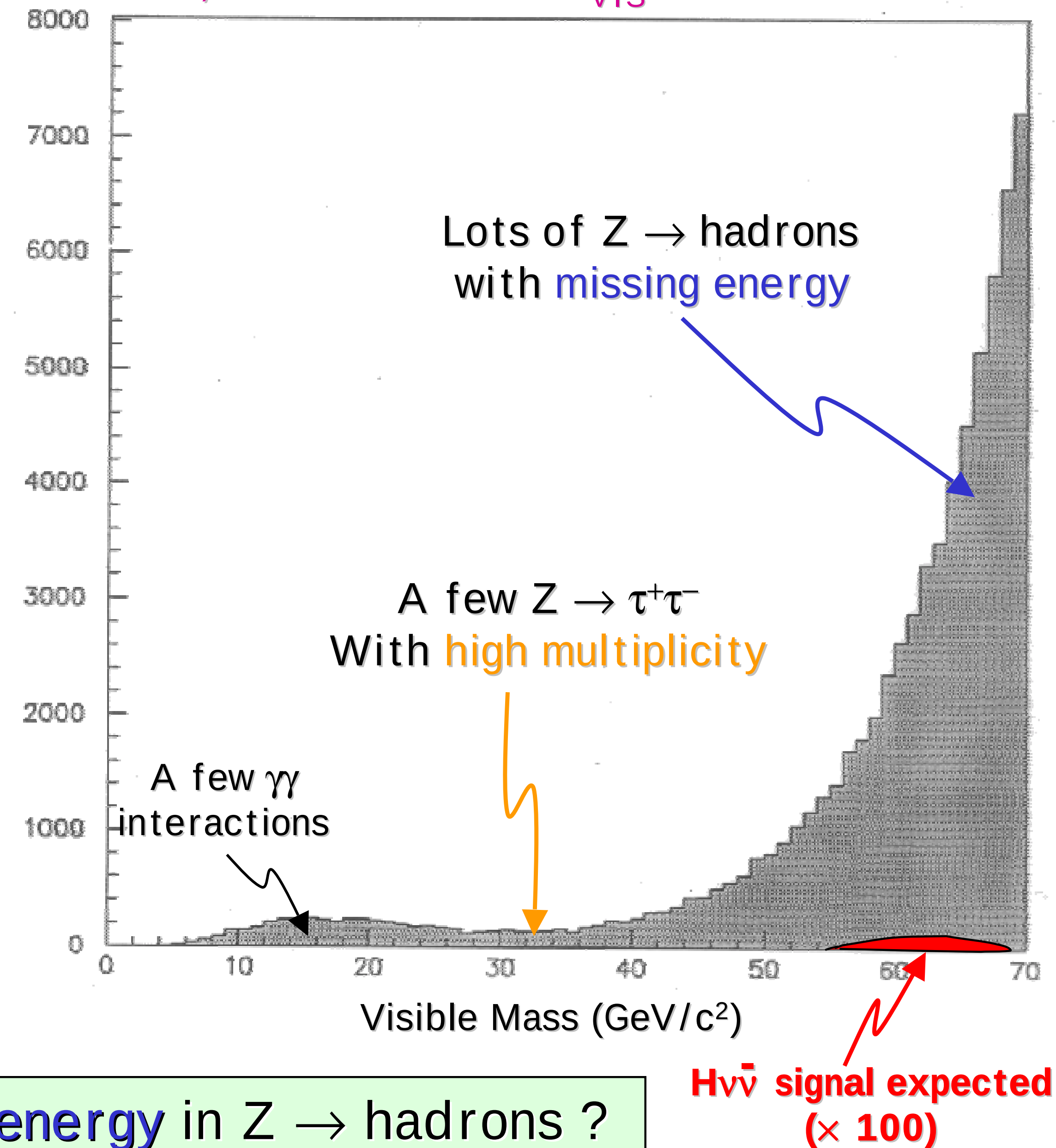
Two main subsamples:

1) High Multiplicity (Selected)



2) Low Multiplicity (Rejected)

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



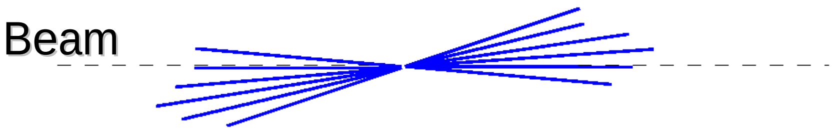
Origin of missing energy in $Z \rightarrow$ hadrons ?

Energy Losses in the Beam Pipe

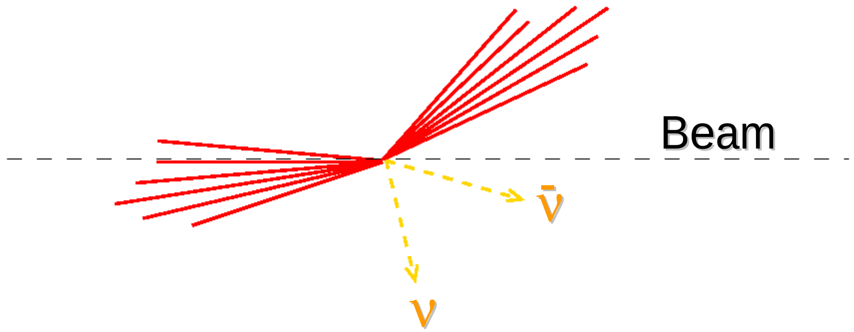
(Not instrumented)

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

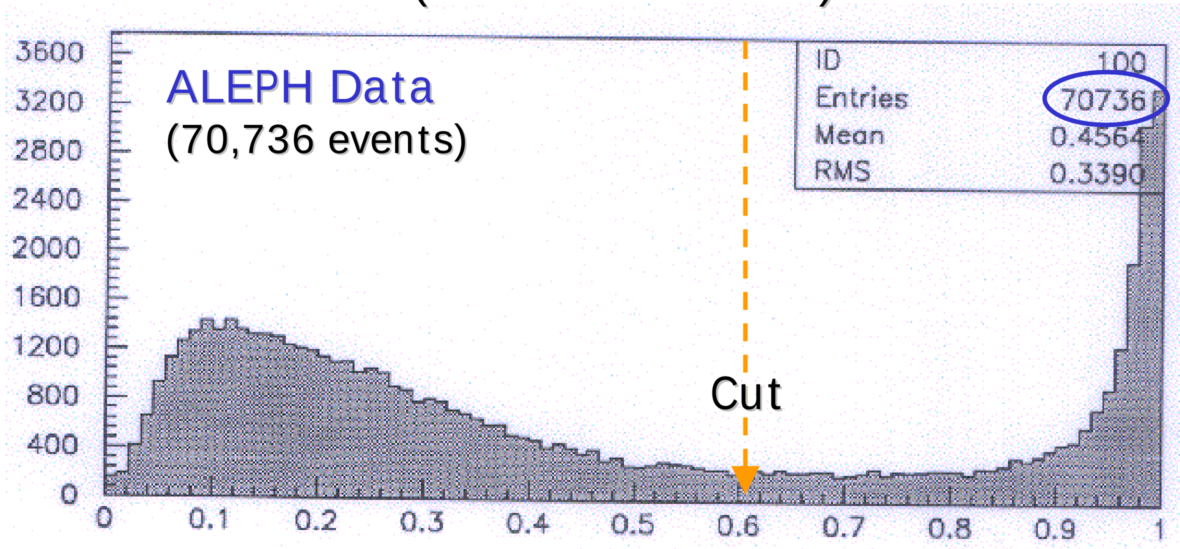
Two back-to-back jets

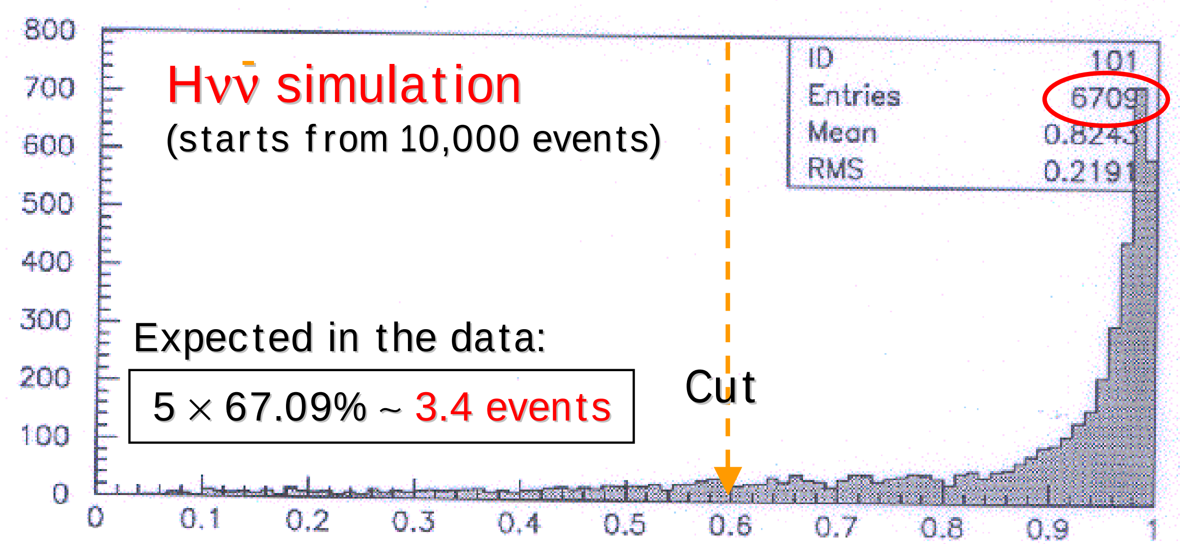


$H\nu\bar{\nu}$ signal



$X_{30} \geq 60\%$



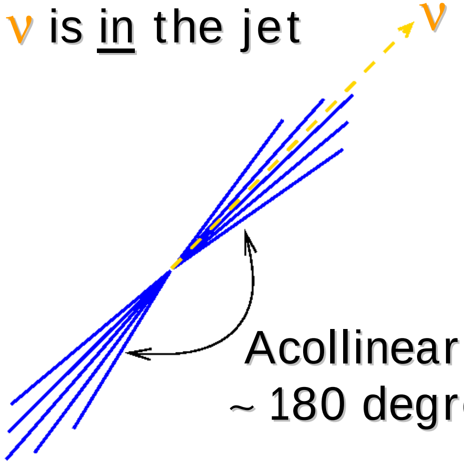


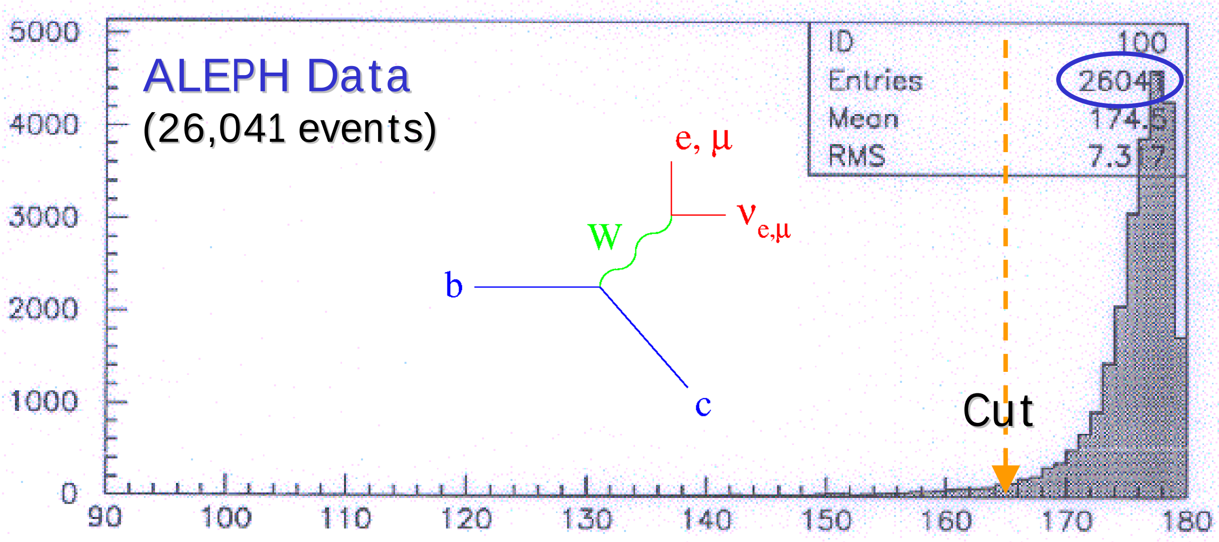
X_{30} = Fraction of measured energy above 30 degrees from the beam axis

Energy Losses in Semi-Leptonic b decays

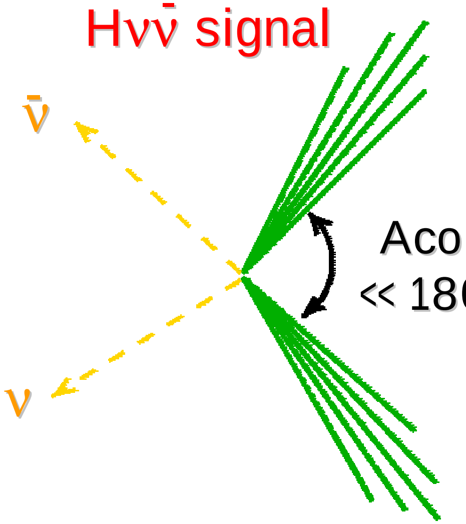
$Z \rightarrow b\bar{b}$ events:

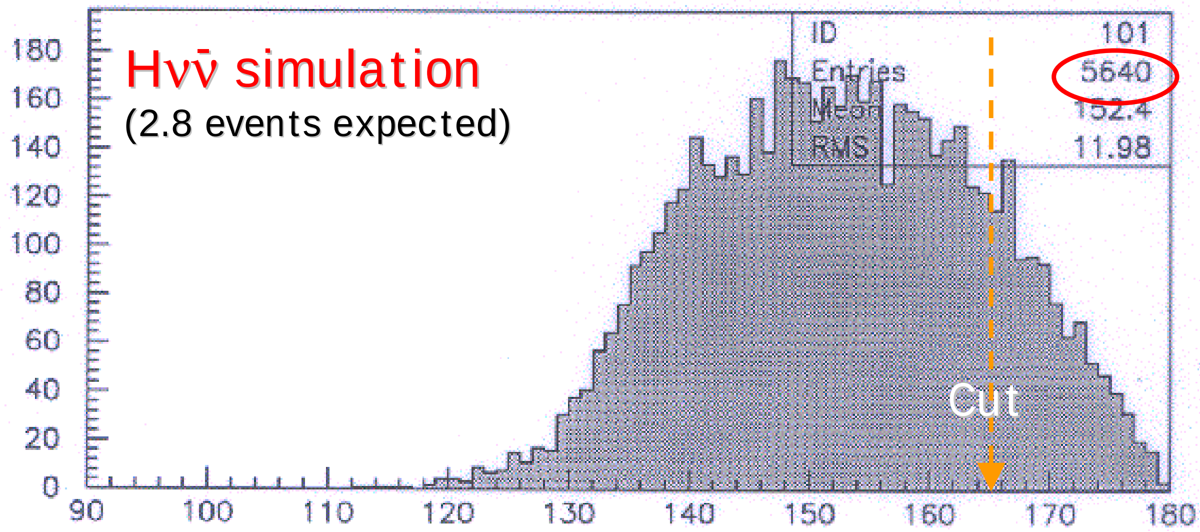
The ν is in the jet





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





Acollinearity Angle (Degrees)

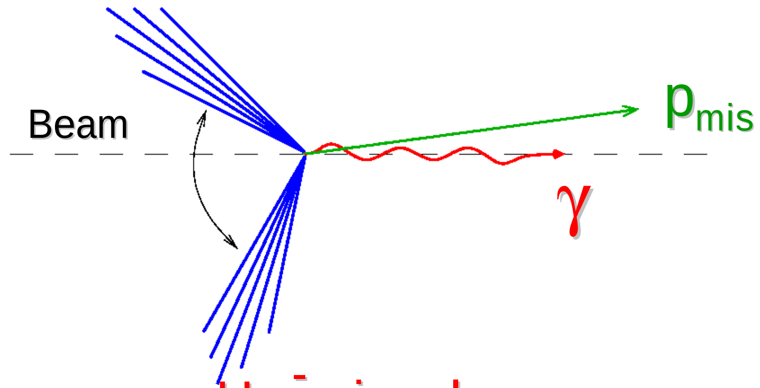
Acoll. ≤ 165 deg.

Energy Losses due to I.S.R.

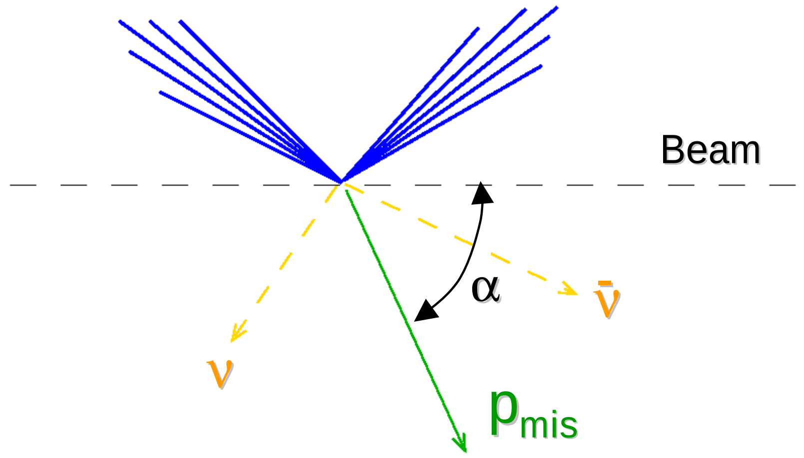
(Initial State Radiation)

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

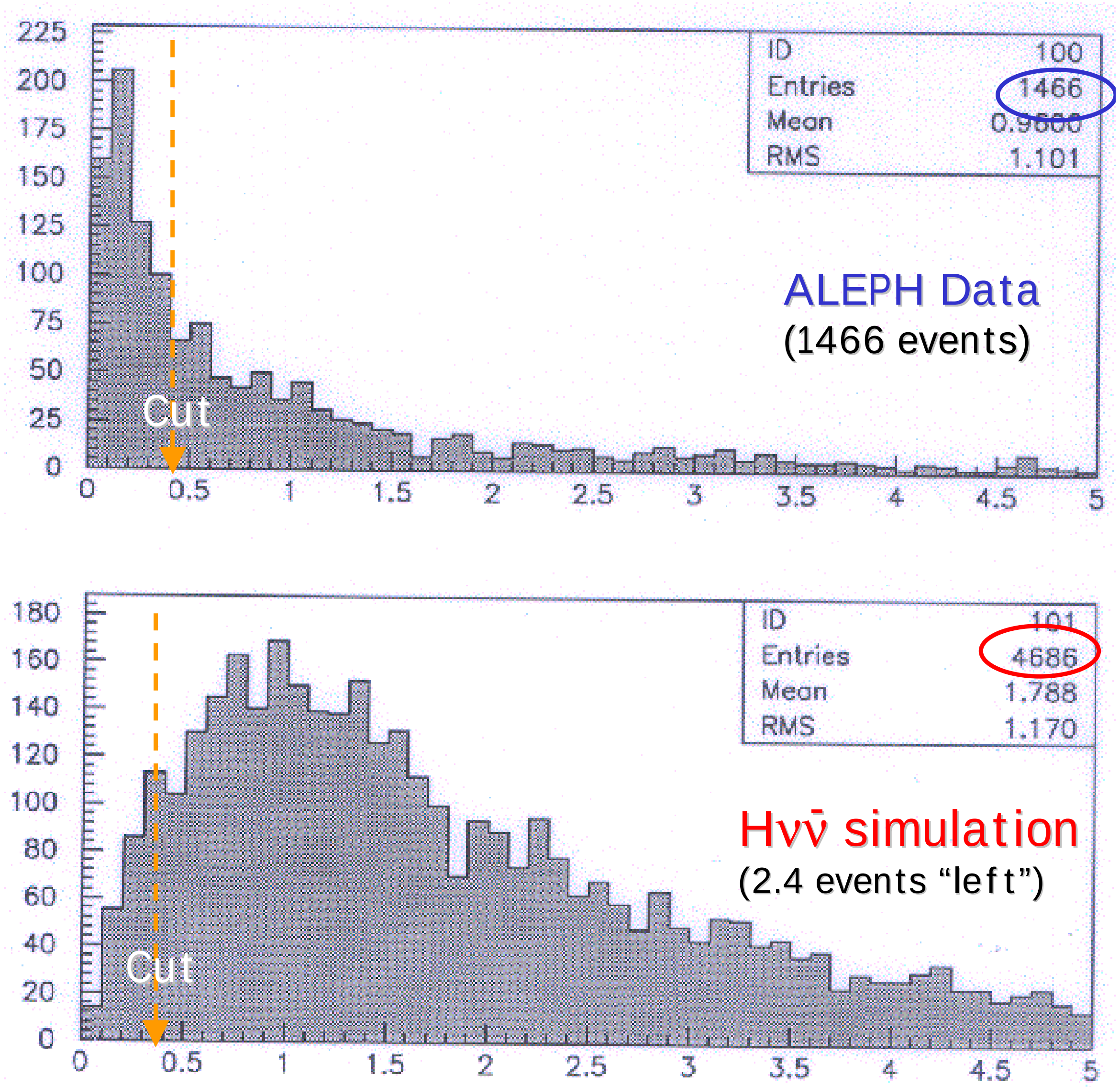
The p_{mis} is along the beam



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



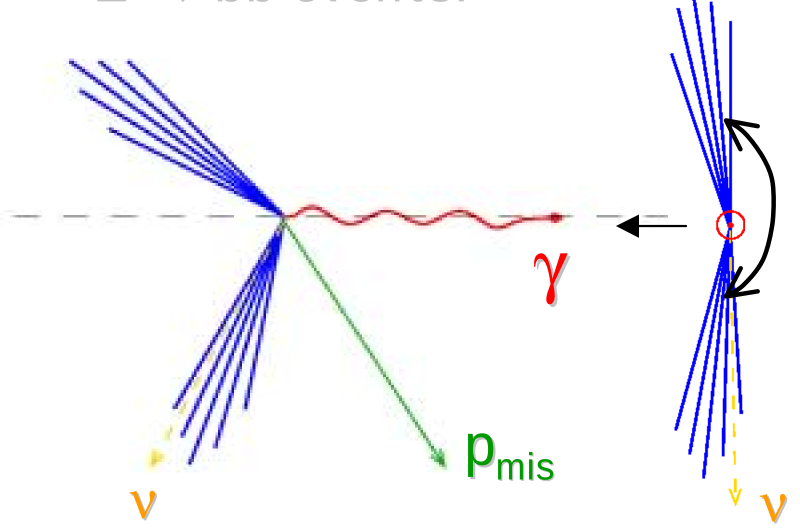
$\tan\alpha \geq 0.4$

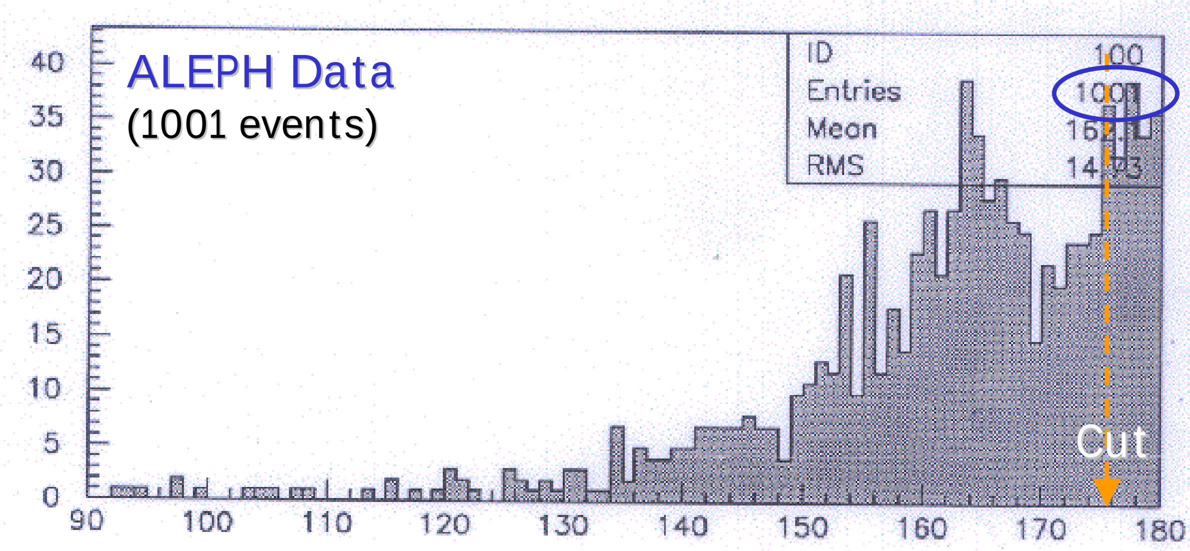


$\tan\alpha$

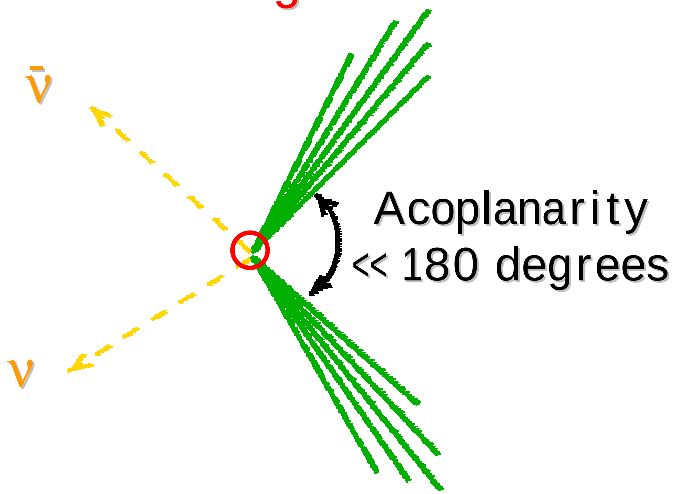
Energy Losses due to I.S.R. + Semi-Leptonic b decay

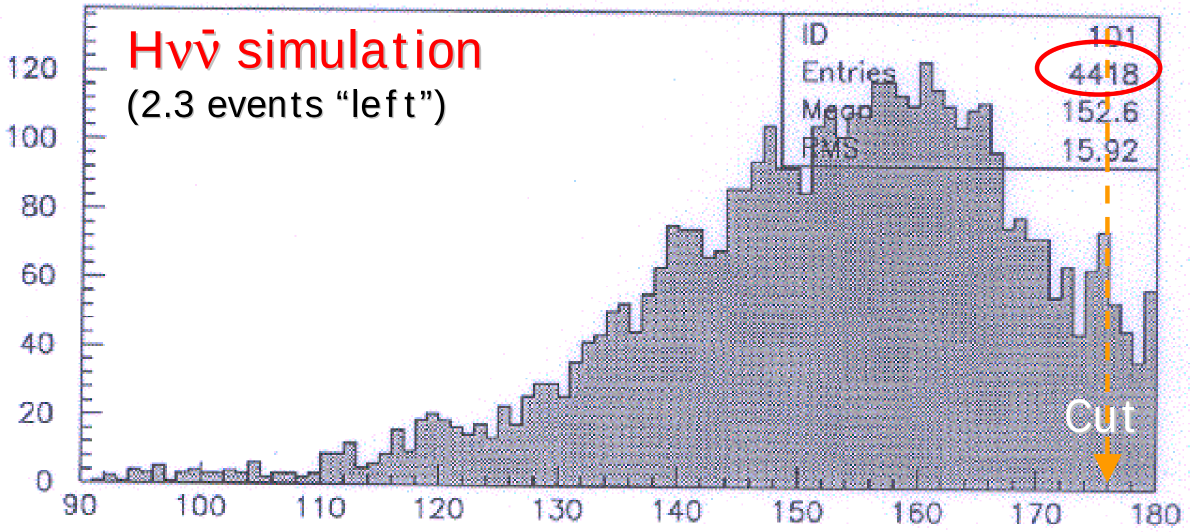
$Z \rightarrow b\bar{b}$ events:





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





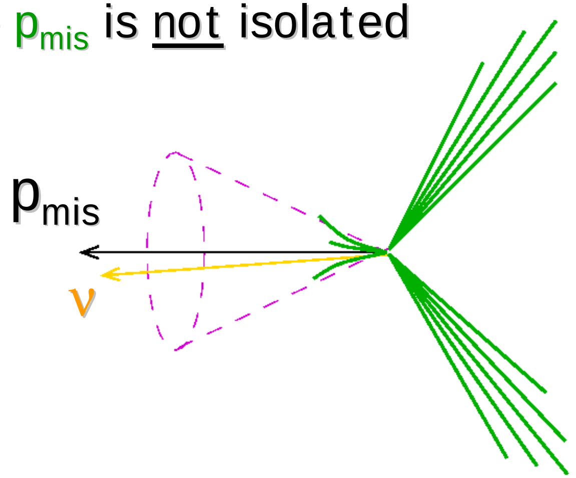
Acoplanarity Angle (Degrees)

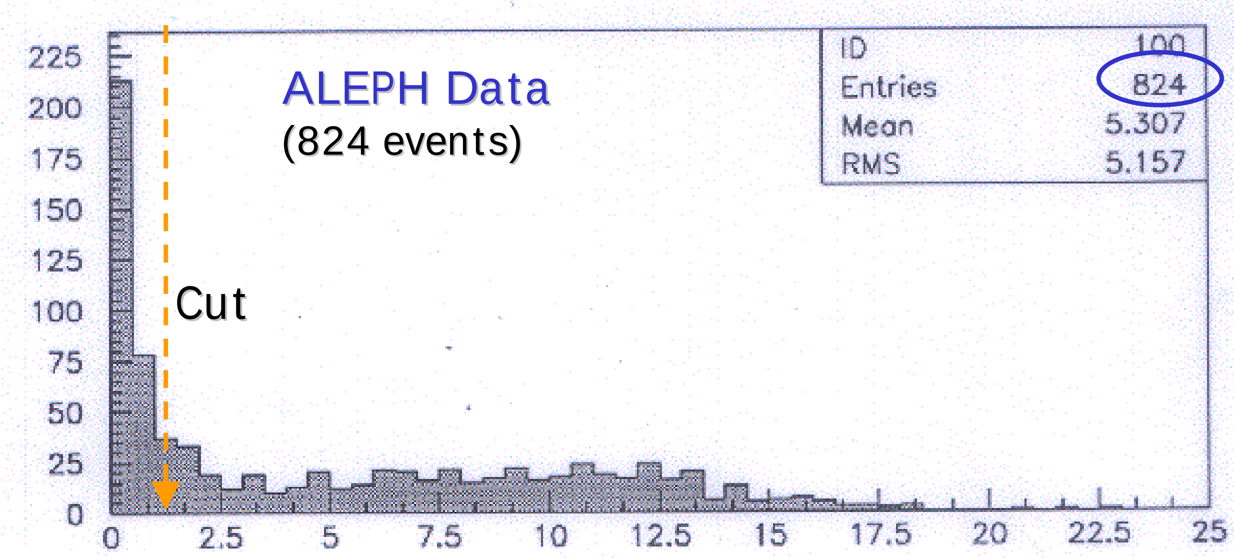
Acop. ≤ 175 deg.

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

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

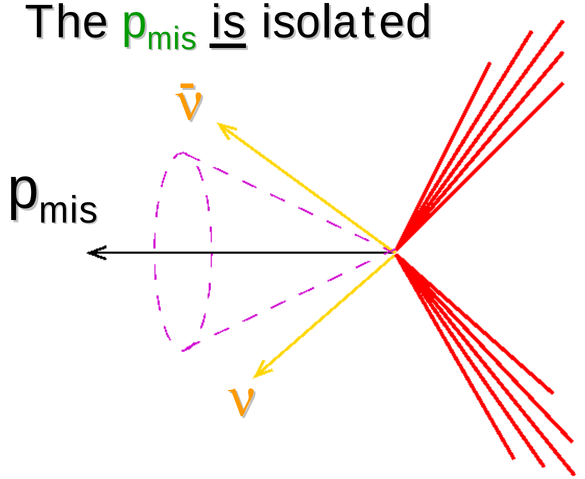
The p_{mis} is not isolated

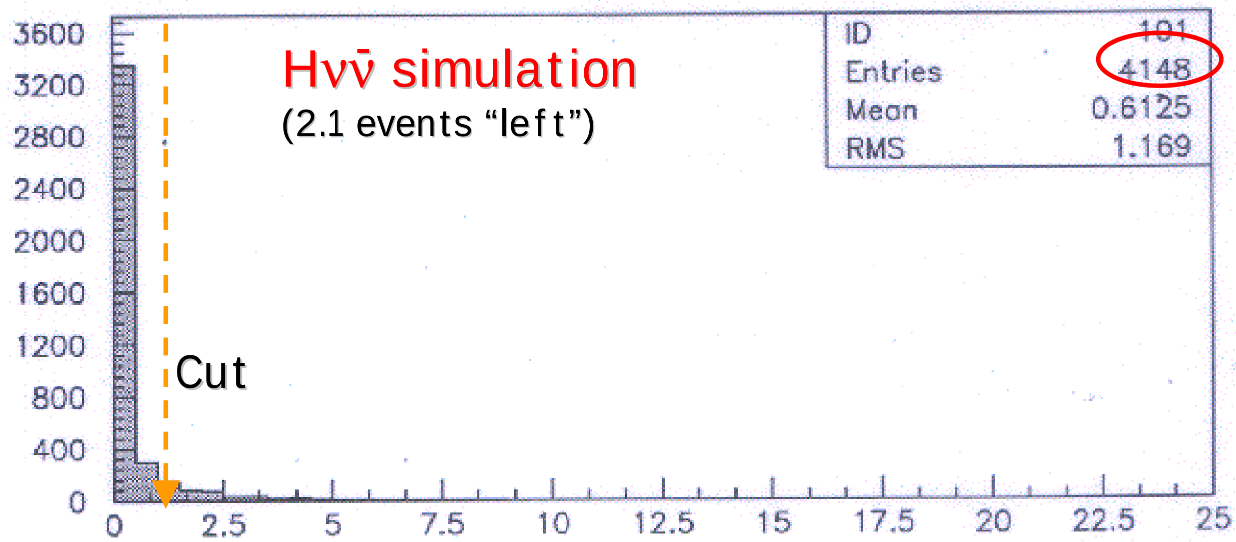




$H\nu\bar{\nu}$ signal:

The p_{mis} is isolated





$E_{CONE} \leq 1$ GeV

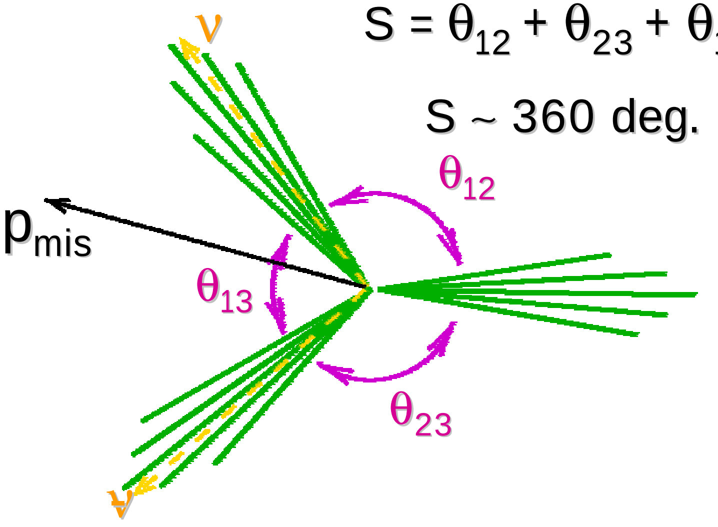
E_{CONE} (GeV) = Energy contained in a cone of half-angle 30 degrees around p_{mis}

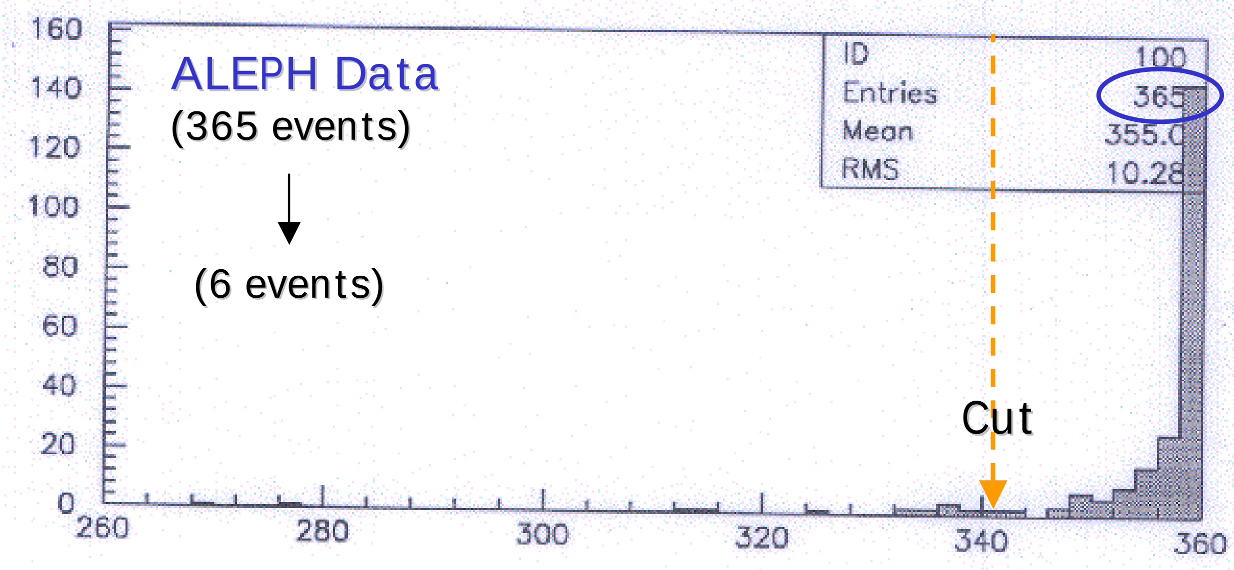
Two Semi-Leptonic decays in $b\bar{b}g$ (3-jet) events

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

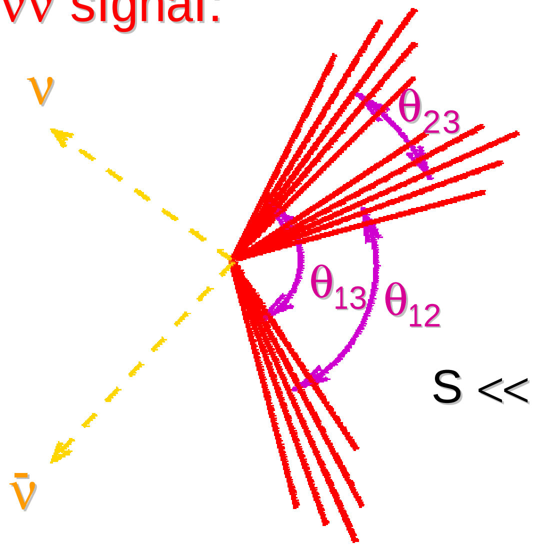
$S = \theta_{12} + \theta_{23} + \theta_{13}$

$S \sim 360$ deg.

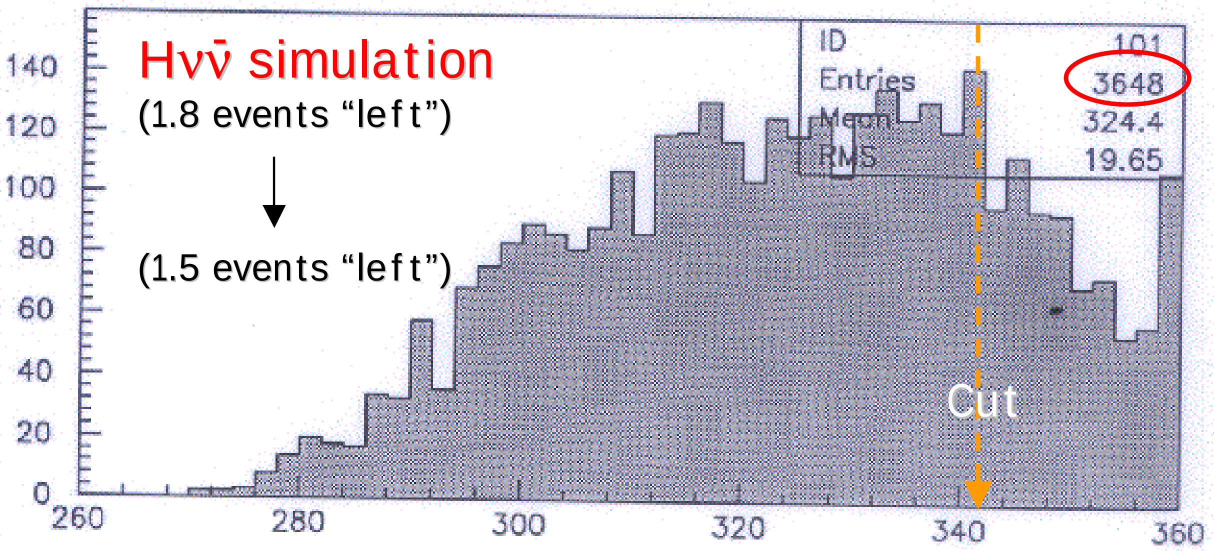




$H\nu\bar{\nu}$ signal:



$S \ll 360$ deg.

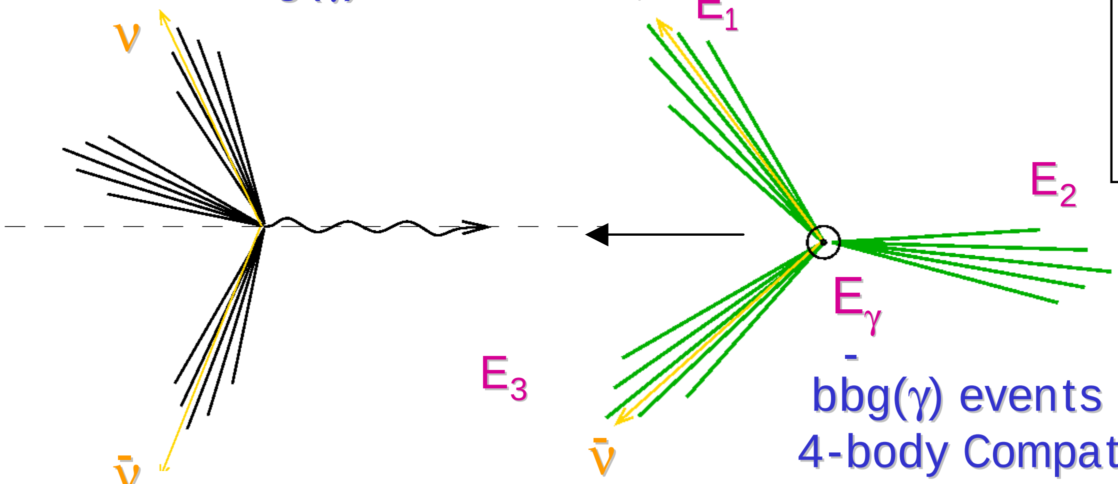


$S \leq 342$ degrees

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

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

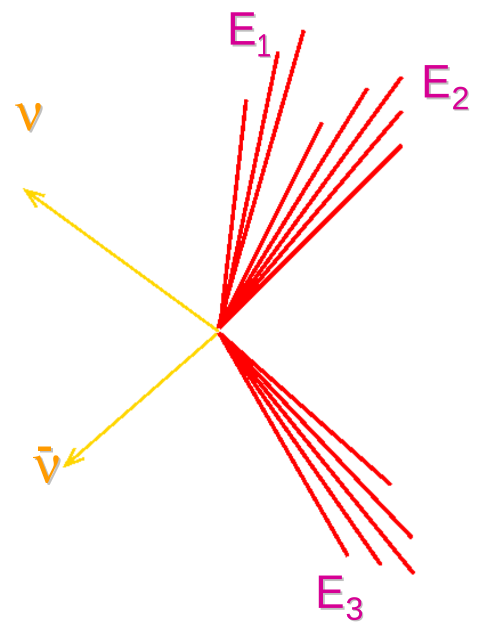
$e^+e^- \to b\bar{b}g(\gamma)$ events:



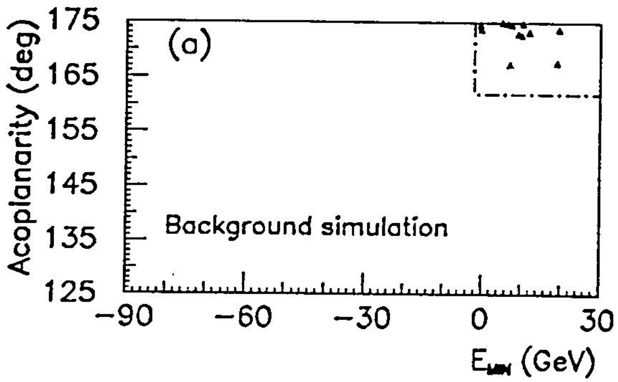
E_1, E_2, E_3, E_γ = Energies Recomputed with energy-momentum conservation constraint

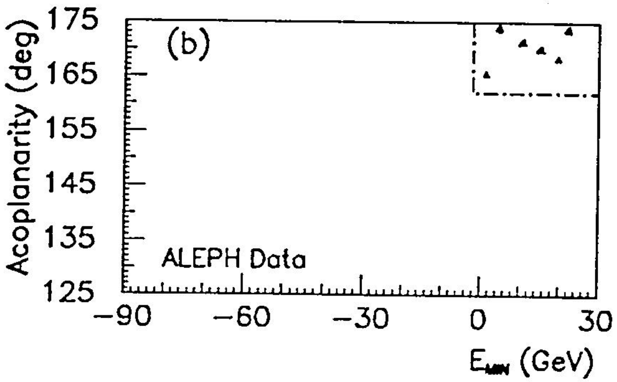
E_{MIN} = MIN (E_1, E_2, E_3)

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

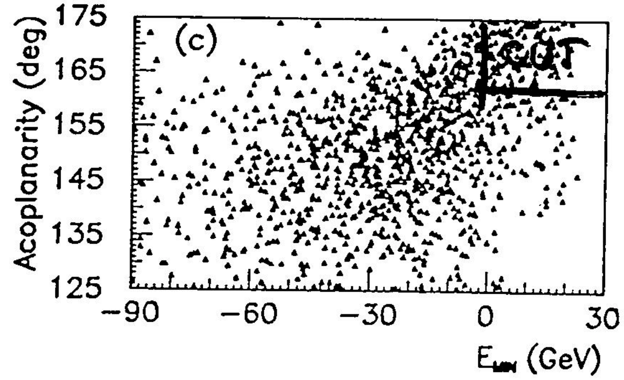


$b\bar{b}g(\gamma)$ events are 4-body Compatible: E_{MIN} is positive





Signal simulation

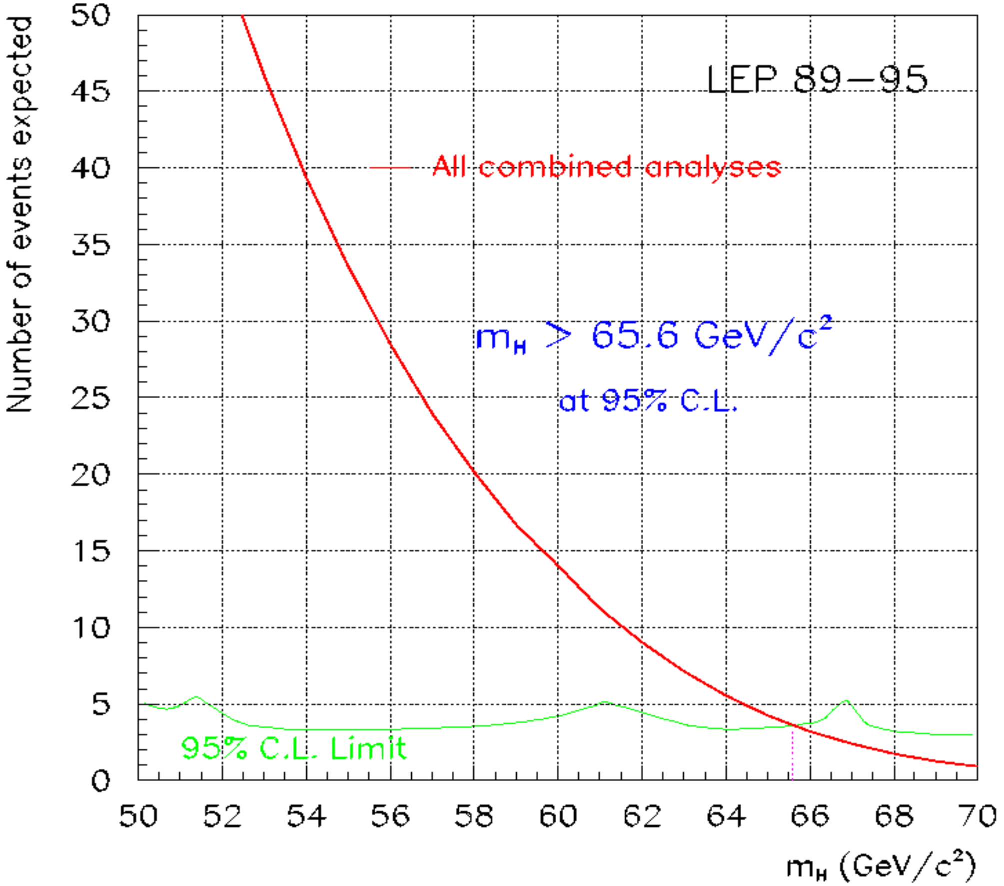


$H\nu\bar{\nu}$: The three jets are in the same hemisphere. One of the E_i tend to be negative

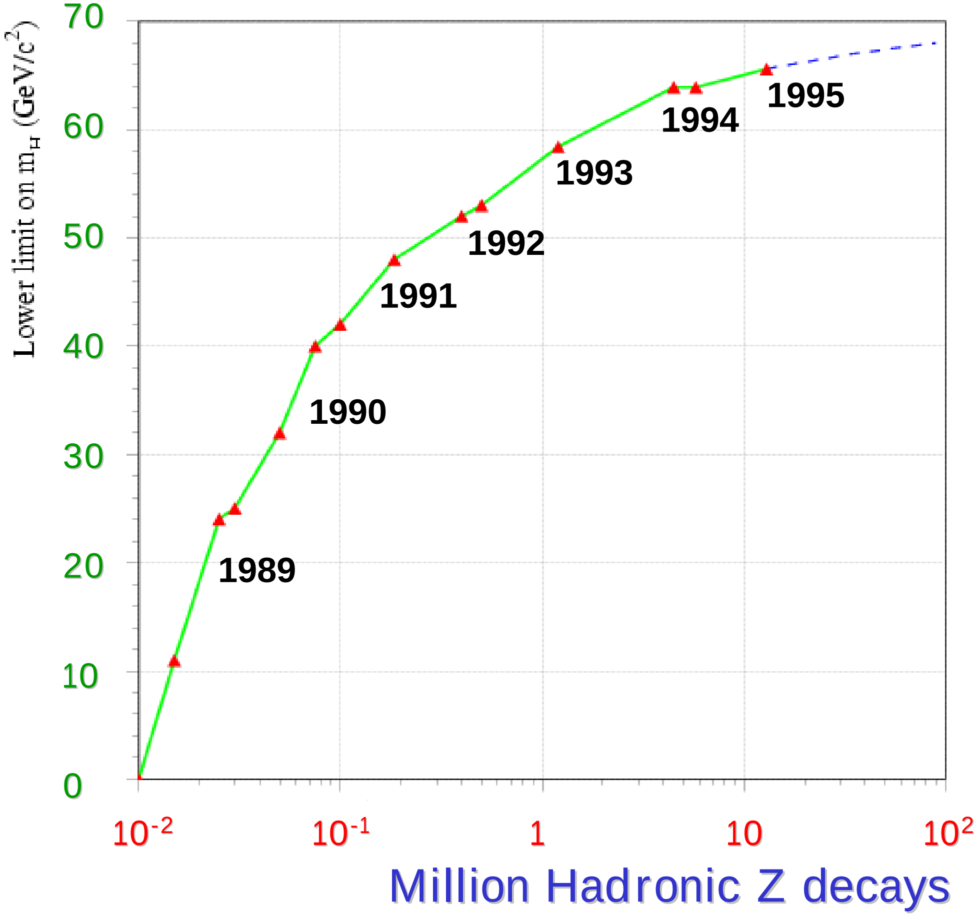
No events left in the data;
Still 1.3 event expected from $H\nu\bar{\nu}$

Higgs Boson Searches at LEP 1: Result

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



Saturation was being reached:

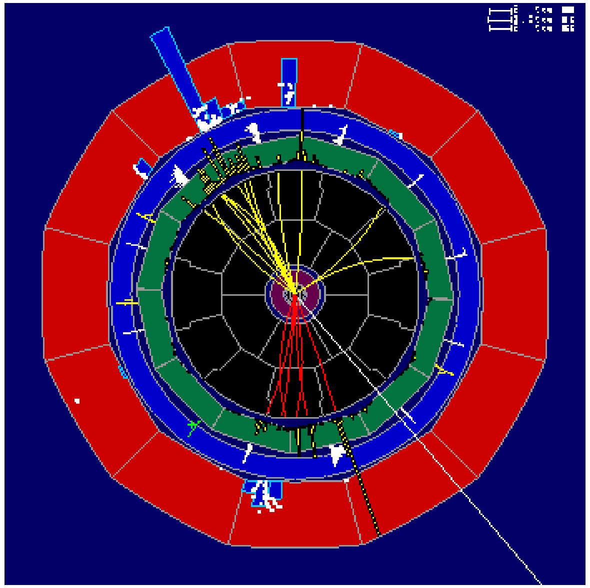


$0.0 < m_H < 65.6$ GeV/c^2
Excluded at 95% C.L.

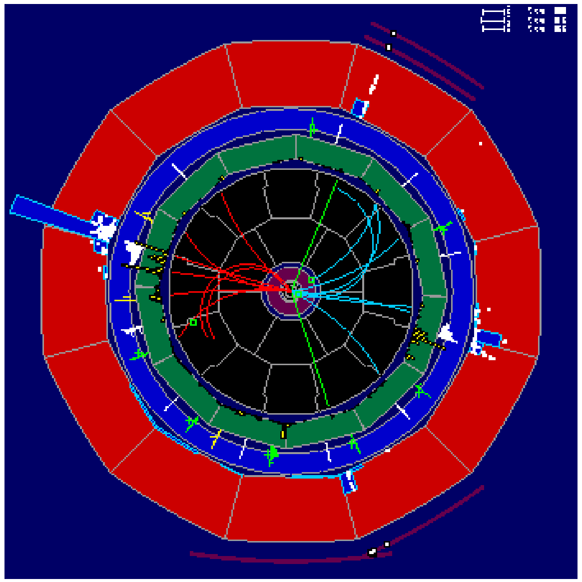
GO FOR LEP 2 !

Direct Searches at LEP 2

$H\nu\bar{\nu}$

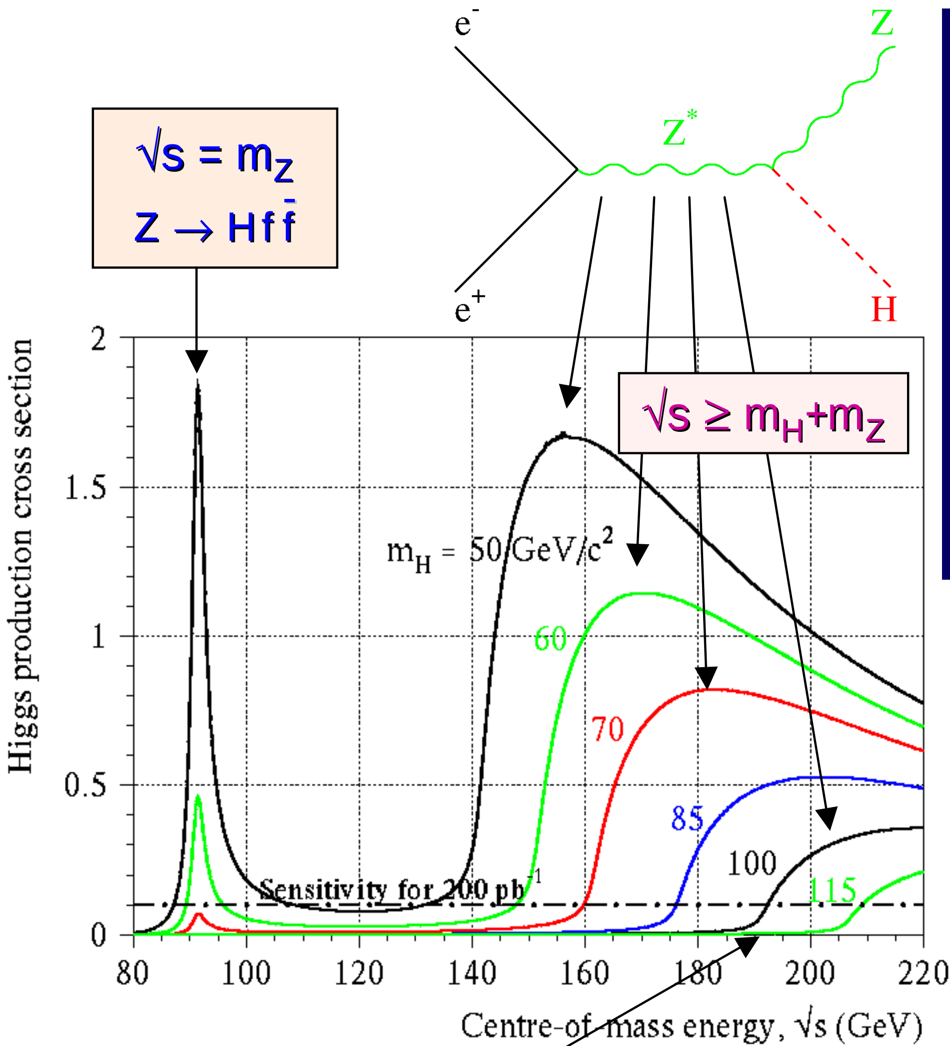


$H\mu^+\mu^-$



$\sqrt{s} = m_Z$

$Z \to H f \bar{f}$

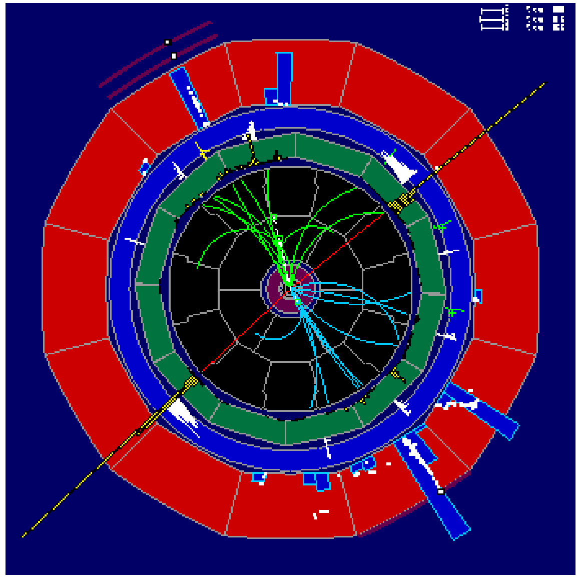


$\sqrt{s} \geq m_H + m_Z$

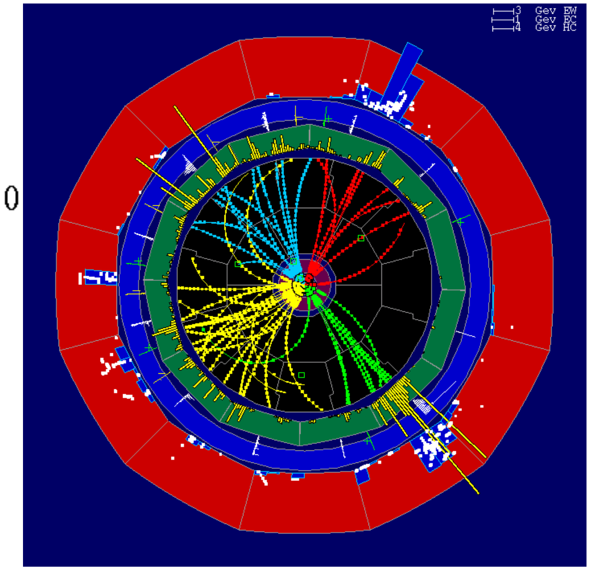
5σ sensitivity for 200 pb⁻¹:

- $\sqrt{s}$ = 192 GeV for m_H = 100 GeV/c²;
- $\sqrt{s}$ = 210 GeV for m_H = 115 GeV/c²;

He^+e^-



$Hq\bar{q}$

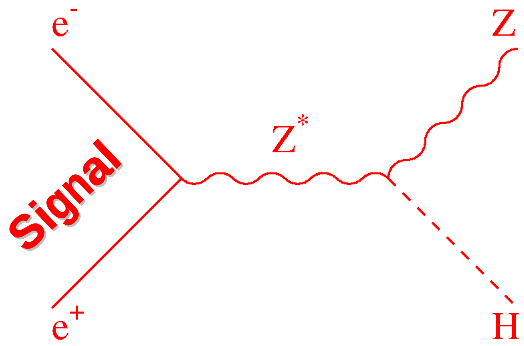


Signal vs Background (I)

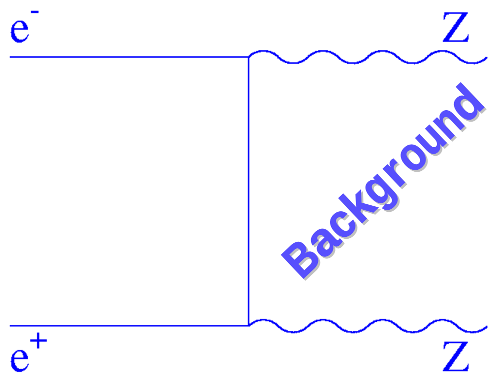
$e^+e^- \to HZ$
$\sigma = 0.1$ pb

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

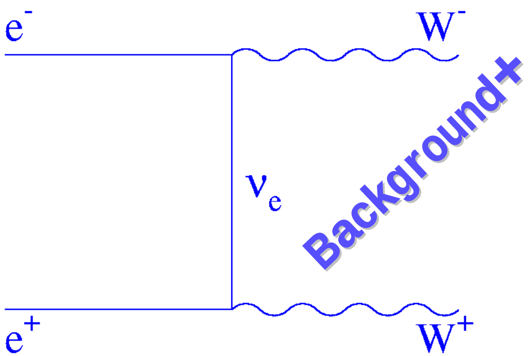
$e^+e^- \to ZZ$
$\sigma \sim 2$ pb

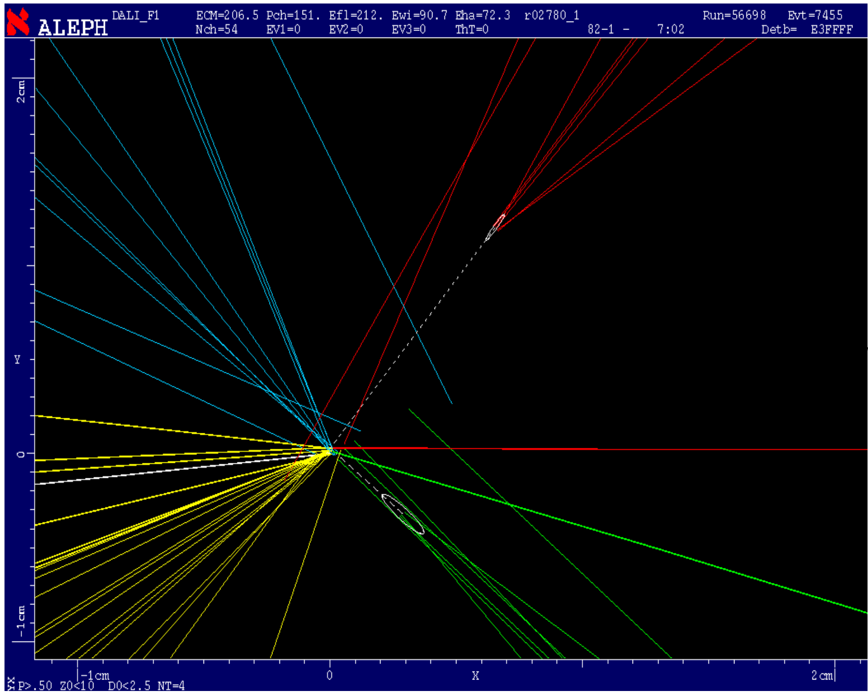


- Reconstructed Higgs boson mass;
- Other kinematic variables;
- b-tagging (lifetime, leptons, …);

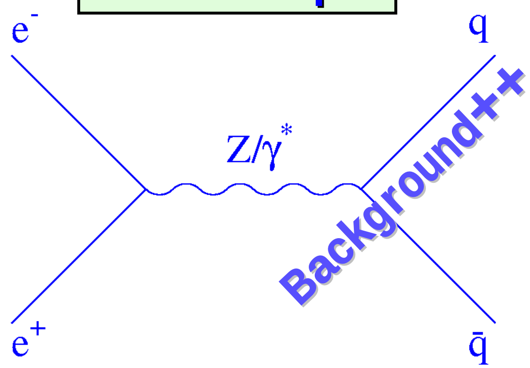


$e^+e^- \to W^+W^-$
$\sigma \sim 20$ pb



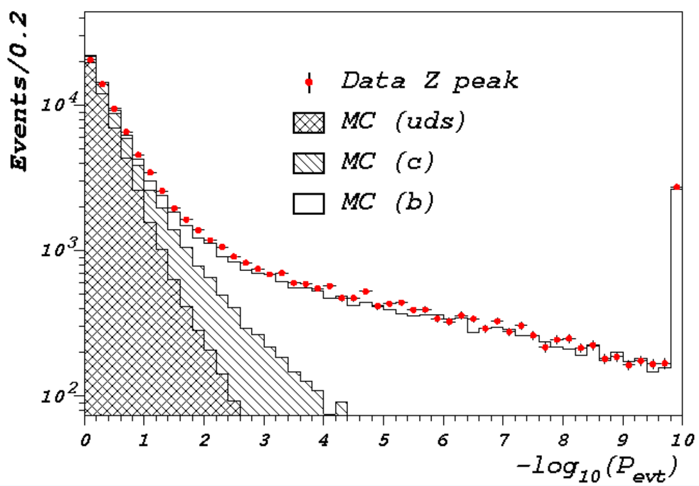


$e^+e^- \to q\bar{q}$
$\sigma \sim 100$ pb

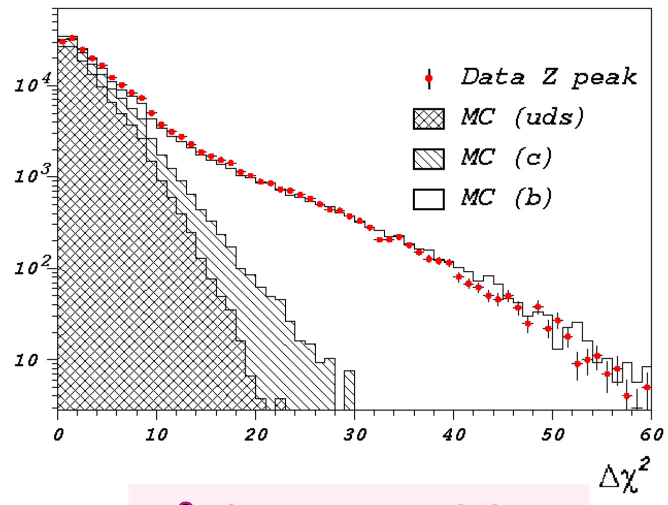


Zoom of ±1cm around the interaction point

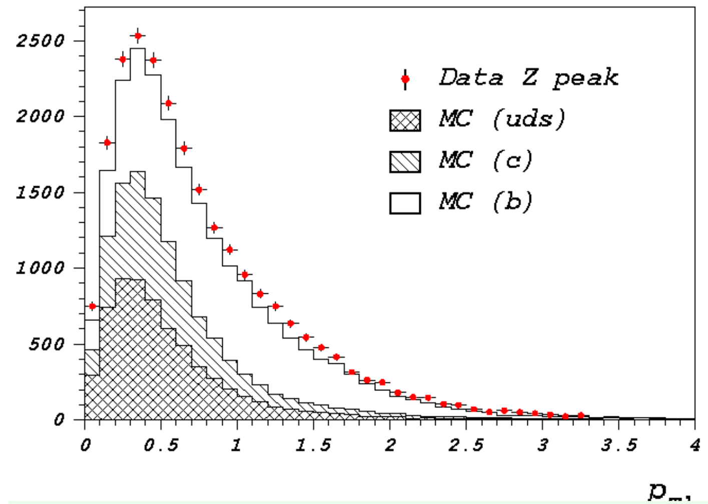
Elements of b tagging (I)



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)

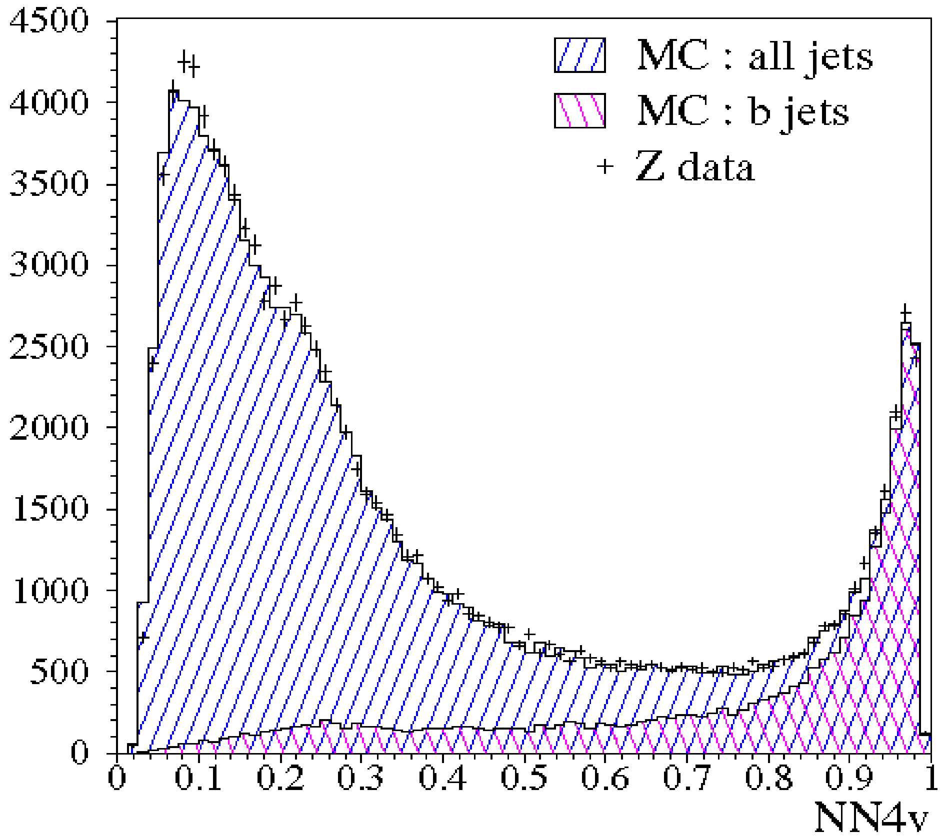
Elements of b tagging (II)

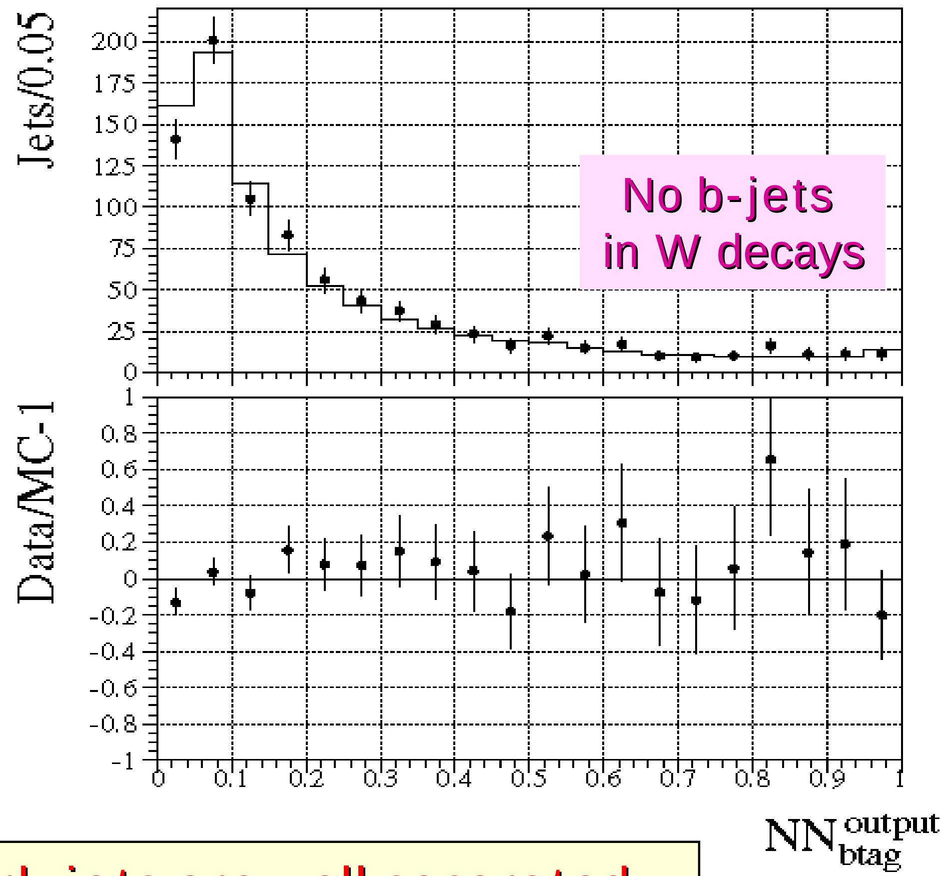
Result on jets from hadronic Z decays

(collected every year for calibration)

Result on jets from hadronic W decays

(from semi-leptonic $e^+e^- \rightarrow W^+W^-$ events)



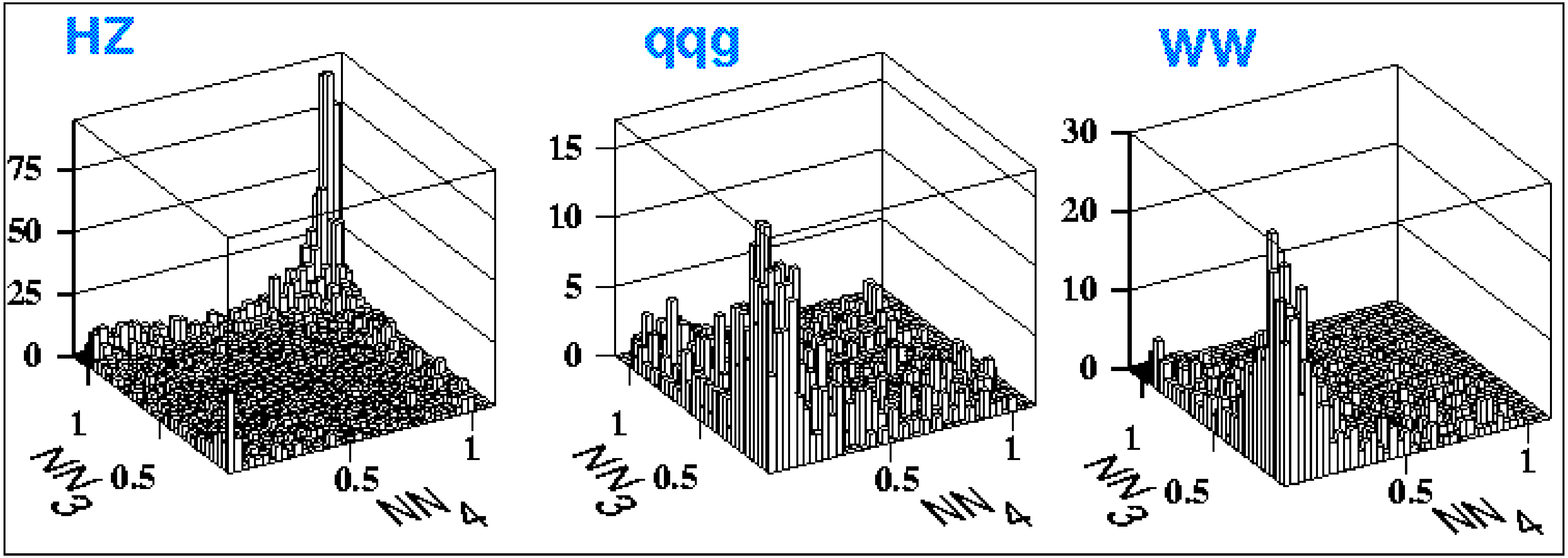


- b-jets and light-quark jets are well separated;
- Simulation reproduces well the data. (Essential)

Elements of b tagging (III)

Separation of HZ, W^+W^- and $q\bar{q}$ events at LEP 2 energies

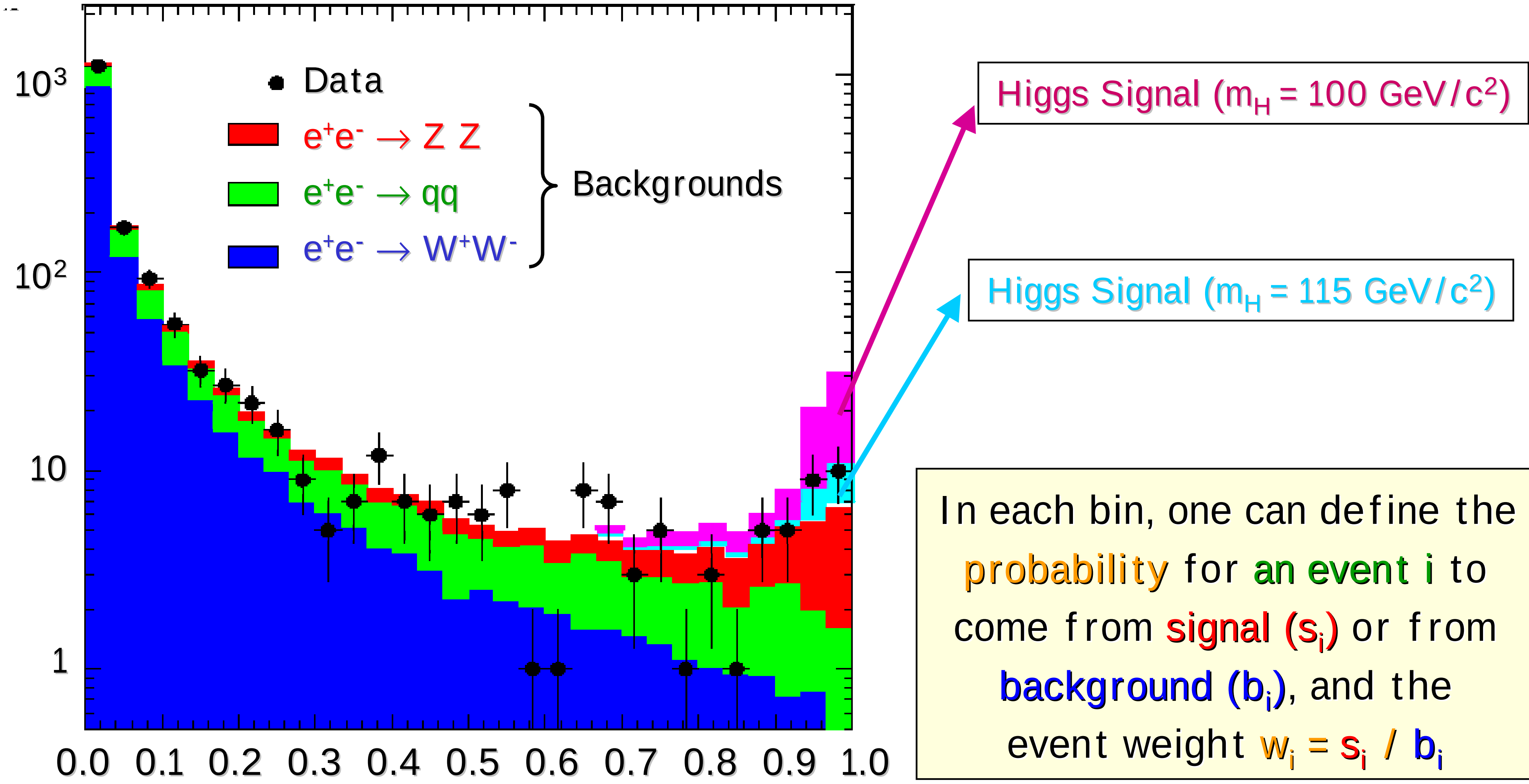
(b tagging only)



(Jets 1 and 2 are chosen to be the jet-pairing most compatible with originating from a Z decay, according to the di-jet invariant mass, the decay angle, … etc.)

Signal vs Background (I I)

Combine b-tagging and kinematics in a single Neural Network / Likelihood / ... :

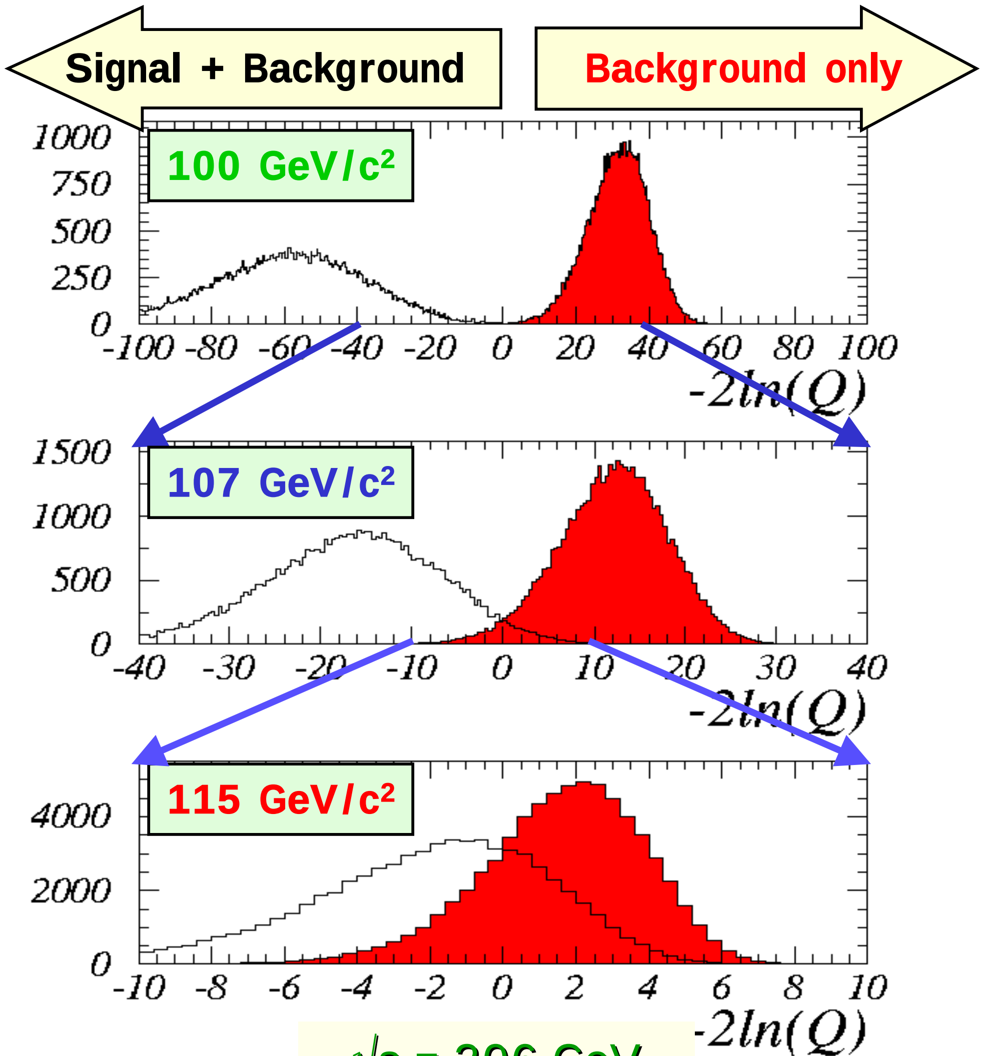


GLOBAL NEURAL NETWORK OUTPUT

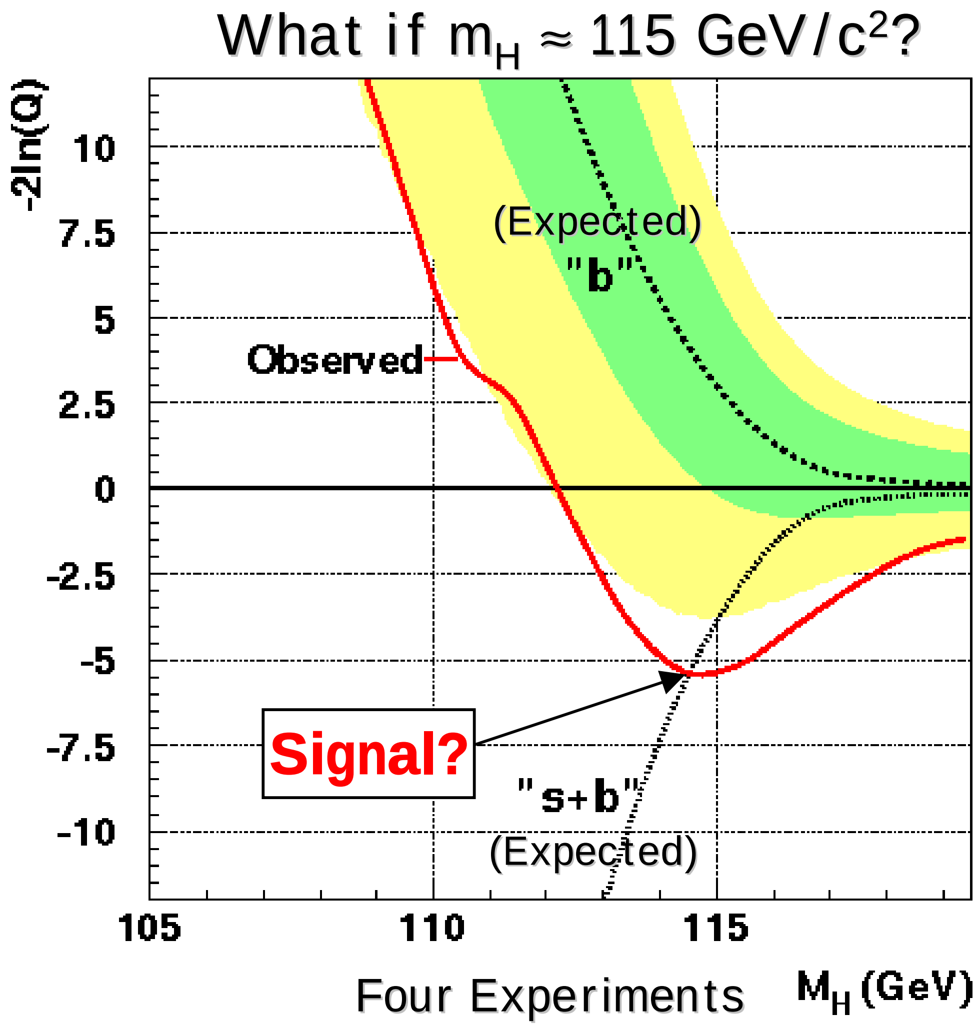
In each bin, one can define the probability for an event i to come from signal (s_i) or from background (b_i), and the event weight $w_i = s_i / b_i$

Signal vs Background (III)

- **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).**

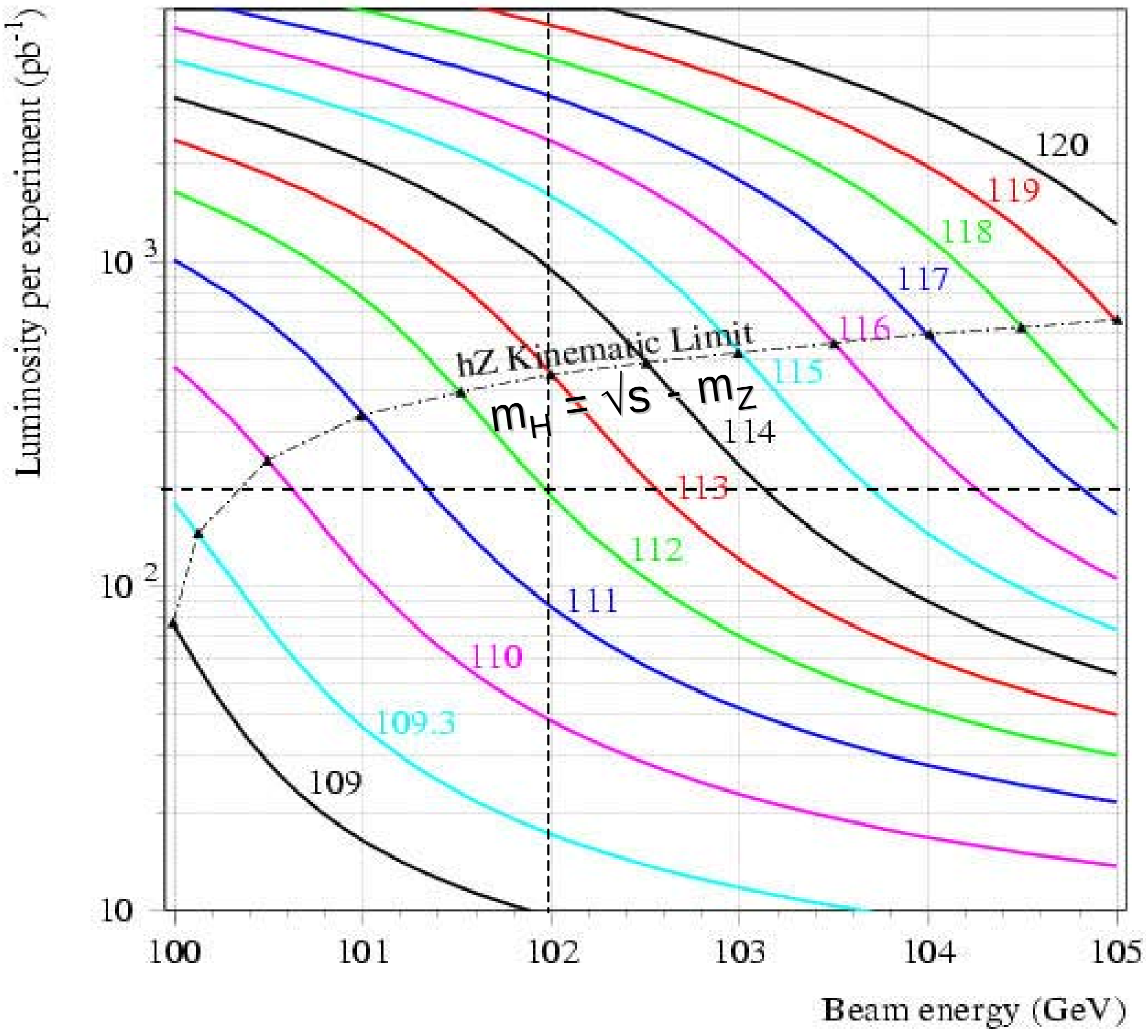


√s = 206 GeV
One Experiment



LEP Optimization: Luminosity or Energy ?

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



A typical (and realistic) example:

- ❑ Beam Energy: 102 GeV;
- ❑ 200 pb^{-1} / experiment.

The 3σ sensitivity of the Higgs boson search is about 112 GeV/c^2, i.e., only 1 GeV/c^2 away from the "kinematic threshold" $m_H = \sqrt{s} - m_Z$.

To gain 2 GeV/c^2 of sensitivity, two possibilities :

- ➢ Increase the beam energy by 1 GeV;
- ➢ Multiply the luminosity by 4.

1 GeV of beam energy (feasible) ⇔ A factor of 4 in luminosity (just a dream)

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;

  ≥ 3 GV for E = 100 GeV;

  → Go for SC RF Cavities)

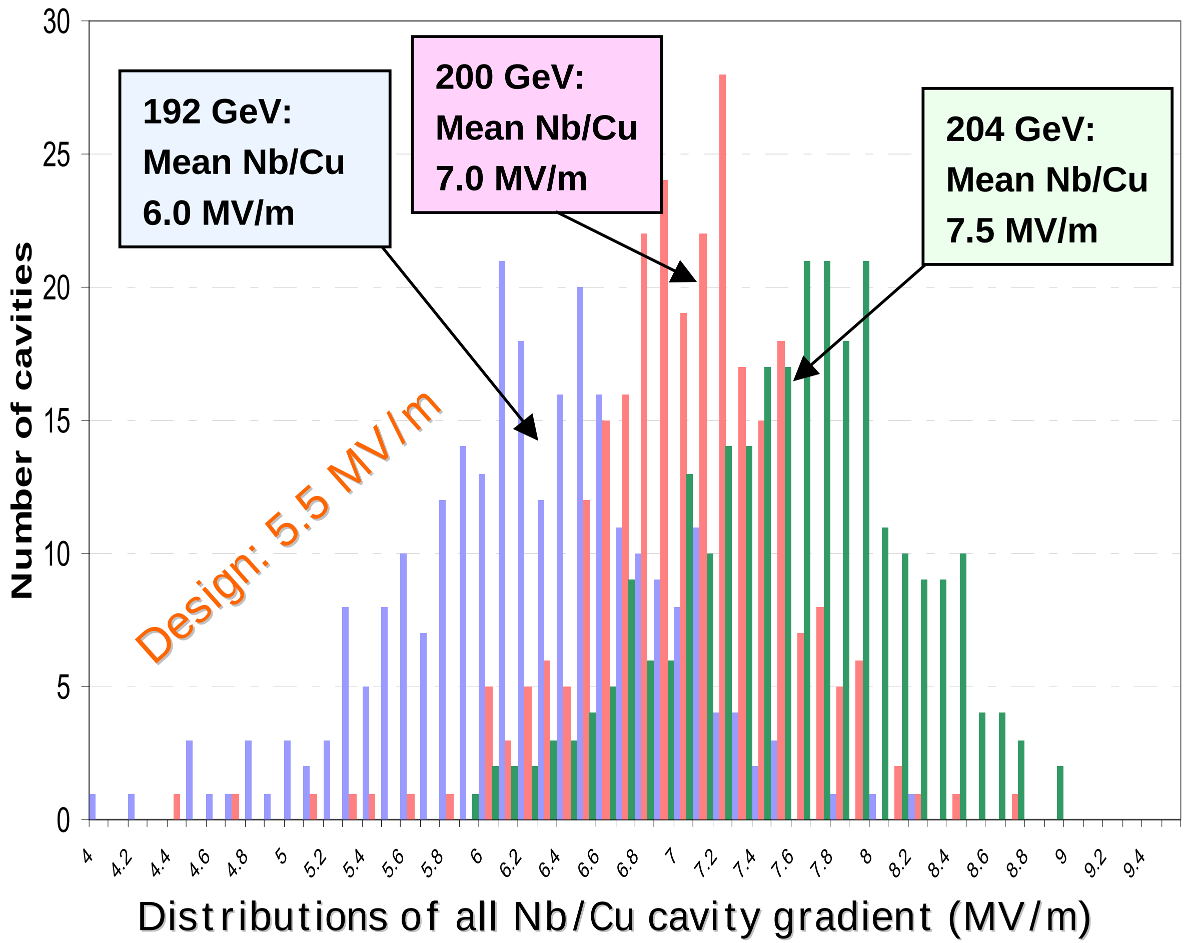
- Increase Bending Radius!
- Or increase both.

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

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

Improvements in 1999/2000 (Cont'd)

2) Improve stability & Decrease security margin

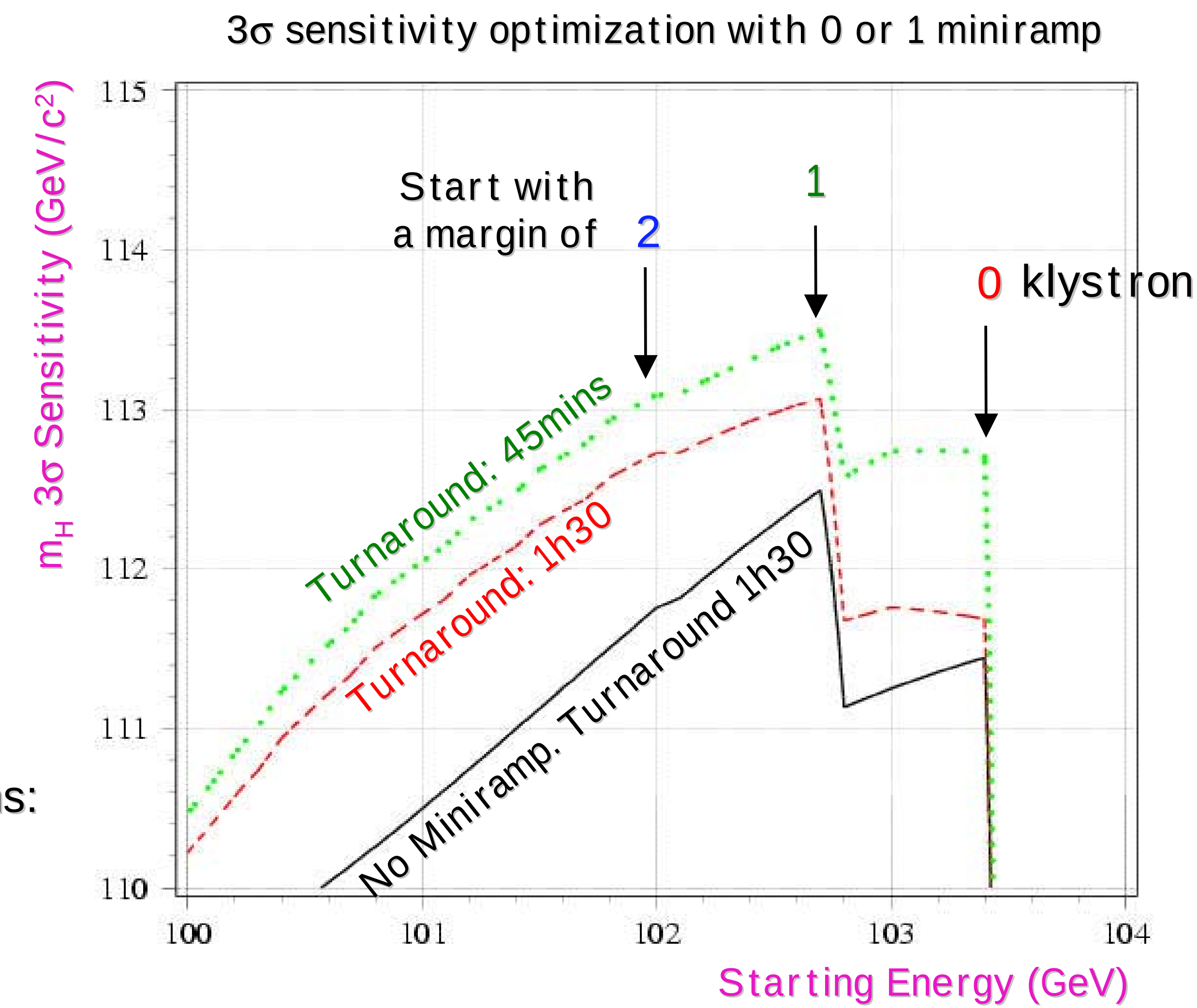
- Two- to one-klystron margin (Fill duration 2h30 → 1h30):

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



Improvements in 1999/2000 (Cont'd)

3) Re-install 8 Cu cavities

Adds 30 MV (0.8% of total RF Voltage)

E: 207 → 207.4 GeV;

m_H: 114 → 114.25 GeV/c^2

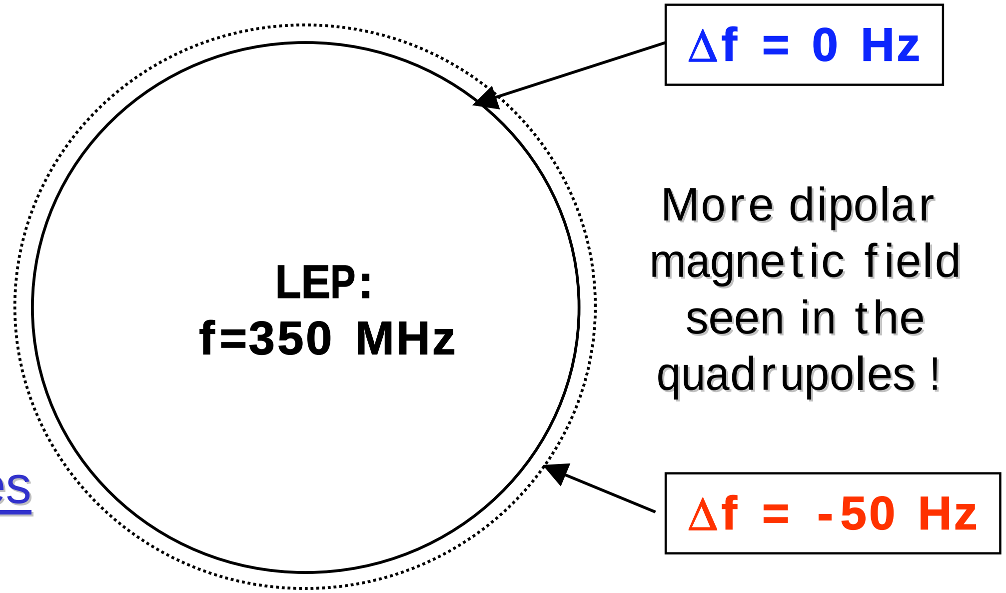
4) Use orbit correctors as magnetic dipoles

Increases LEP radius !

E: 207.4 → 207.8 GeV;

m_H: 114.25 → 114.5 GeV/c^2

5) Decrease the RF frequency



More dipolar magnetic field seen in the quadrupoles !

But ... 10-20% luminosity reduction

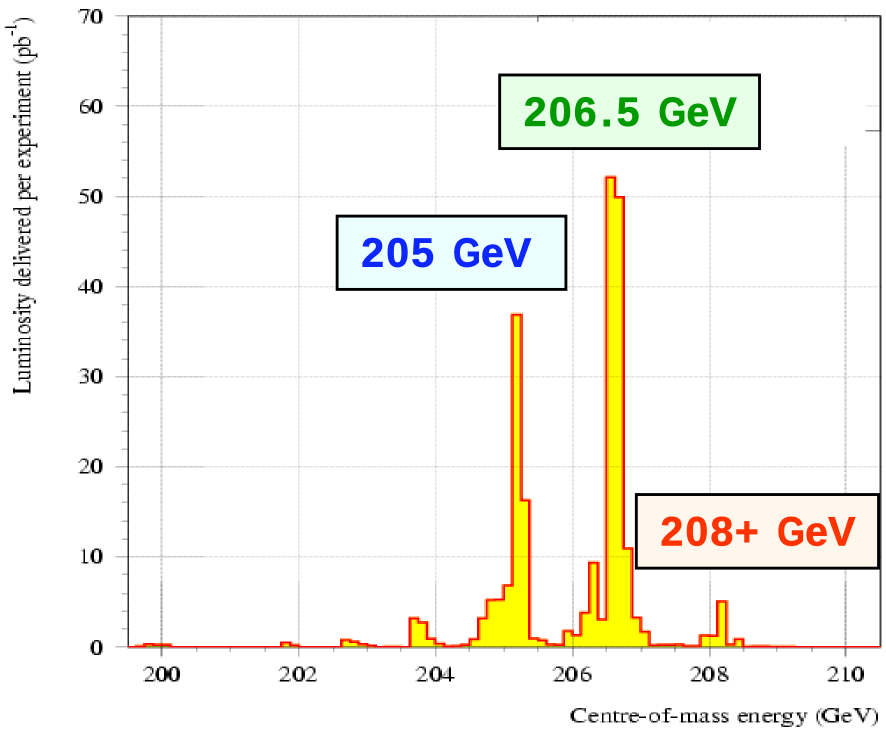
E: 207.8 → 209.2 GeV;

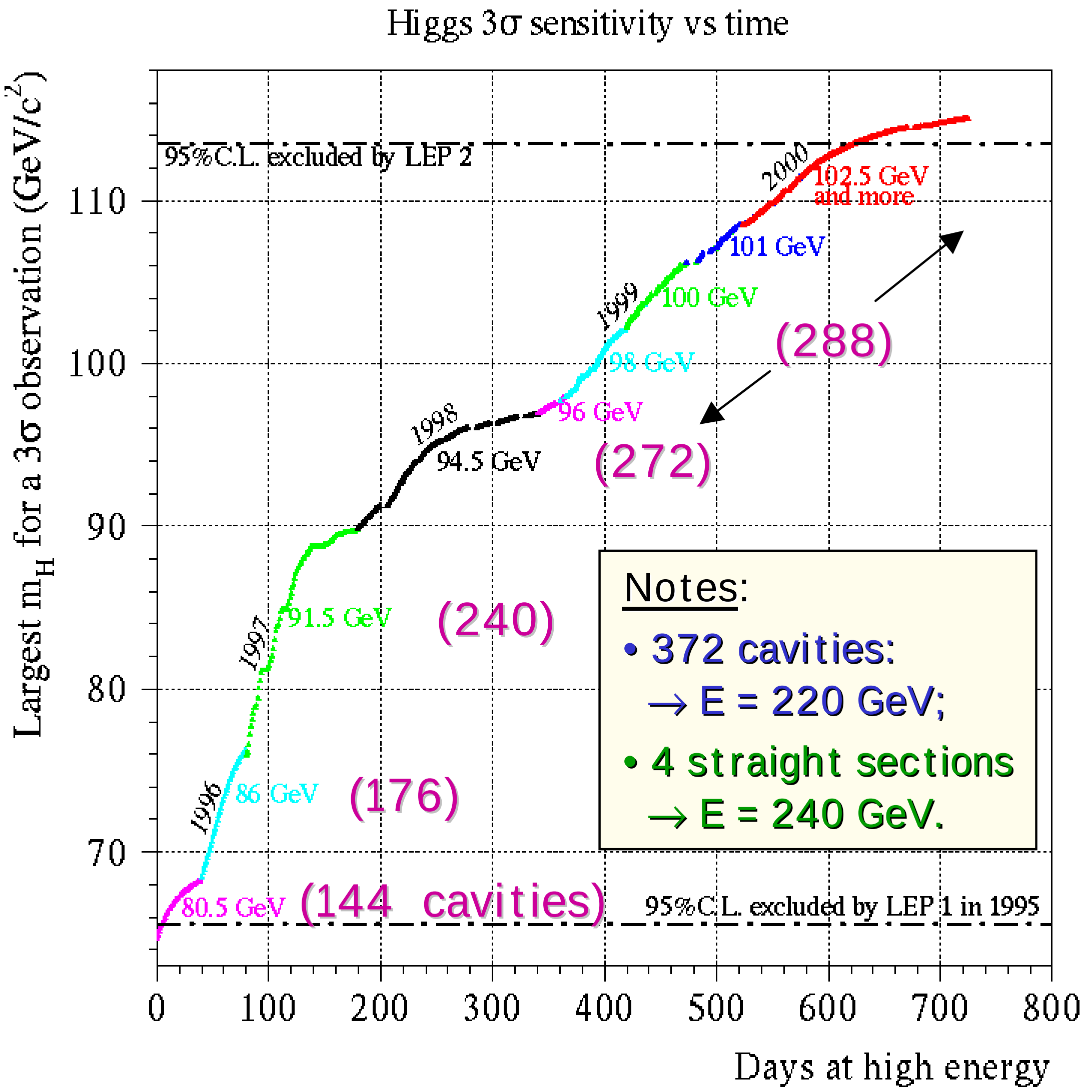
m_H: 114.5 → 115.1 GeV/c^2

Improvements in 1999/2000: Results

220 pb^{-1} delivered in 2000:

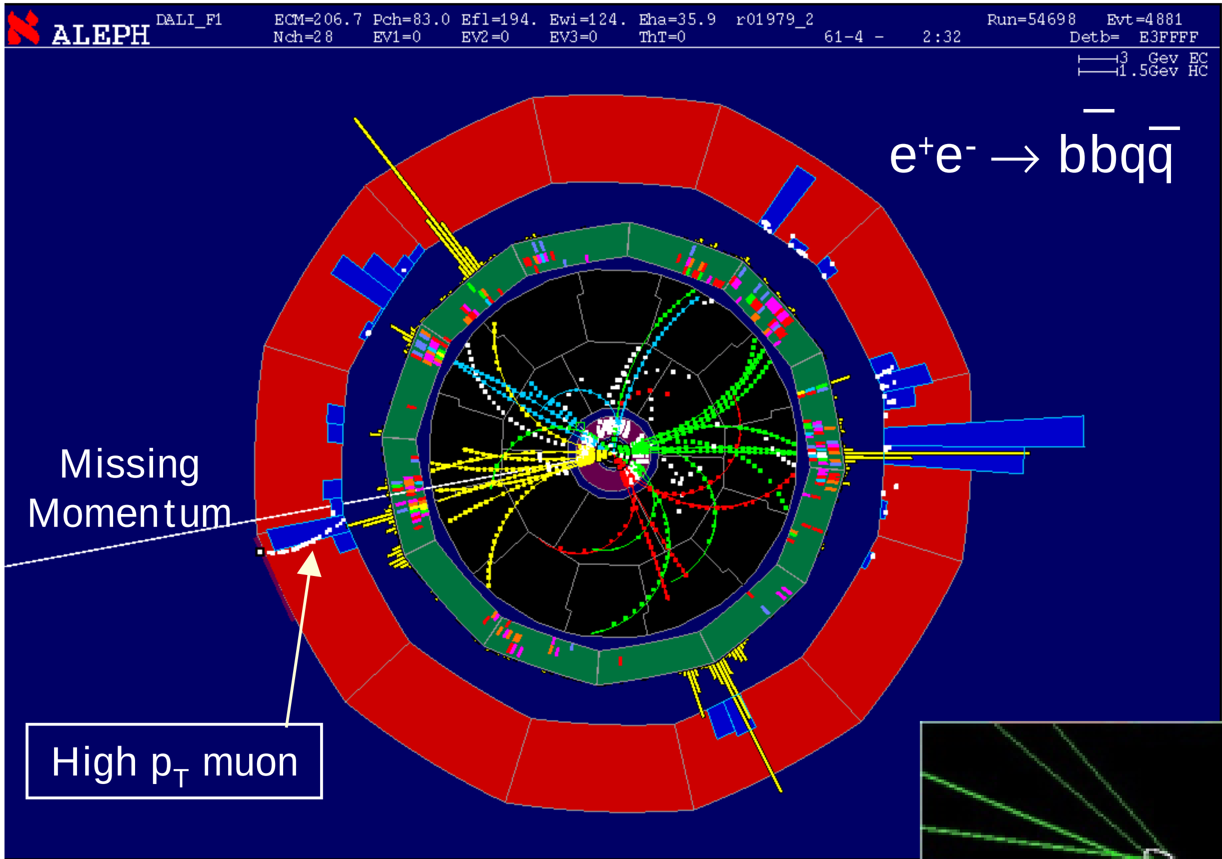
- starting at 204-205 GeV (April-May)
- Regularly above 206 GeV (from June onwards)
- Only above 206.5 GeV (September to November)





$m_H < 114.1\ \mathrm{GeV}/c^2$
excluded at 95% C.L.

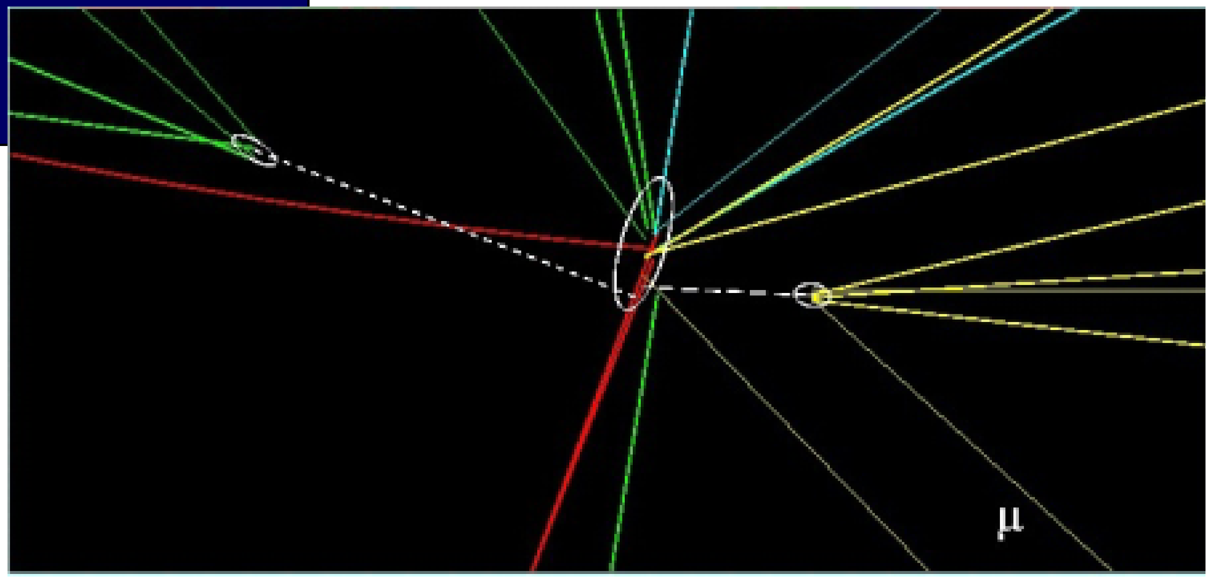
First pb^{-1}'s above 206 GeV:
First thrills at 115 GeV/c^2



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

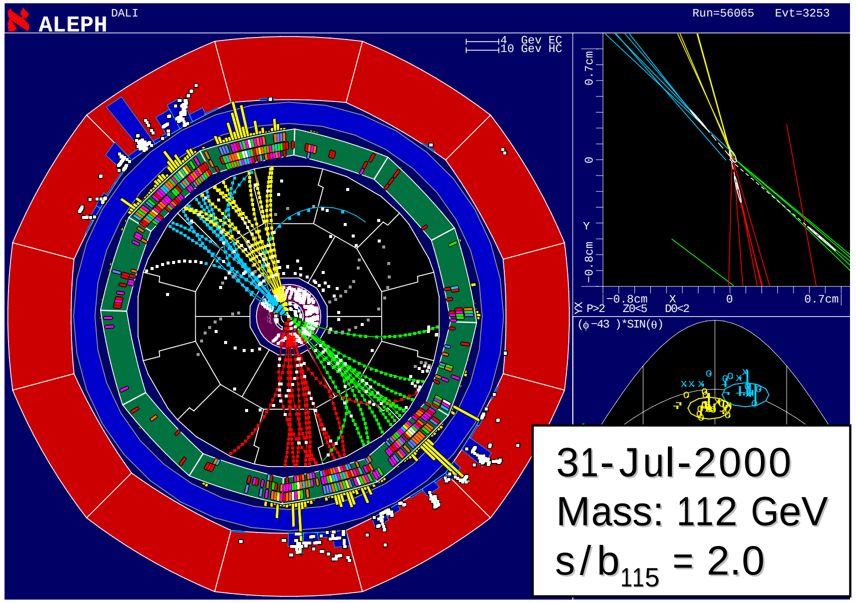
The purest candidate event ever!



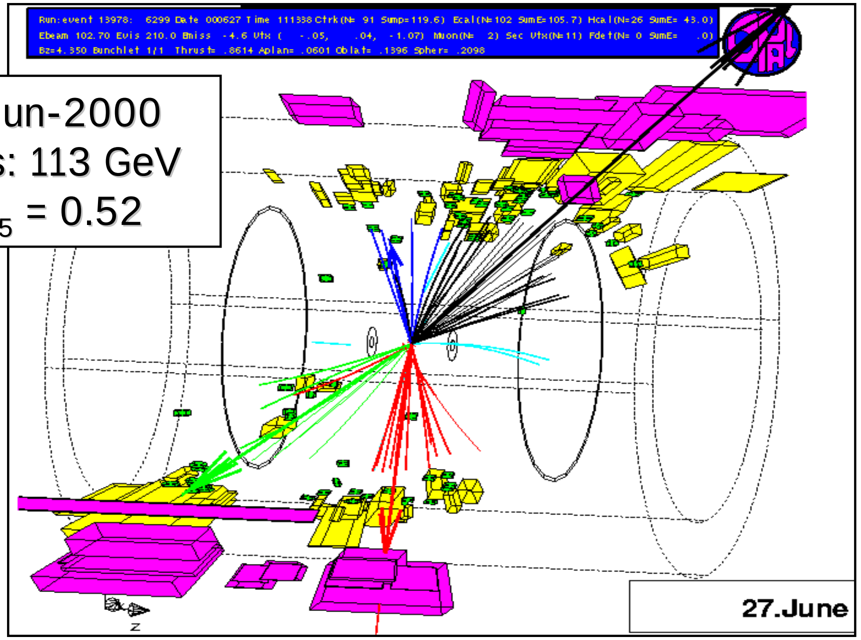
b-tagging
(0 = light quarks, 1 = b quarks)

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

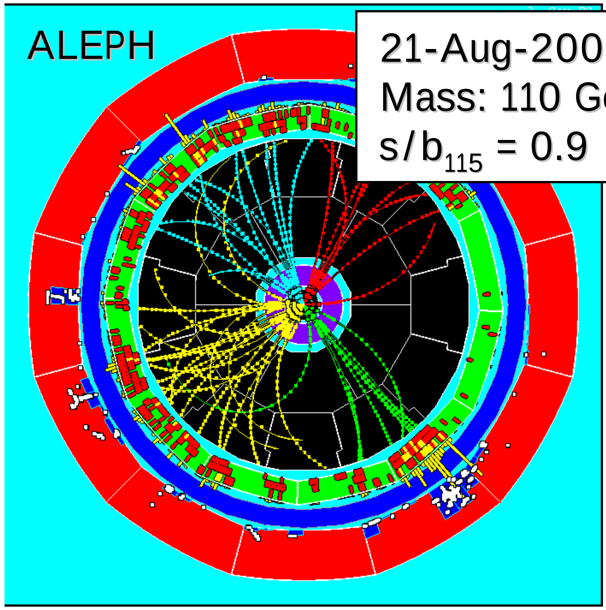
A few candidate events at 115 GeV/c^2



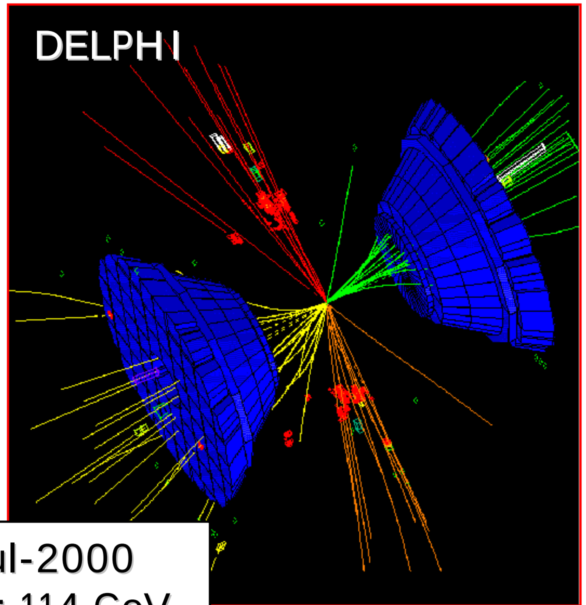
31-Jul-2000
Mass: 112 GeV
s/b_{115} = 2.0



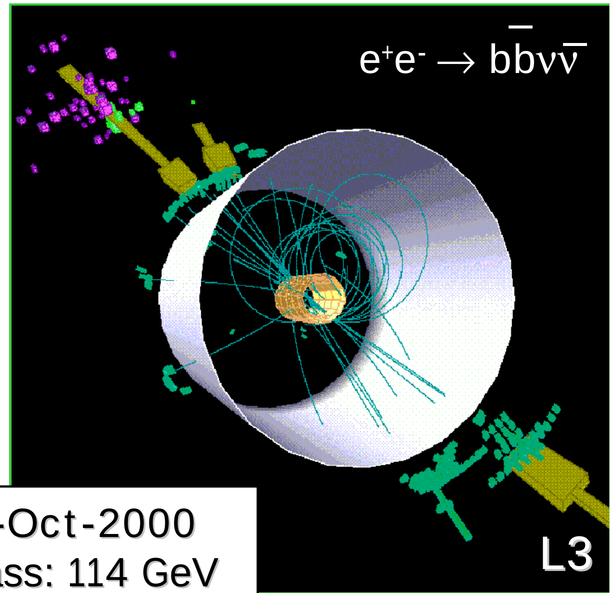
27-Jun-2000
Mass: 113 GeV
s/b_{115} = 0.52



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%)

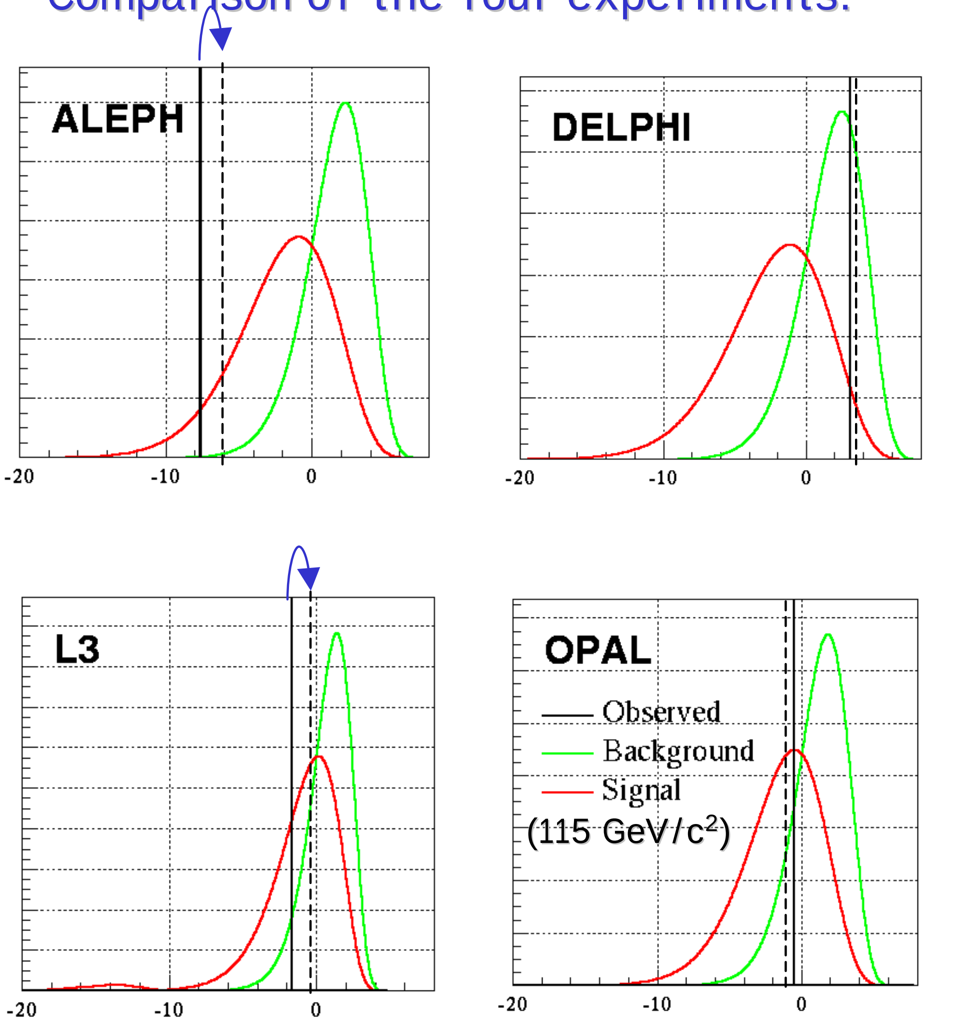
Number of events in each Z decay compatible with HZ predictions

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

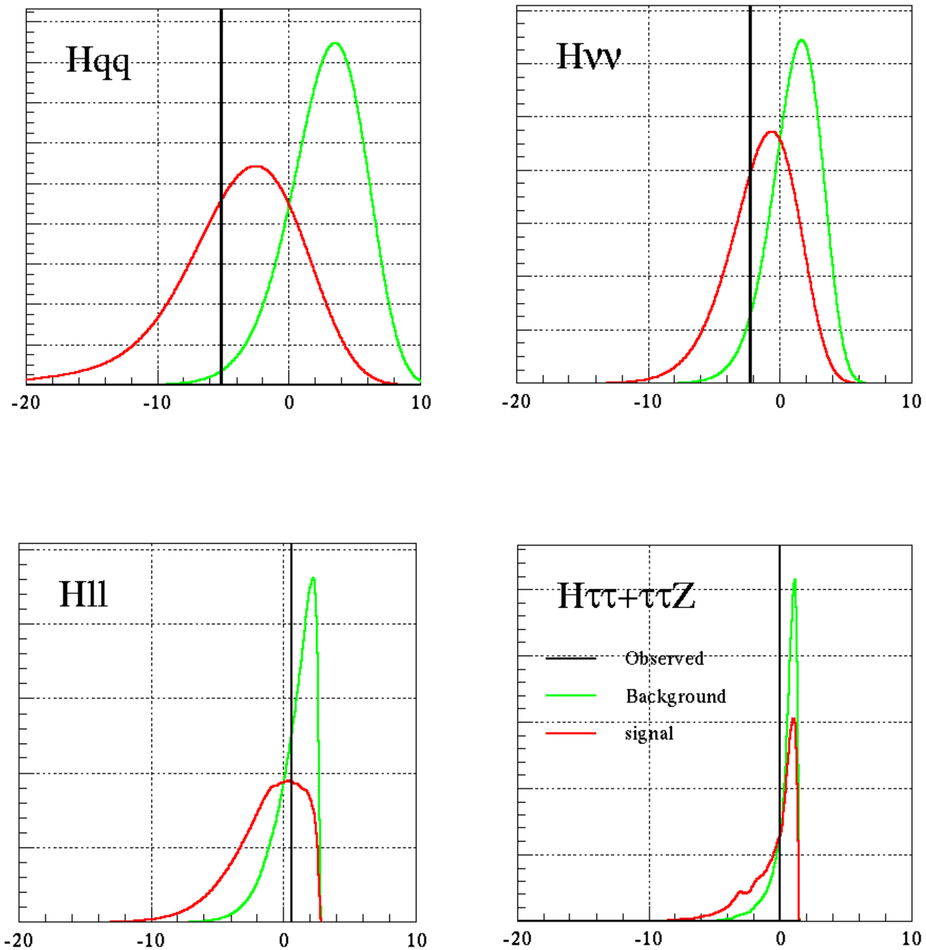
Values as of Nov 5th, 2000

A Few Consistency Checks (I)

Comparison of the four experiments:



Comparison of the four channels:



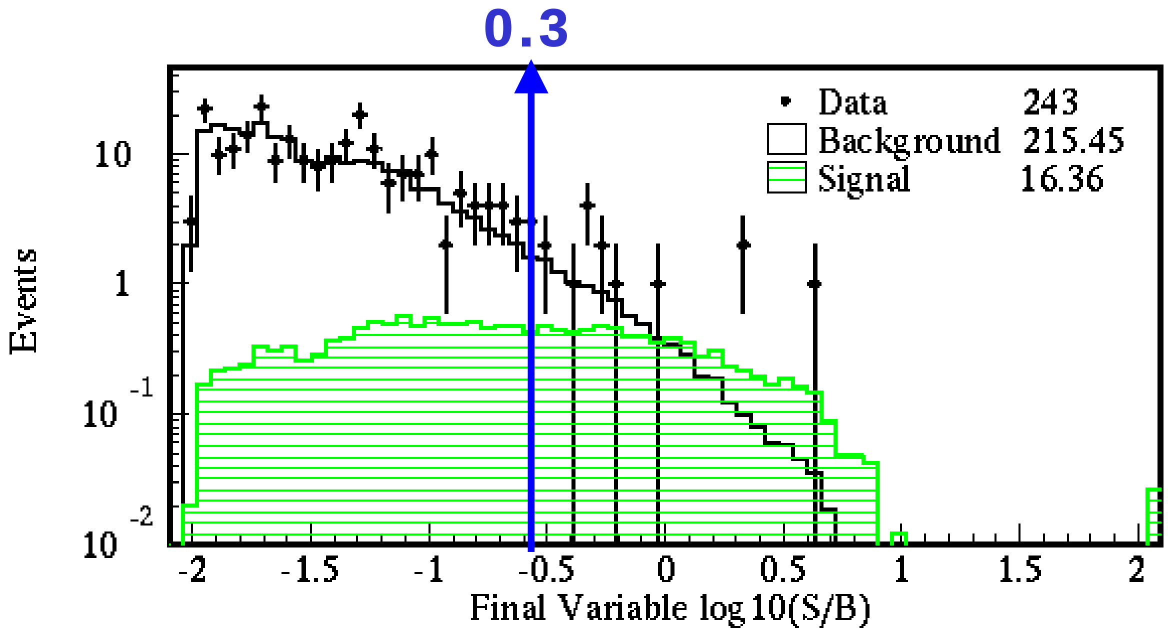
Good consistency with s+b distribution;
Not an “ALEPH excess”, but a LEP excess

Good consistency with s+b according to expected separation;
Not a “4-jet excess”, but a Higgs excess

A Few Consistency Checks (II)

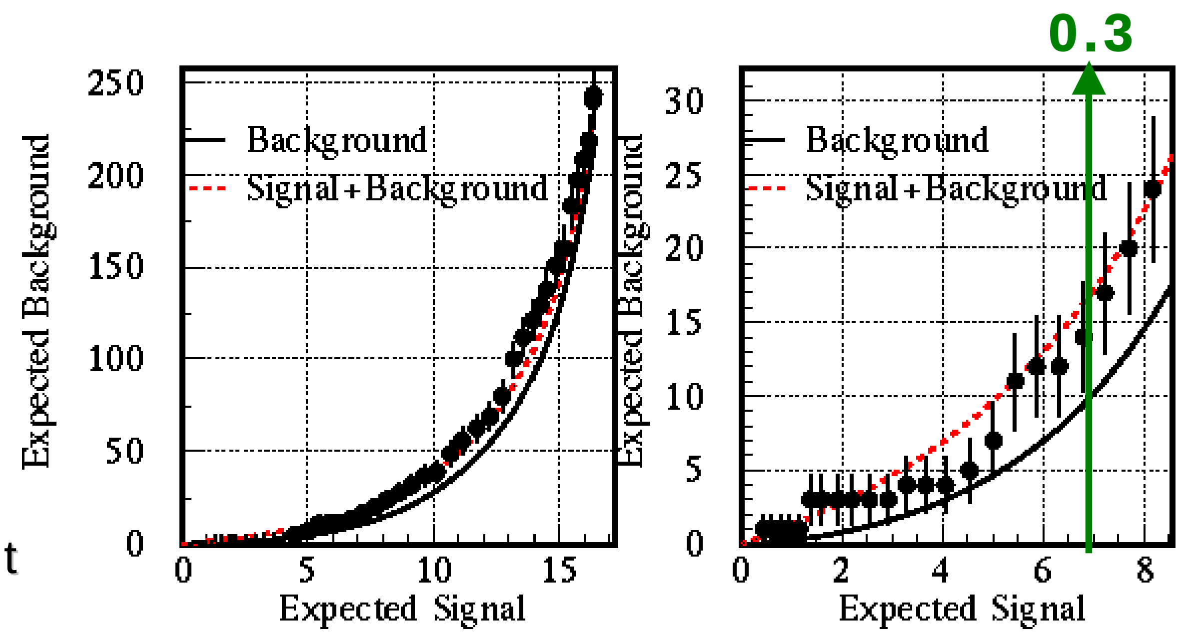
Distribution of s/b for the whole data sample:

Excess visible all the way down to ~ 0.1



Cutting tighter or looser on s/b:

Good Consistency with Signal+Background Hypothesis For Any Purity Cut

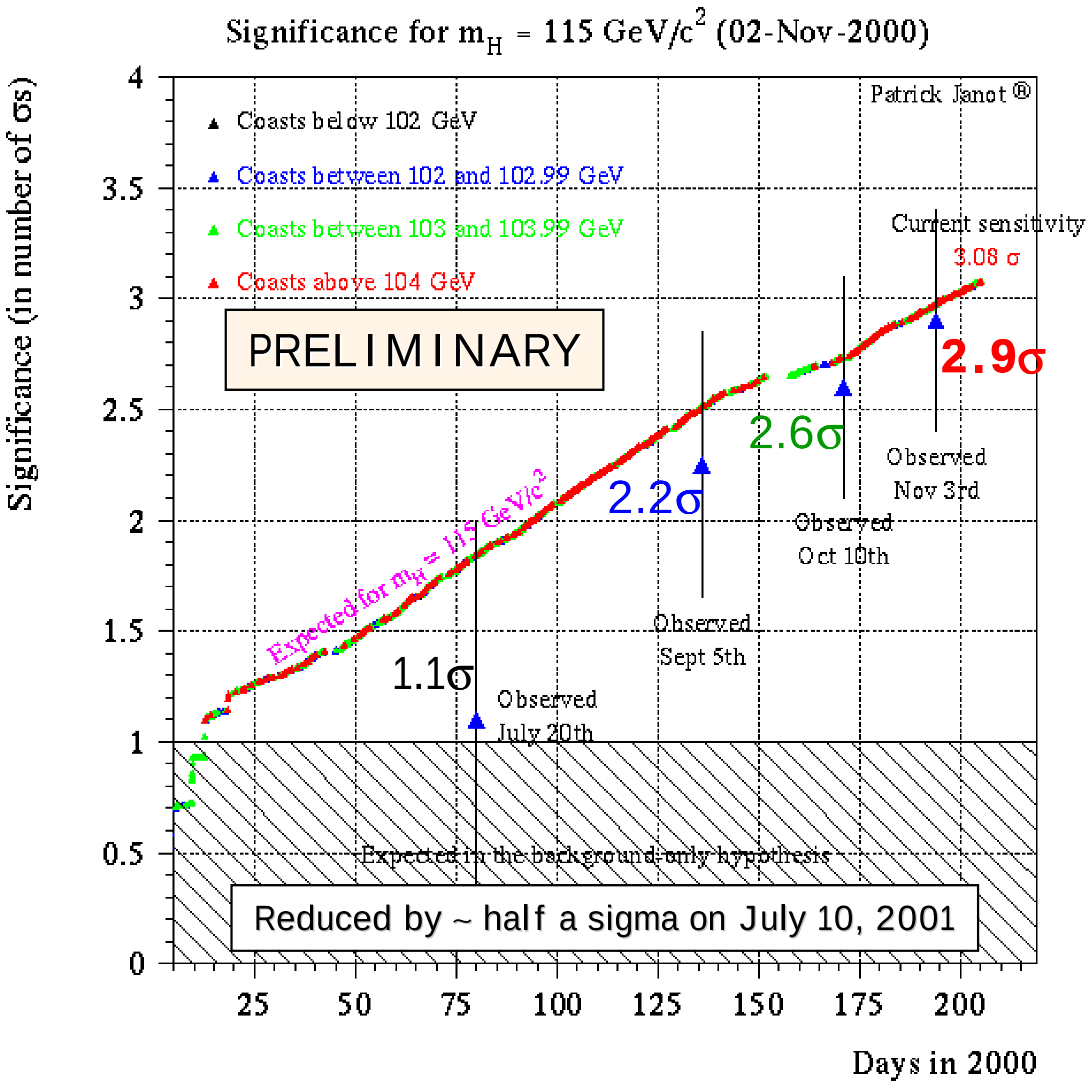


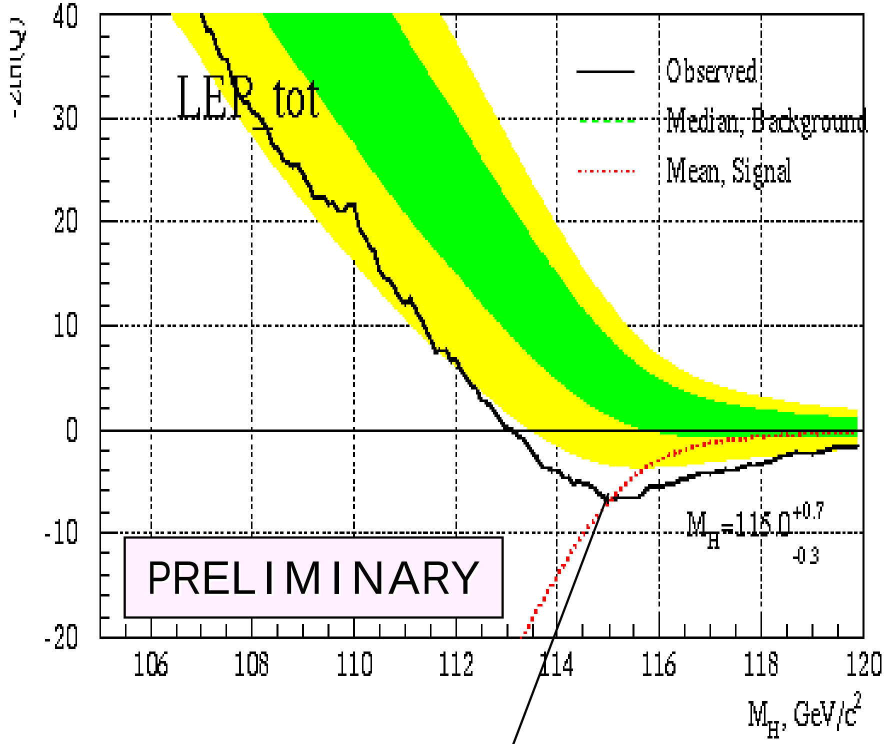
Not a "cut-around-the data" effect

A Few Consistency Checks (III)

- Regular increase of the significance;
- Overall compatibility with m_H = 115 GeV/c^2.

Minimum of the log-likelihood as deep as could have been a priori expected





When interpreted as a Higgs signal:

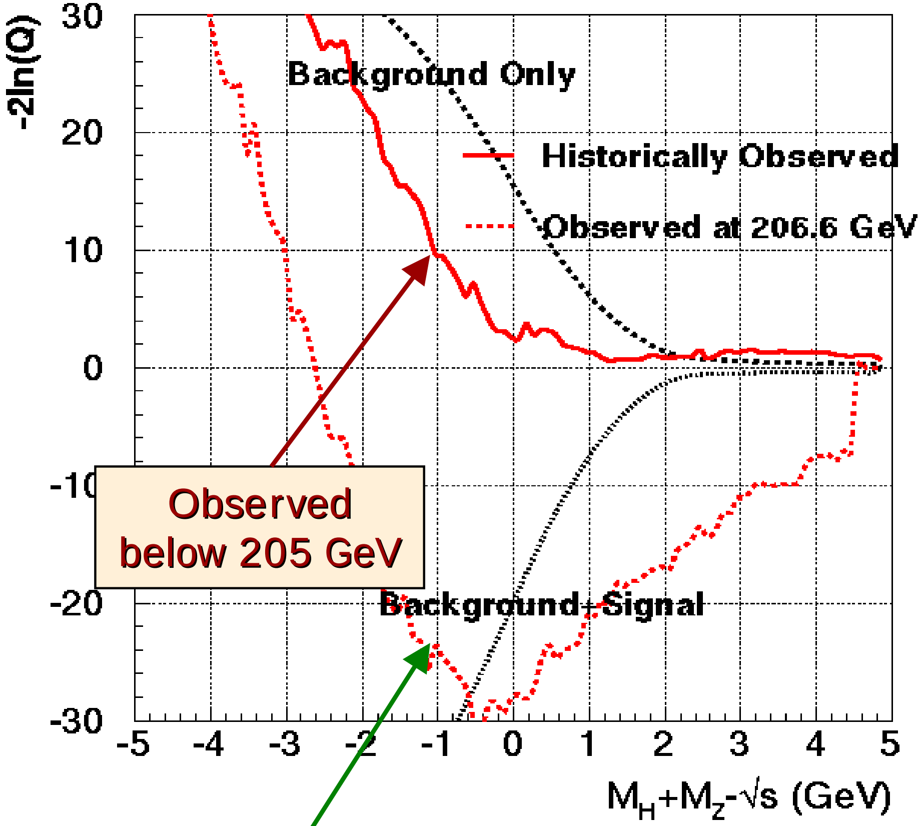
$$m_H = 115.0^{+0.7}_{-0.3}\ \text{GeV}/c^2$$

Increased by half a GeV/c^2 on July 10, 2001

A Few Consistency Checks (IV)

Question: Is the background understood at the kinematic limit (115+91 = 206 GeV)?

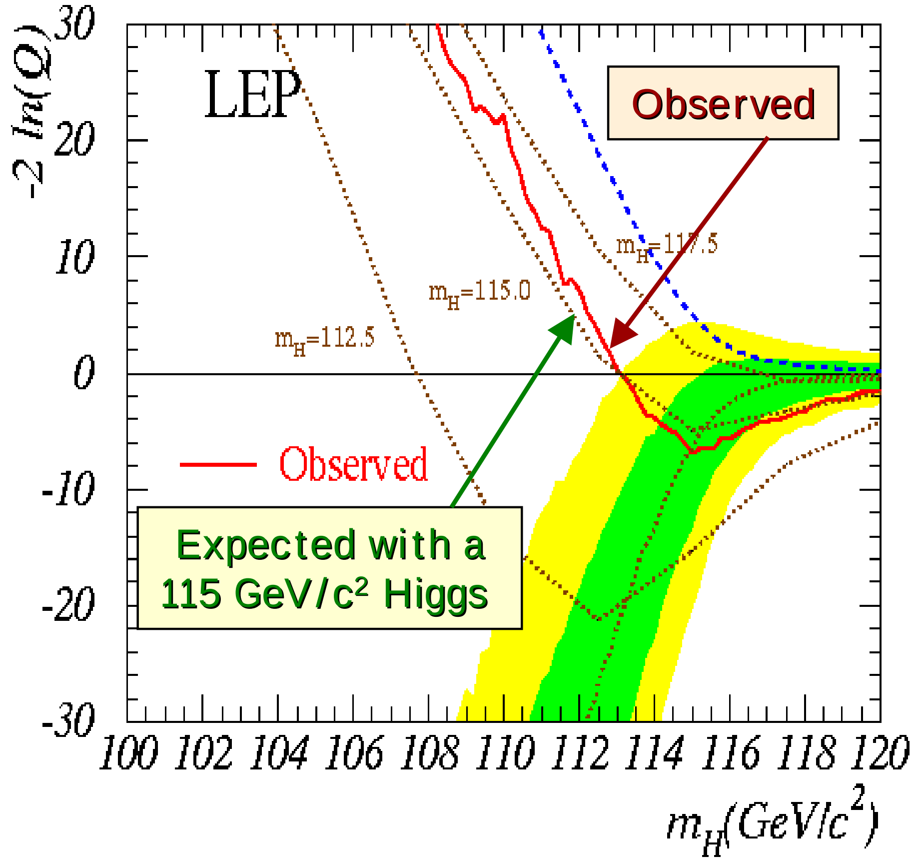
Answer: Let's have a look at lower energy data (500 pb^{-1} between 183 and 205 GeV)



What would have been observed if the excess above 205 GeV were due to a systematic effect !!!

Question: Why is there a 2σ excess all the way down to 100-105 GeV

Answer: It is as expected for a 115 GeV/c^2 Higgs signal because of mass resolution.

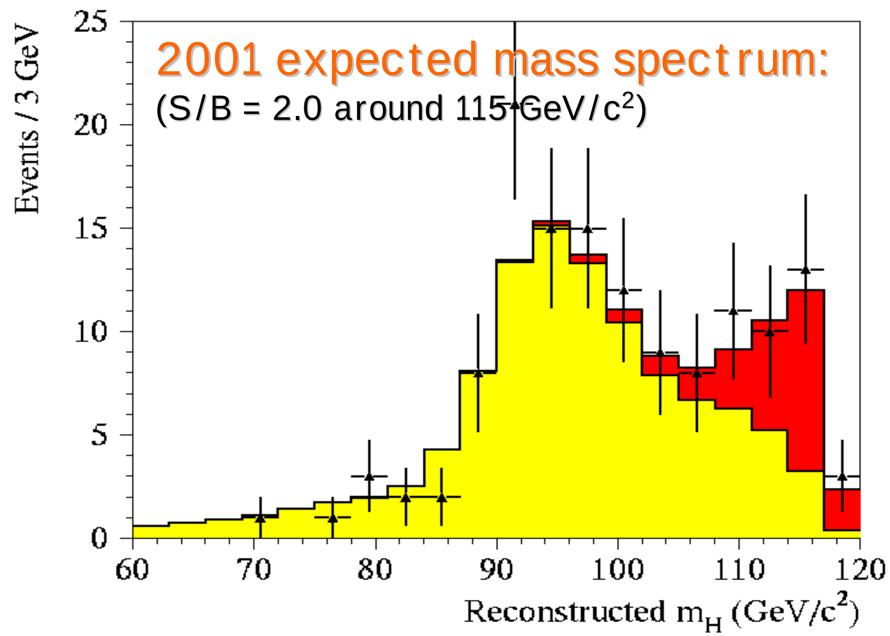


2001: A Spoilt Odyssey

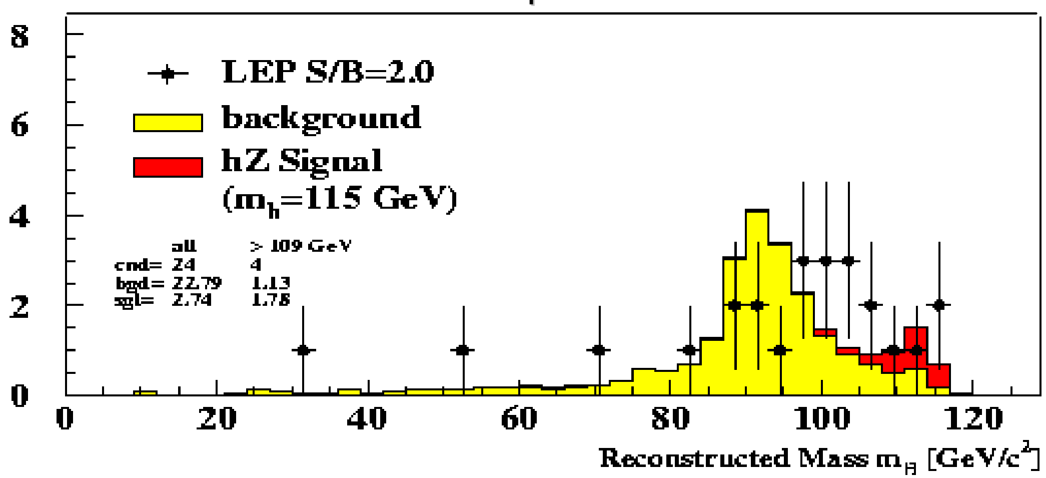
- With six more months in 2001;
- With a integrated luminosity of 200 pb^{-1};
- With an energy of 208.5 → 210 GeV;
(made possible with add'l cavities and a few tricks)

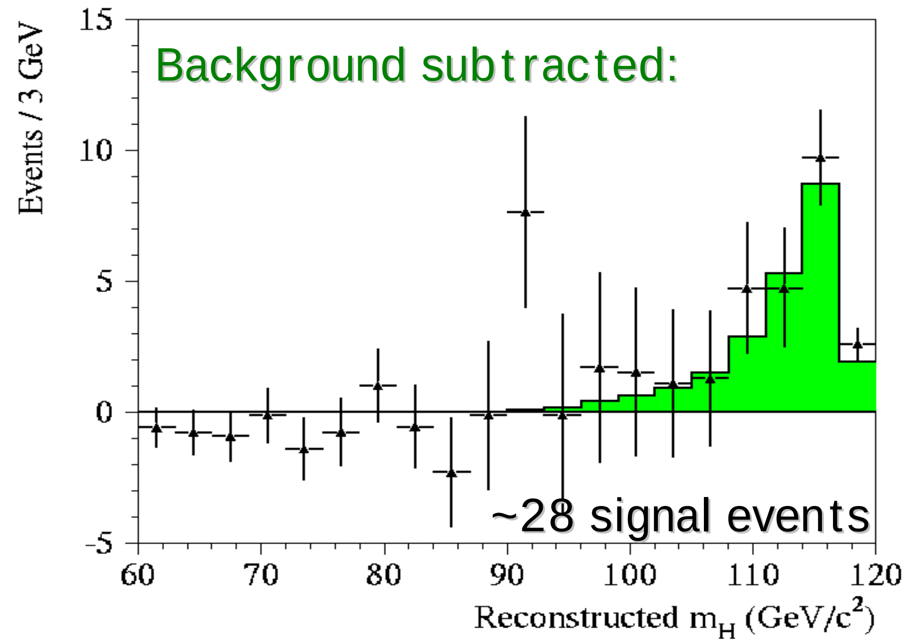
The 3σ evidence could have been turned into

$$A\ 5.5^{+0.6}_{-0.9}\ \sigma \text{ discovery}$$

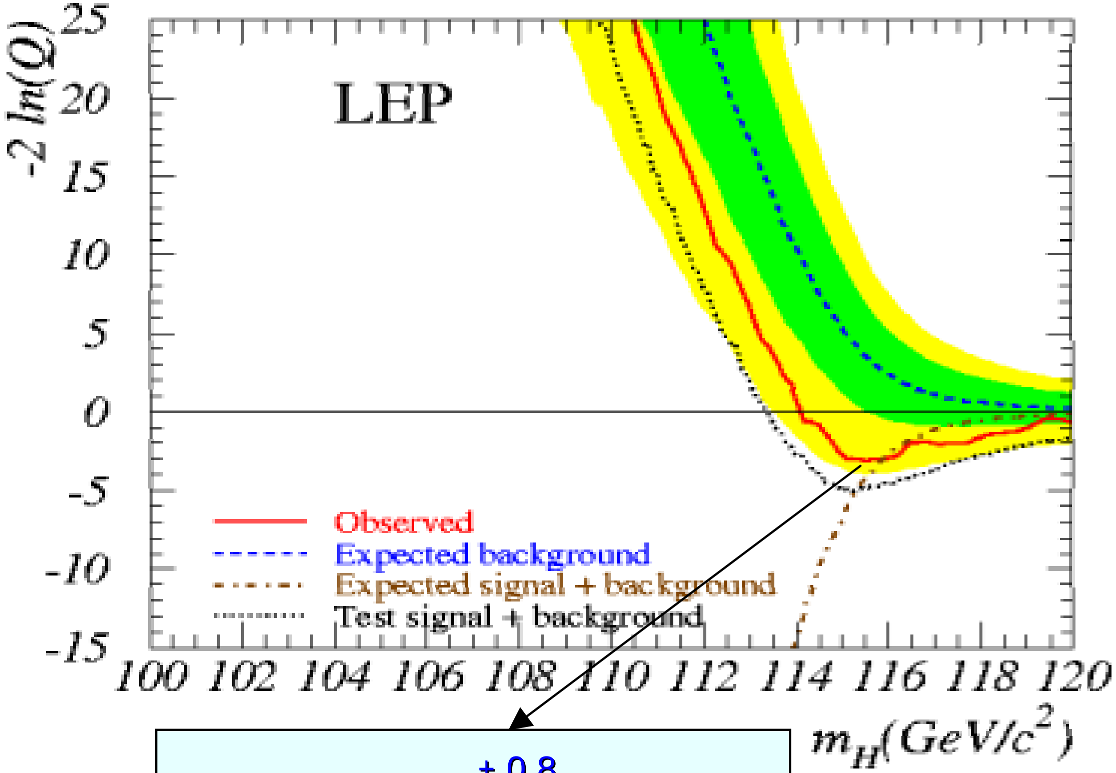


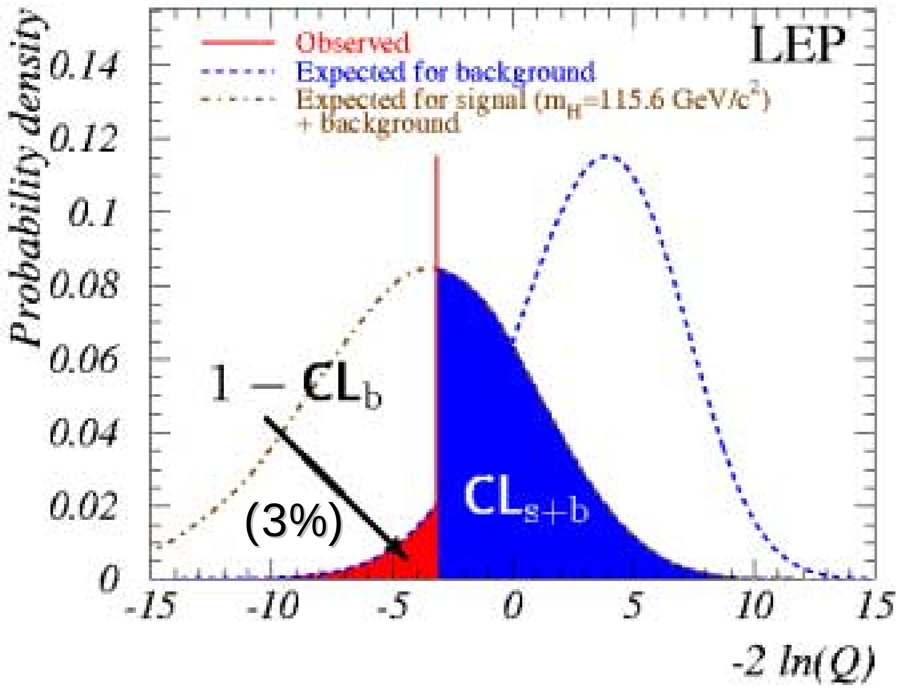
2000 observed mass spectrum:





Ongoing Combination (still preliminary)



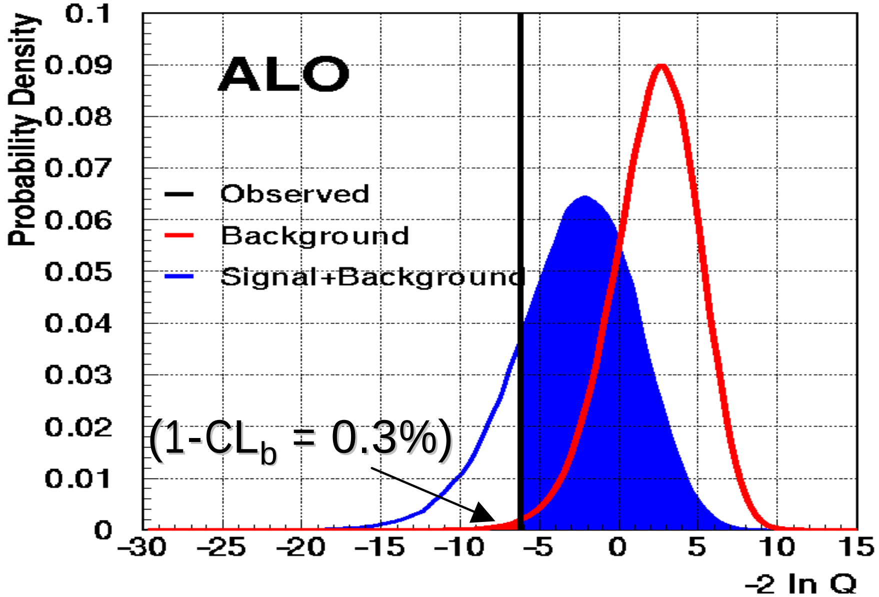


1) $m_H = 115.6 \,^{+0.8}_{-0.7}$ GeV/c^2

2) DELPHI data being reprocessed (deficit?)

3) L3 final, ALEPH and OPAL quasi-final

4) ALEPH, L3 and OPAL (all in excess with respect to the background) combination still leads to a 2.9σ excess.



Conclusions of the 2nd Lecture

After 12 years of outstanding Physics at LEP and SLC:

- Precision electroweak measurements:

$$m_H = 108 \,^{+57}_{-38}\ \mathrm{GeV}/c^2$$

- Direct Searches (~2-3σ effect)

$$m_H = 115.6 \,^{+0.8}_{-0.7}\ \mathrm{GeV}/c^2$$

±15 GeV/c^2 with 5 more years
(two at the Z pole, three at high energy)

Impressive Consistency !

Could have been confirmed in 2001
Δm_H = 100 MeV/c^2 with three years

About 5-10 years needed for a confirmation

- Lots of upgrades still to be done to reach 15 fb^{-1} in 2007 at the Tevatron;
- Lots of things still to be done to make LHC start in 2007;
- The end of the decade might be hot.