# The LEP Higgs Saga

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CERN

**2 August 2003**

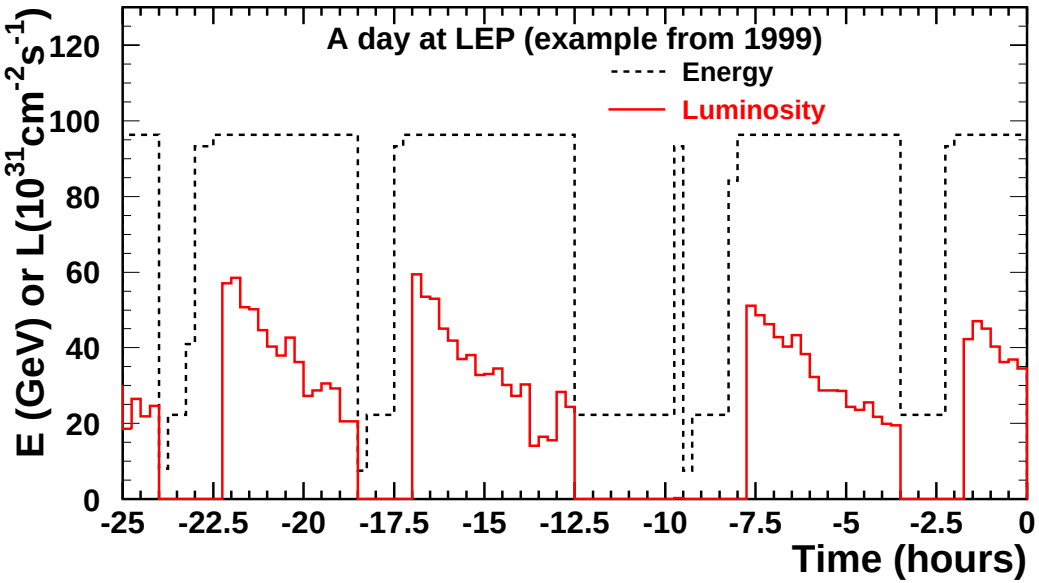
# *Search for the Higgs Boson at LEP*

- Quick reminder
  - The LEP machine and detectors
  - Standard Model processes
- Constraints on the Higgs mass
- Higgs production and decay
- How to tell if candidates are significant?
- What happened in 2000...?

# The LEP Collider

A good fill lasted around

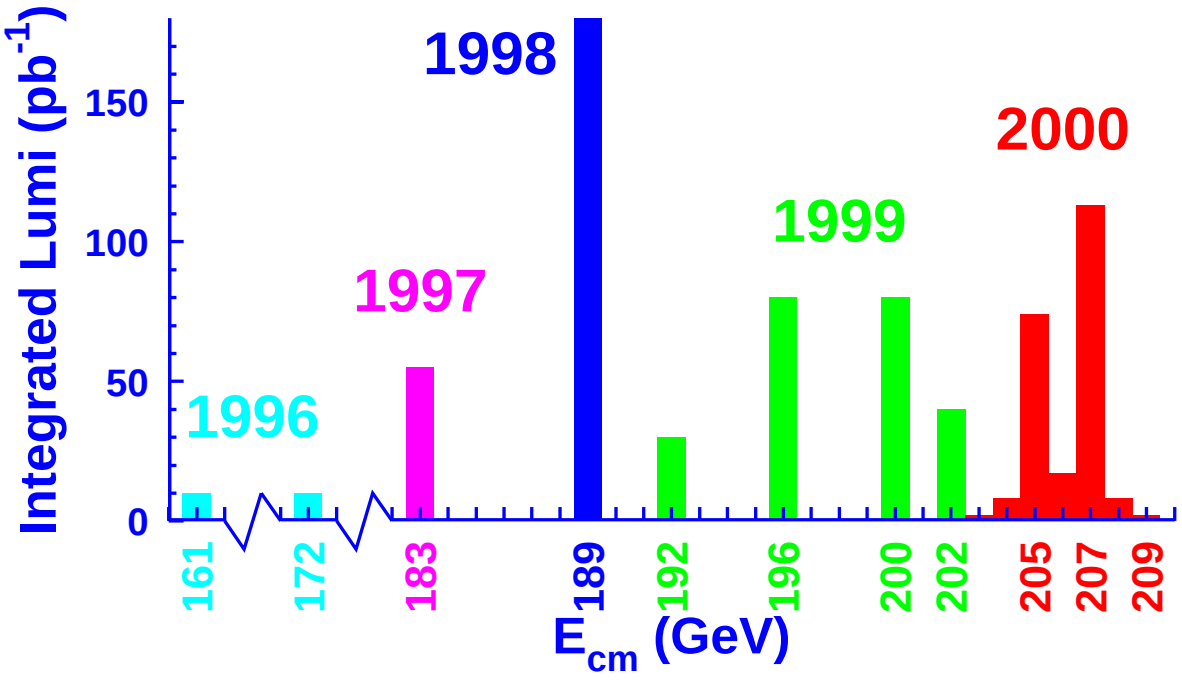
- 10 h at LEP1 ($\sqrt{s} \approx M_Z$)
- 3 h at LEP2




LEP Accelerator and four detectors operated 24h a day, from Spring to Autumn, 1989 to 2000

# LEP2 Machine Performance

- Impressive machine performance - increase beam energy and maintain high luminosity.
- Superconducting RF acceleration system pushed beyond design gradient.
- Max. integrated luminosity per year: 65pb$^{-1}$ (LEP1), 254pb$^{-1}$ (LEP2)



# *LEP: $e^+e^-$ collisions*

ALEPH, DELPHI, L3, OPAL each recorded:

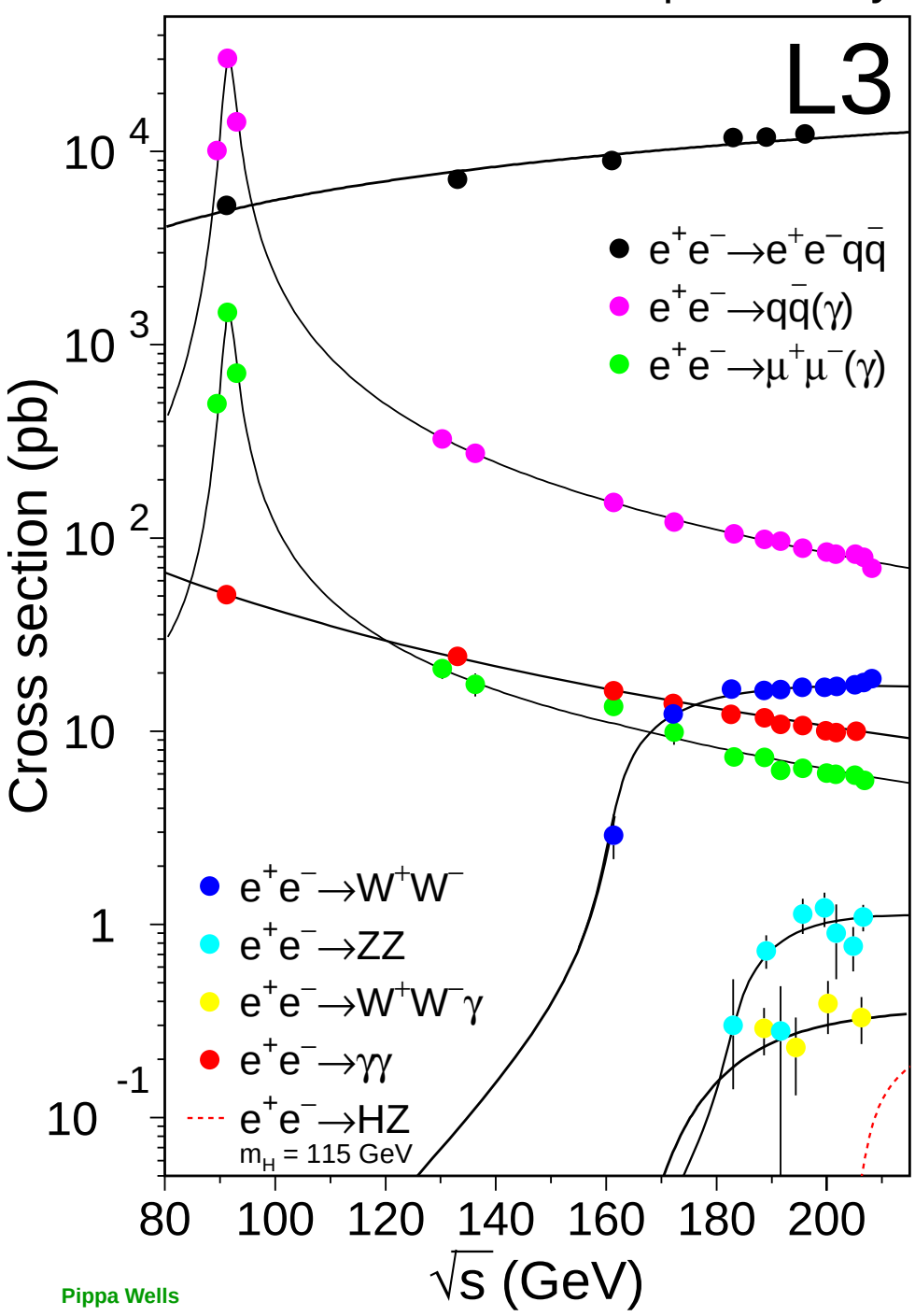
- 4.5M Z at LEP1 including off-peak data.
- 10k W-pair at LEP2

LEP1 dominated by Z resonance

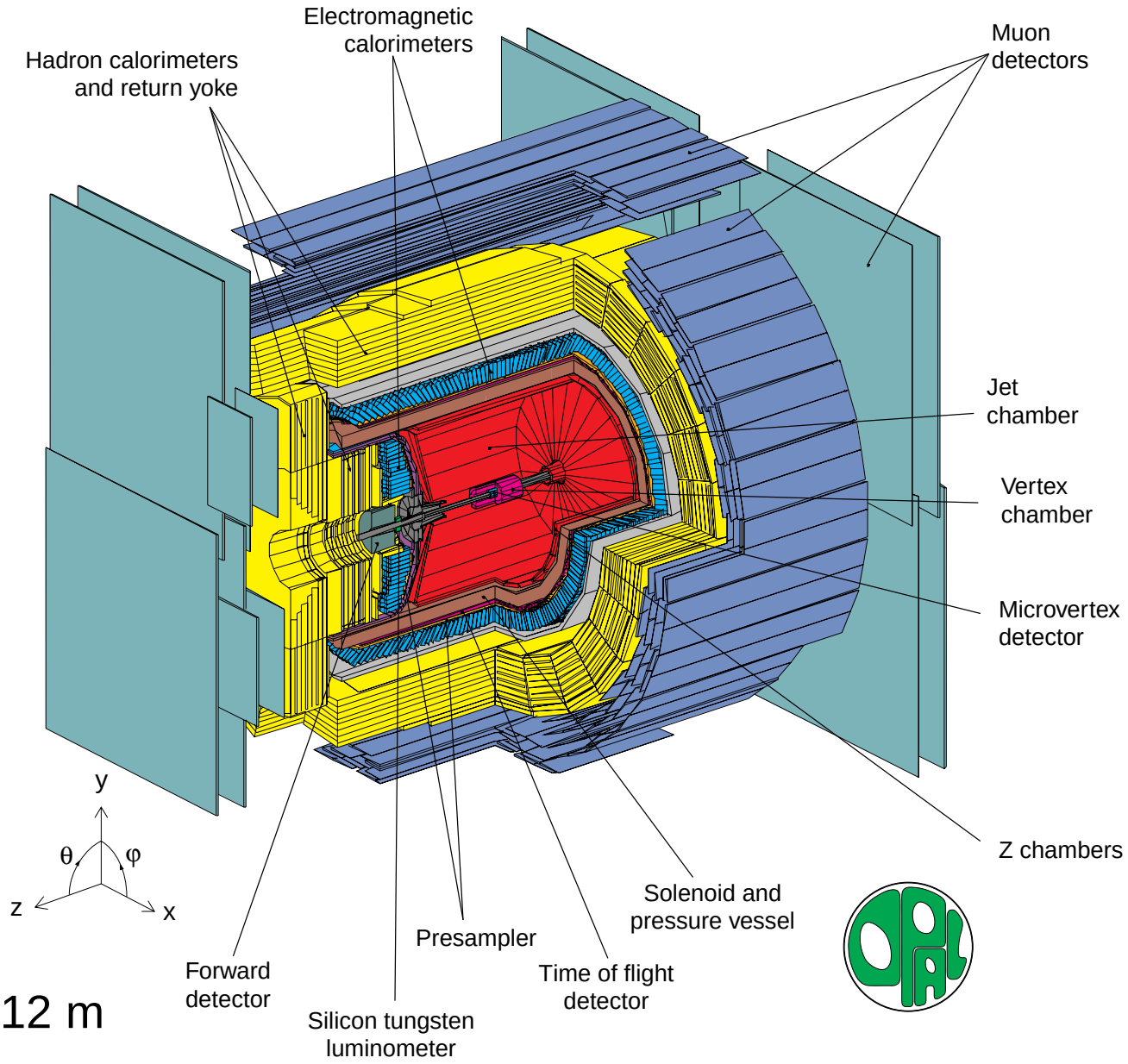
Several processes are important at LEP2

Any sign of $e^+e^- \rightarrow HZ$?

Pick out H and Z decay products against big backgrounds.

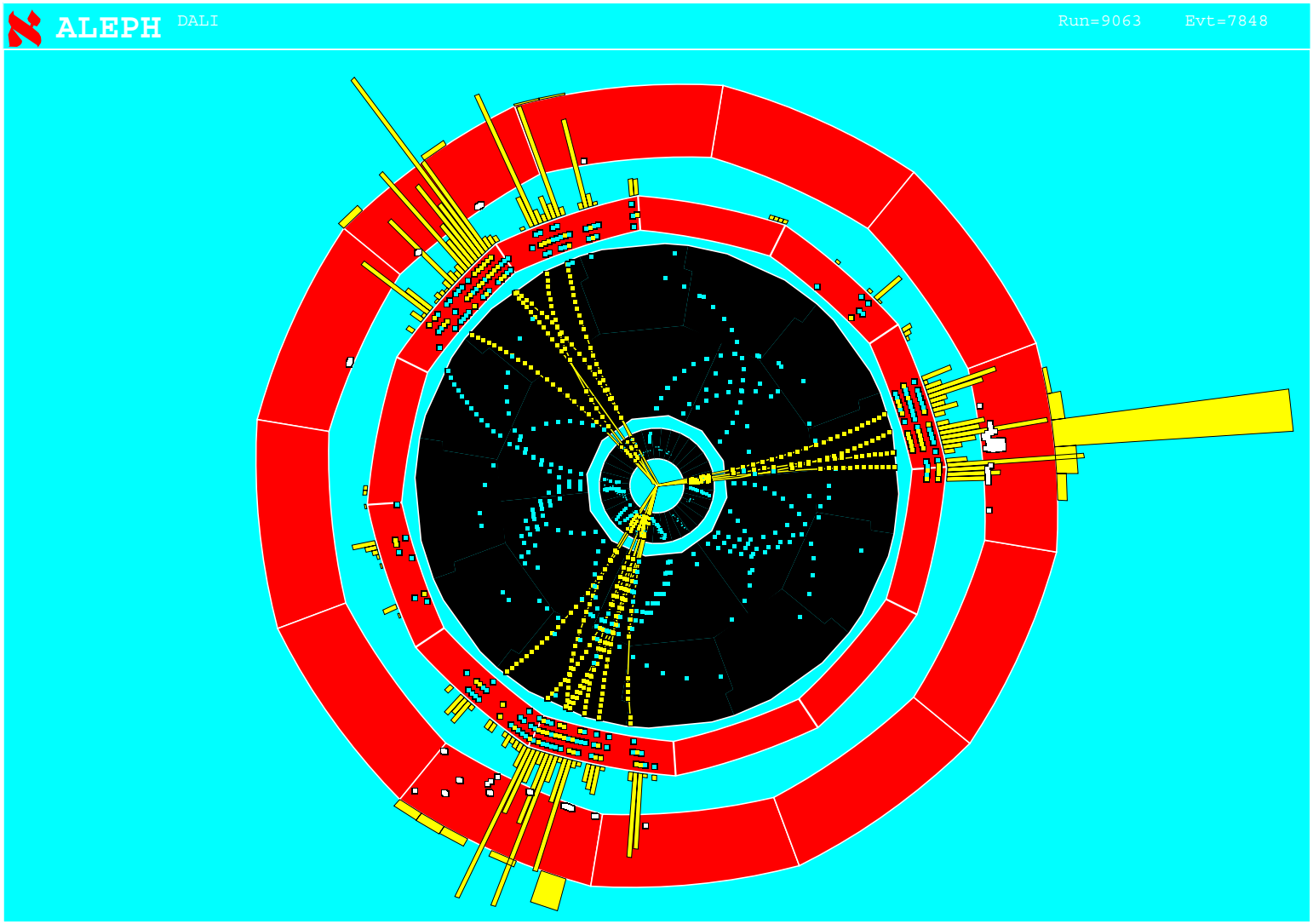


# Cut-away view of OPAL




Overall size 12×12×12 m

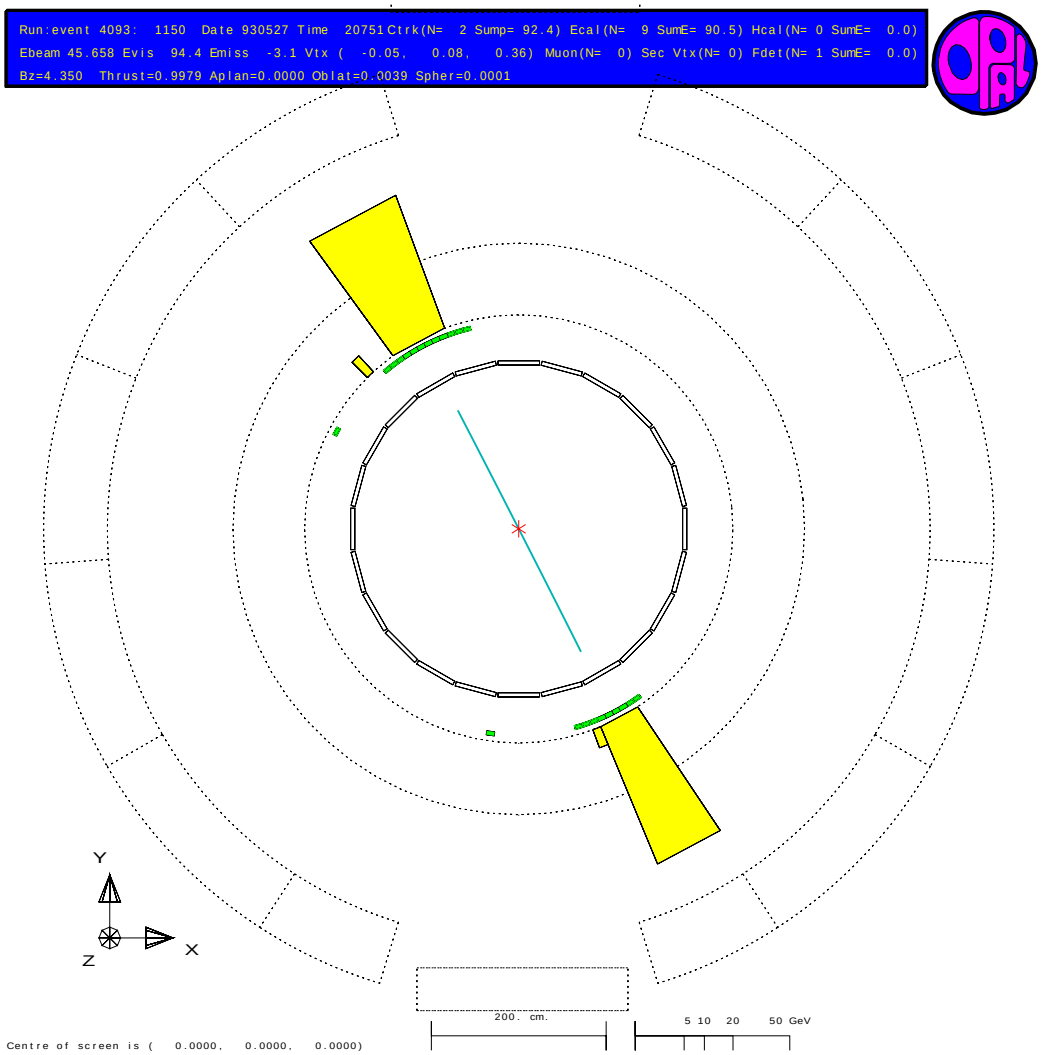
# Z to hadrons event in ALEPH




- This example has 3 jets $e^+e^- \rightarrow qqg$
- Jets include many tracks (curved in B=1.5 T field) and energy clusters

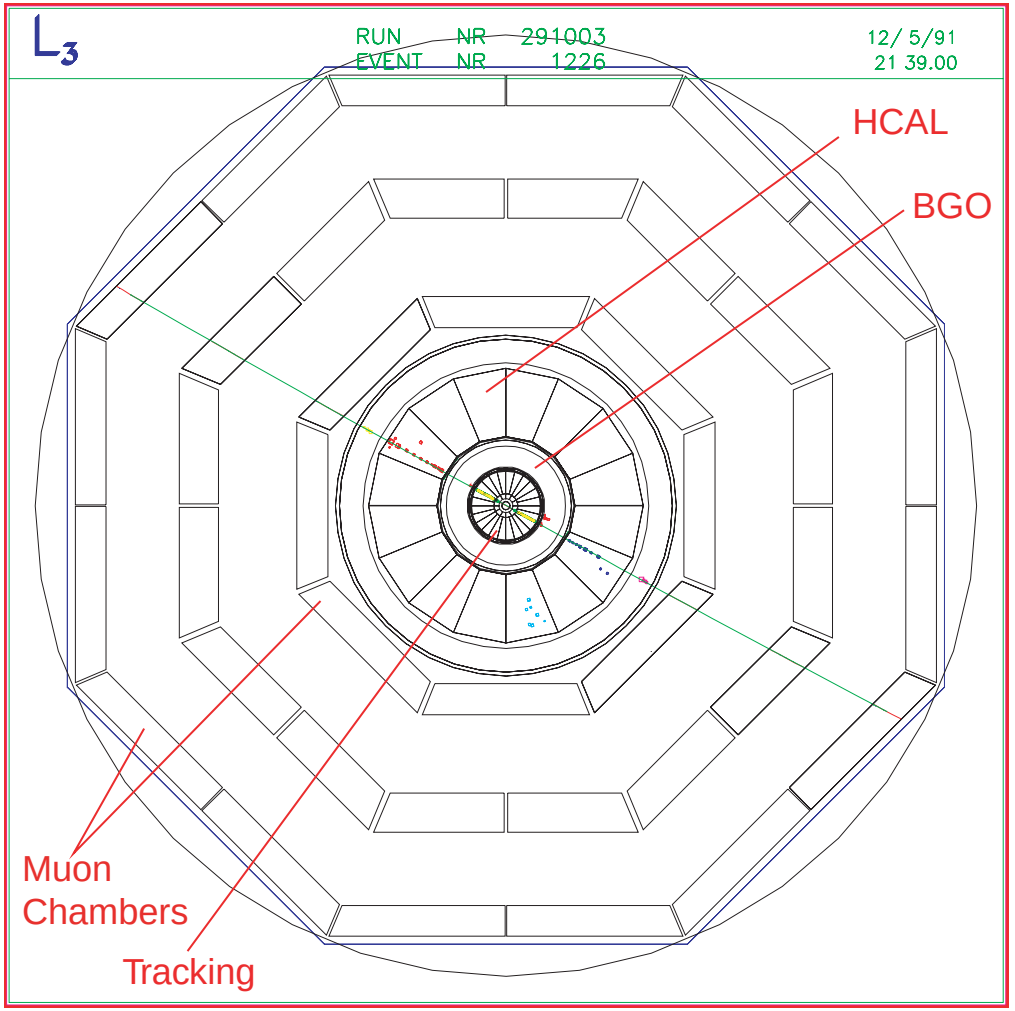
# $e^+e^- \rightarrow Z \rightarrow e^+e^-$ *event in OPAL*

- Lepton pair events have low multiplicity
- Electrons are identified by a track in the central detector, and a large energy deposit in the electromagnetic calorimeter, $E/p = 1$.



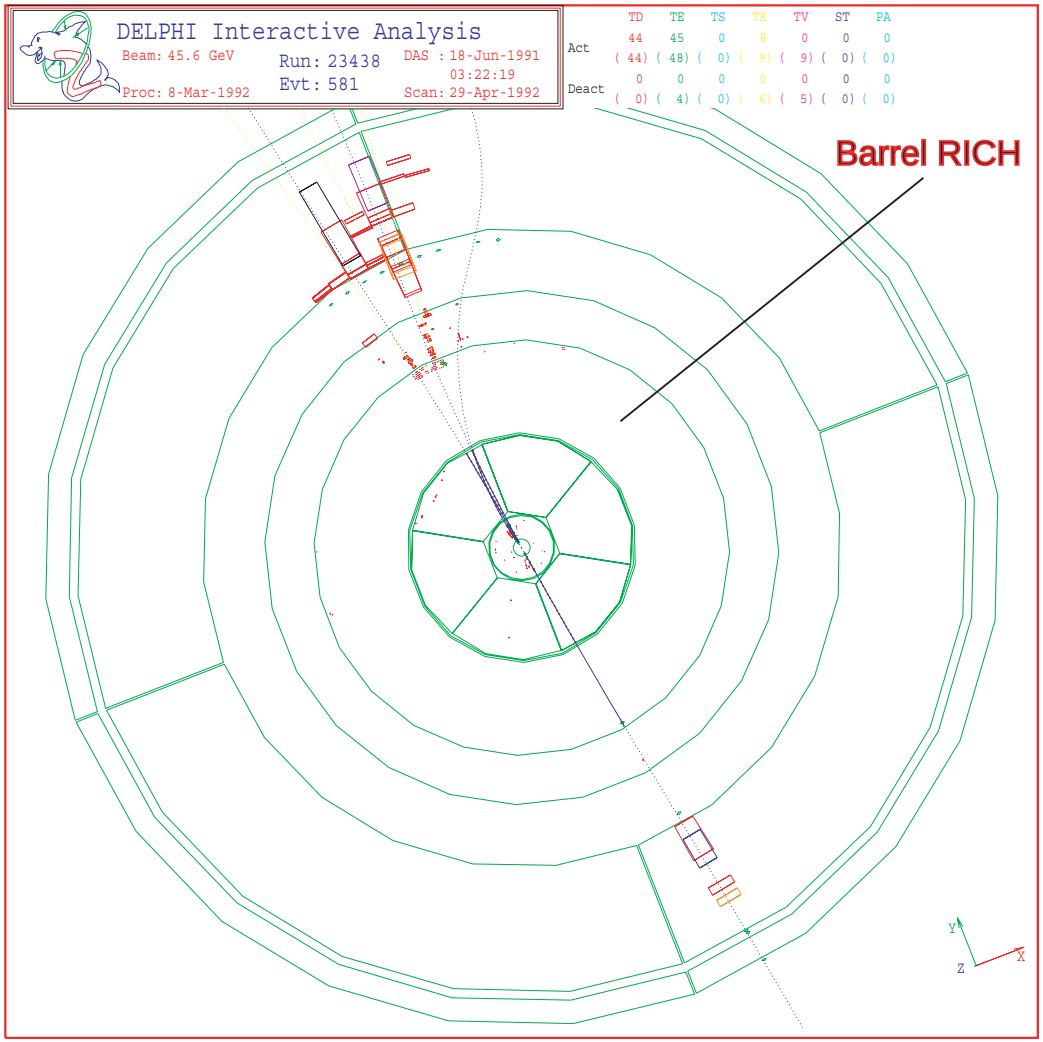
# $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ event in L3

- Muons penetrate entire detector. Little energy in the calorimeters.
- L3 emphasizes lepton and photon id with a precise BGO crystal ECAL, and large muon spectrometer.
- Tracking volume relatively small (r=1m)
- ALL detectors inside r=6m solenoid, B=0.5T.



# $e^+e^- \rightarrow Z \rightarrow \tau^+\tau^-$ *event in DELPHI*

- Tau lepton decays dominated by 1 and 3 charged tracks, with or without neutrals, missing neutrino(s), back-to-back very narrow “jets”.
- DELPHI has extra particle ID detectors, RICH.



# *Tagging heavy quarks - leptons*

Heavy hadrons have weak decays, sometimes final state leptons, long lifetimes, characteristic masses and event shapes.

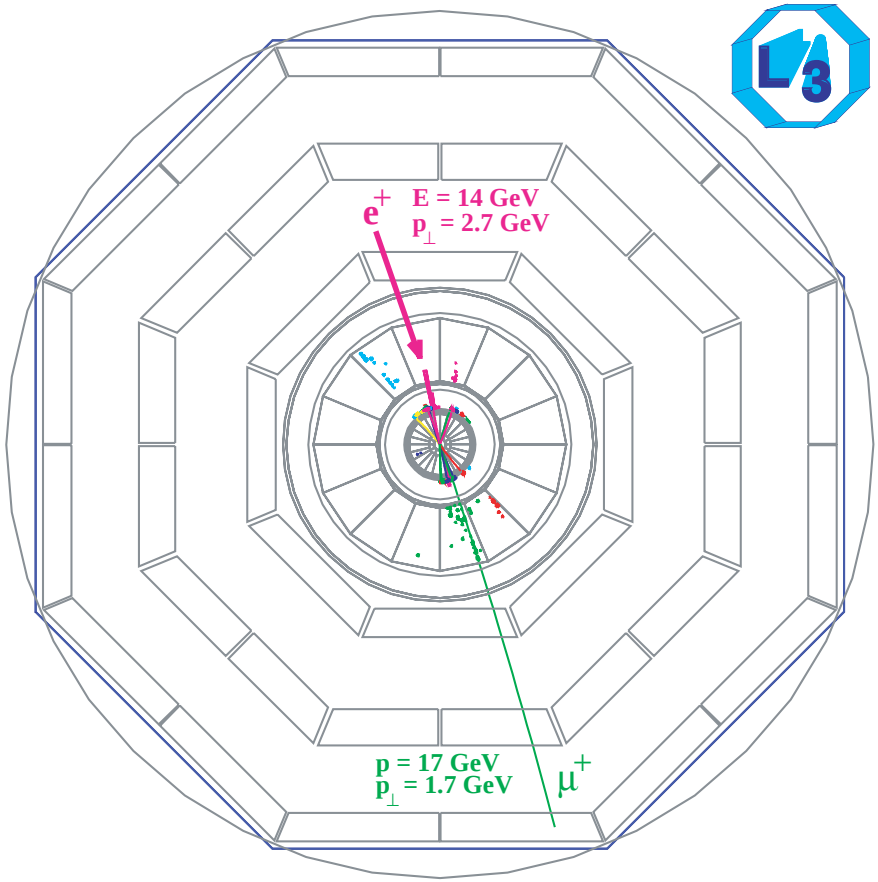
b and c hadrons have ≈ 20% of decays to leptons with high $p$ and for b hadrons with high $p_T$

Electrons: ionisation in tracking chambers $dE/dx$, $E/p$, shower shape

Muons: Match between central track and muon chambers

Leptons also give charge of the decaying hadron

Example shows $e^+e^- \rightarrow Z \rightarrow b\bar{b}$ event in L3



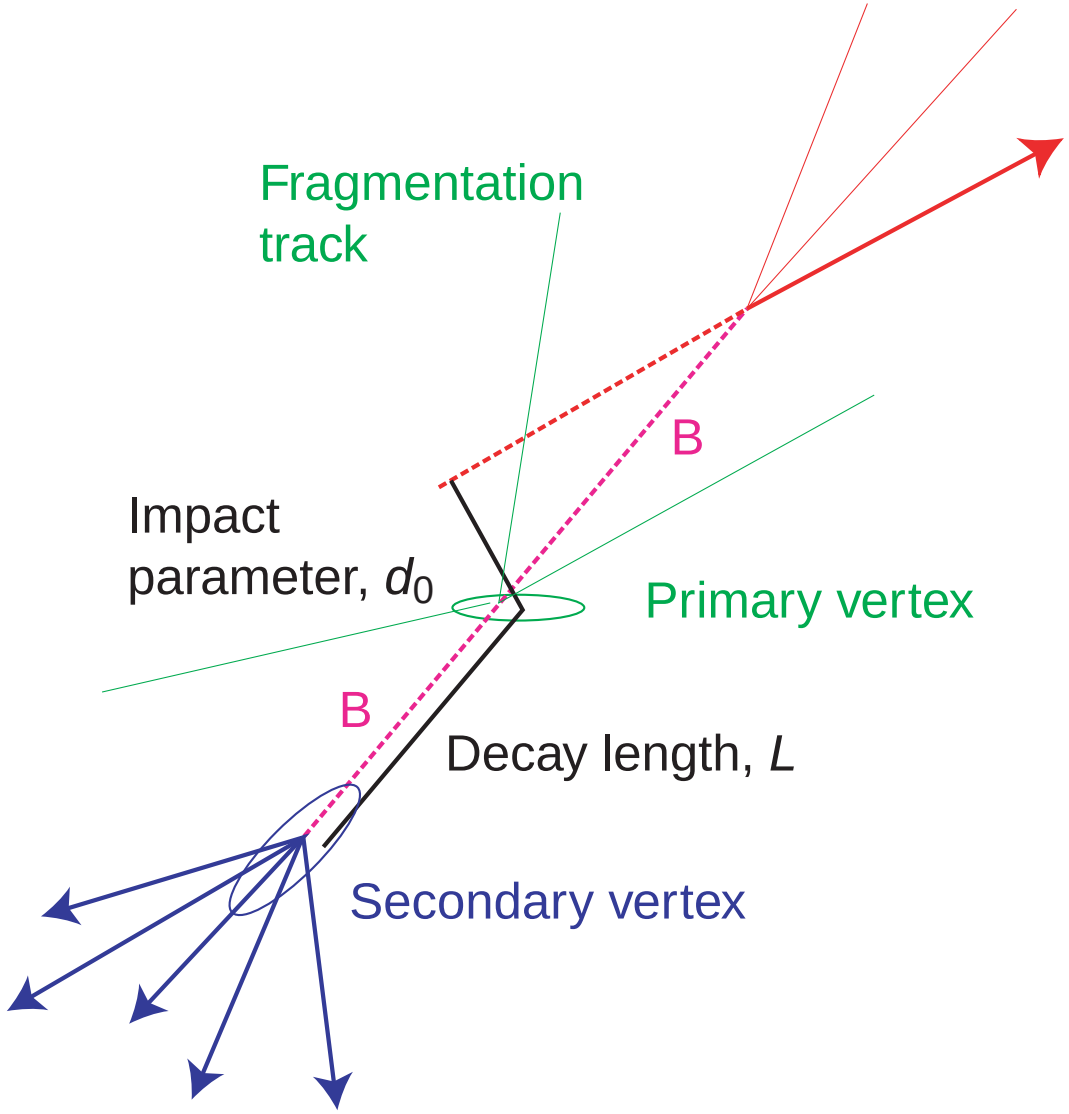
# Tagging heavy quarks - lifetimes

Heavy hadrons have long lifetime and large boost

$d_0$ and $L$ are signed quantities. A badly measured track may intercept the "wrong-side" of the beam spot.

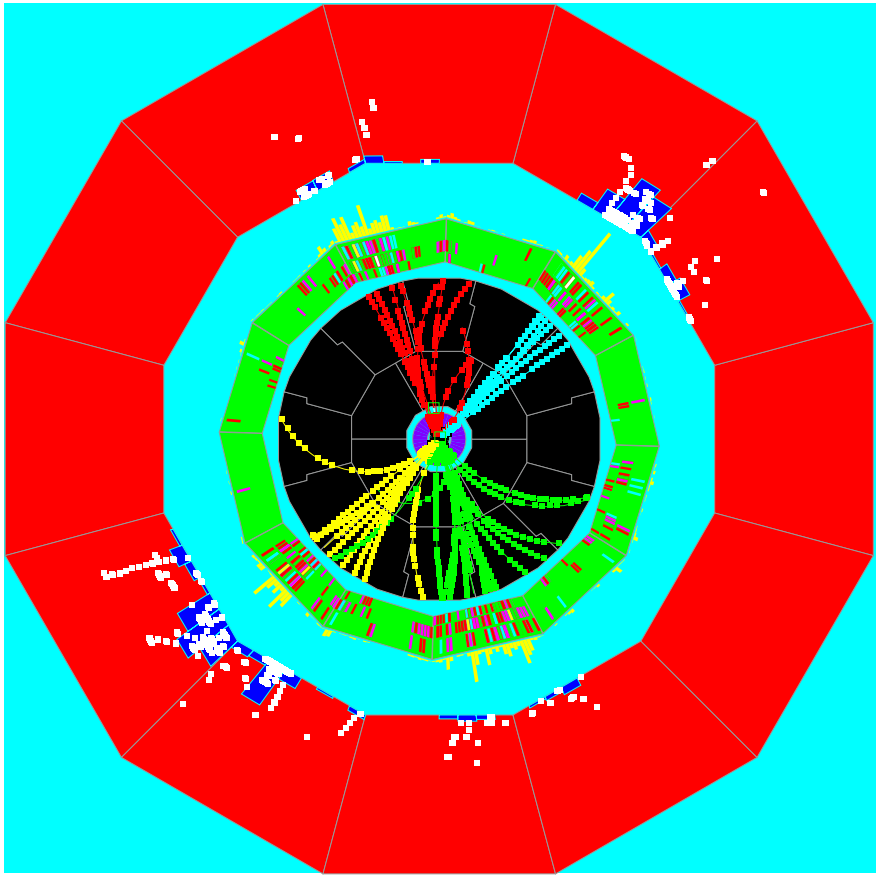
Rely on silicon microvertex detectors for resolution.

Use several variables together.

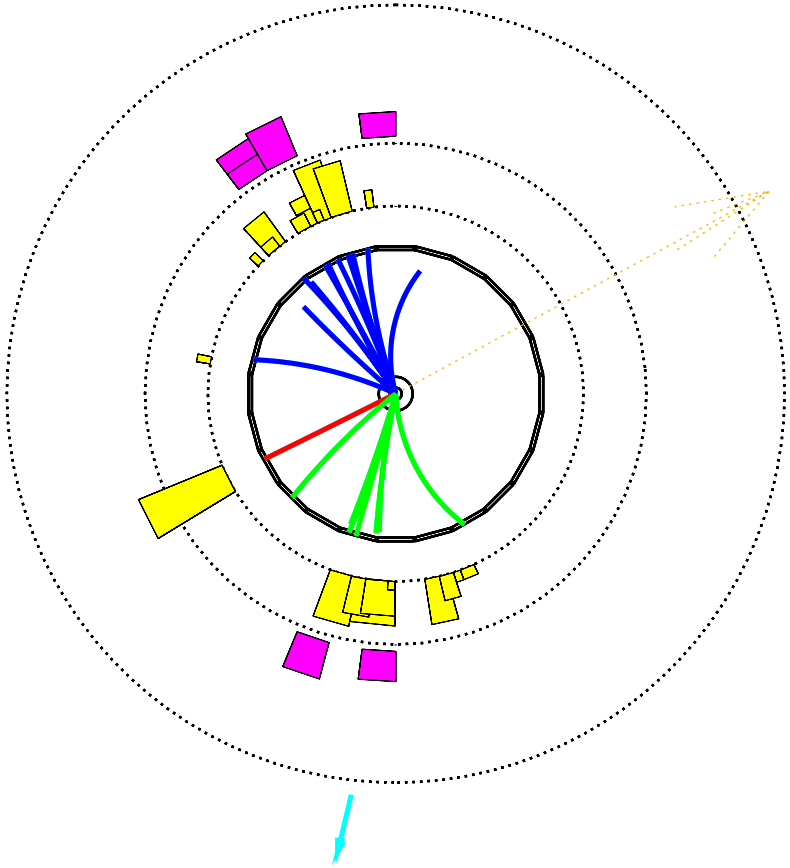


# *W pair events at LEP2*

$WW \rightarrow q\bar{q}q\bar{q}$ (four jets)

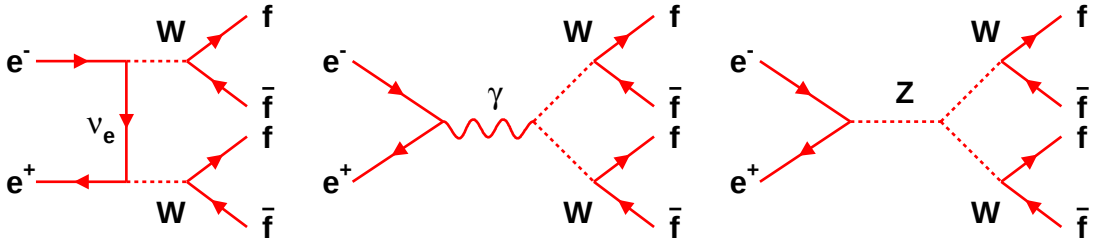


$WW \rightarrow q\bar{q}\ell\nu$ (two jets, lepton and missing energy)

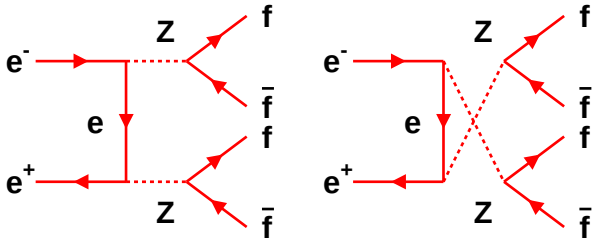


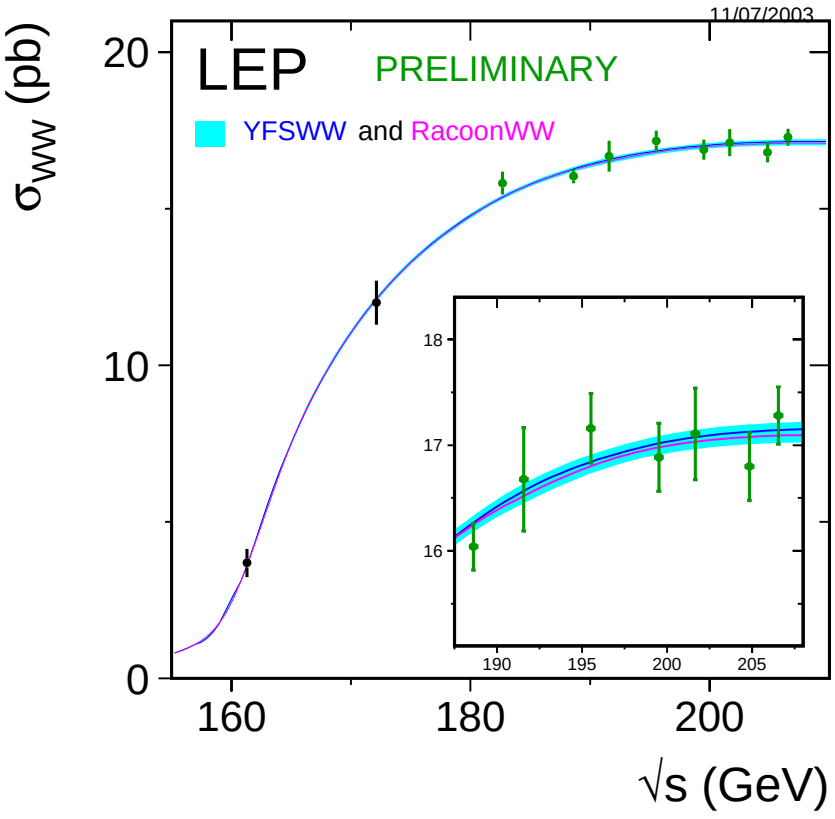
# *WW and ZZ production at LEP2*

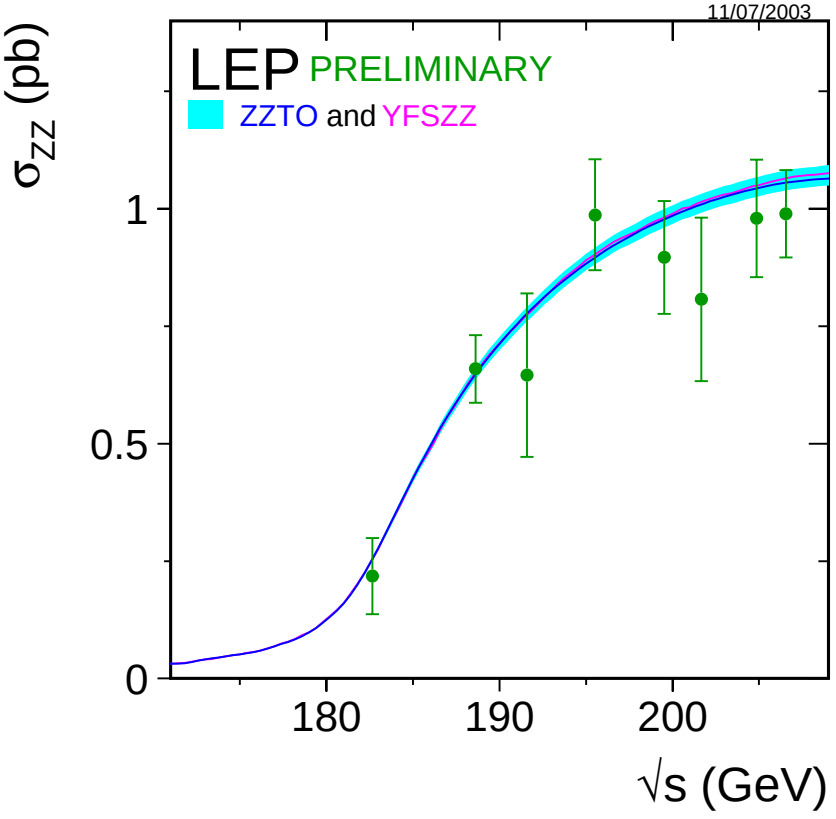
3 diagrams “CC03”




2 diagrams “NC02”




ZZ production is an irreducible background to ZH production.

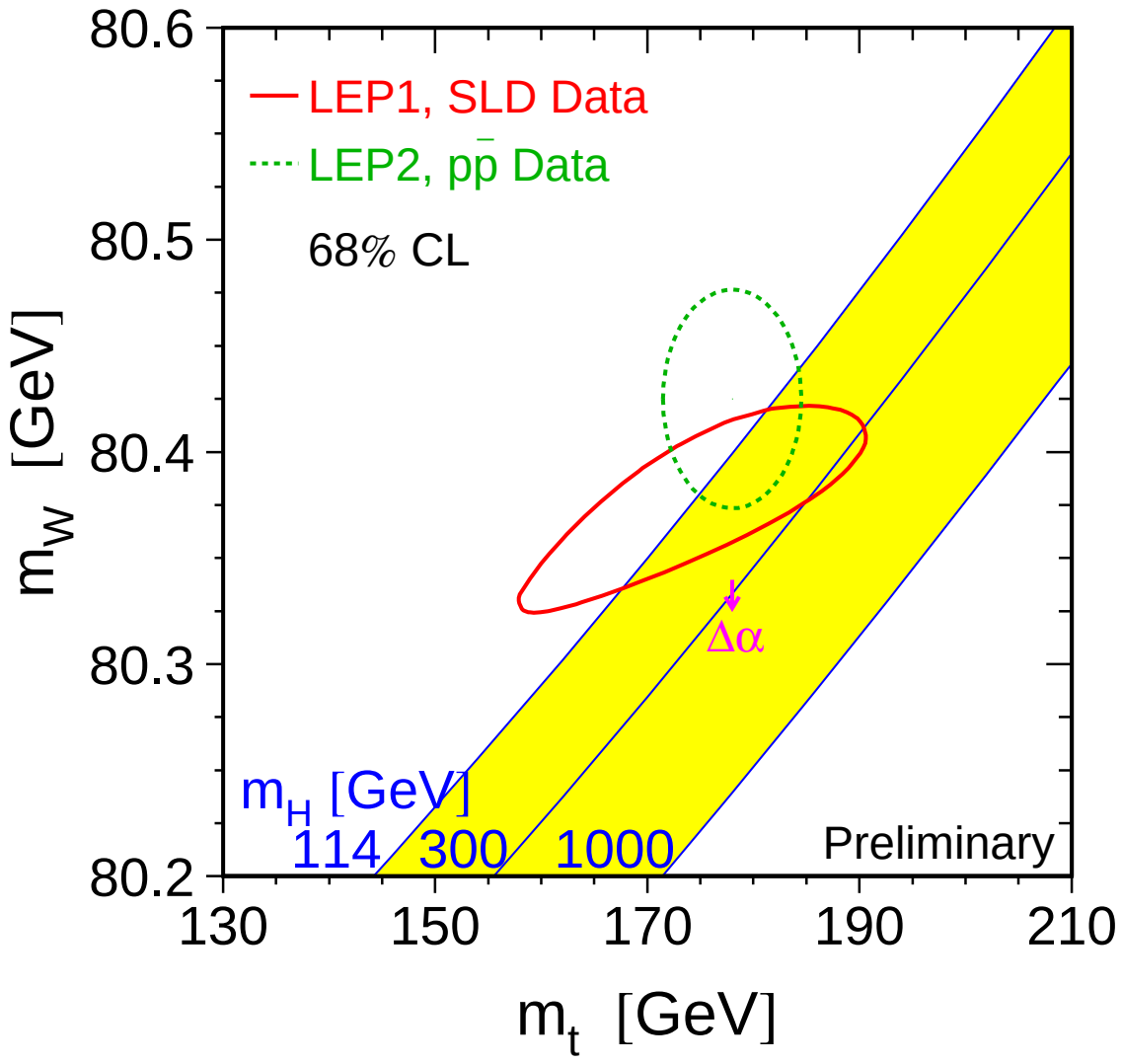
# *Global electroweak fits and Higgs Mass*

Fit to data from LEP, SLD, Tevatron...

Electroweak variables depend on $m_t^2$ and $\log m_H$ through radiative corrections

Consistency between predicted top and W mass (Z pole) and direct measurements

Preference for low Higgs mass.



# Constraints on Higgs mass

Electroweak fits

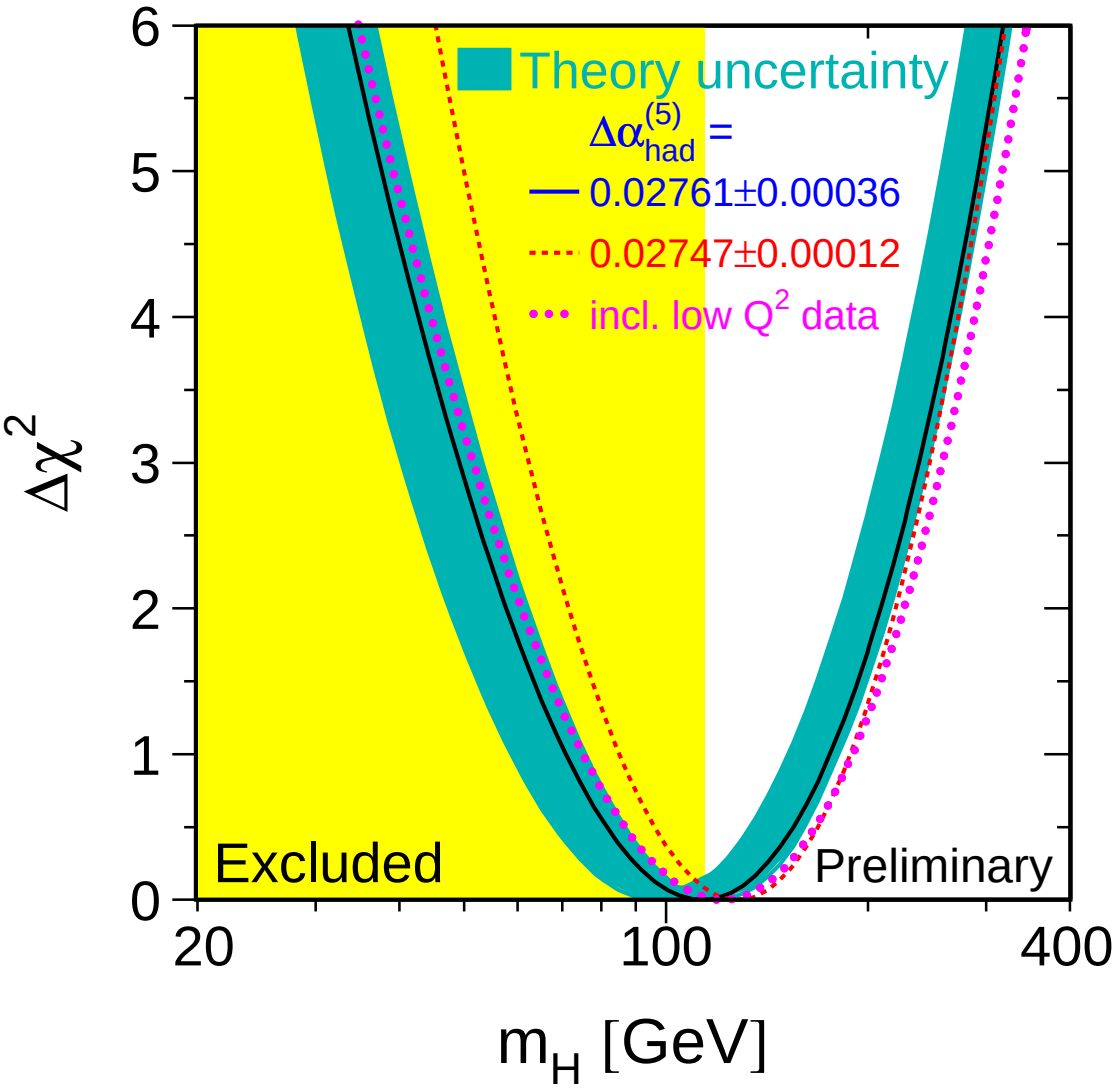
$m_H < 237$ GeV (95% CL)

Theory: self consistency of SM to GUT scale $\approx 10^{16}$ GeV

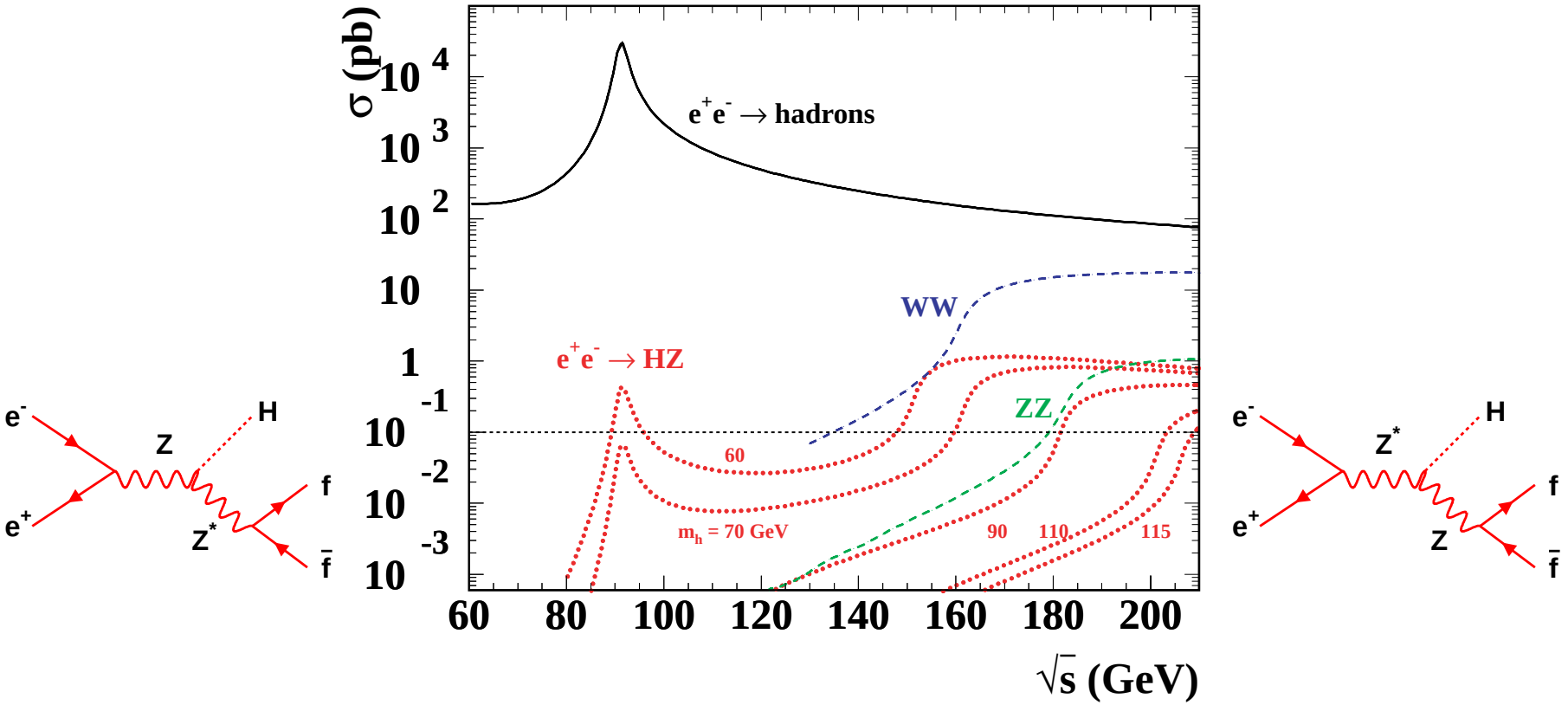
$130 < m_H < 190$ GeV.

$m_H$ higher - theory non-perturbative,

$m_H$ lower - vacuum unstable.



# Higgs production cross-section



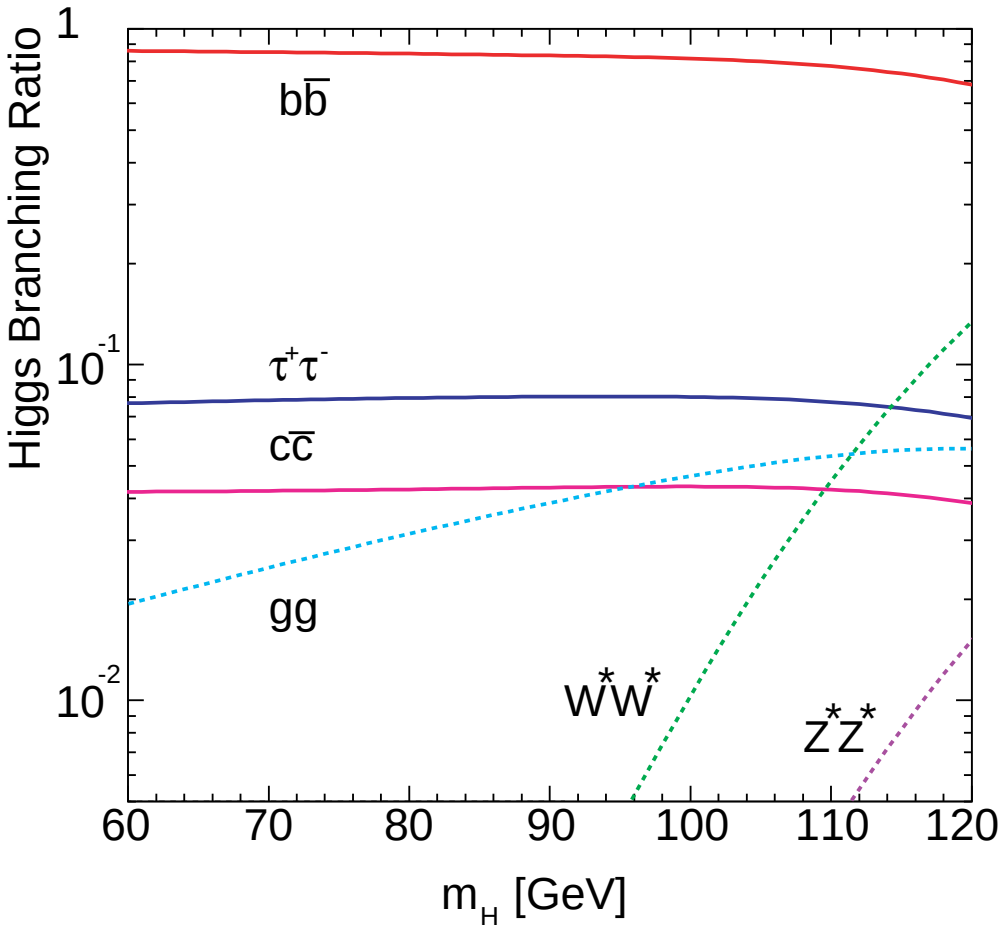

With a luminosity of about 100pb$^{-1}$ and reasonable detection efficiency, sensitive to a cross section of $O(0.1)$ pb.

Need LEP2 to produce $m_H \gtrsim 65$ GeV. Reach $m_H \lesssim \sqrt{s} - M_Z$

Must take into account many background processes

# *Higgs decay branching ratios*

"Higgs couples to mass"

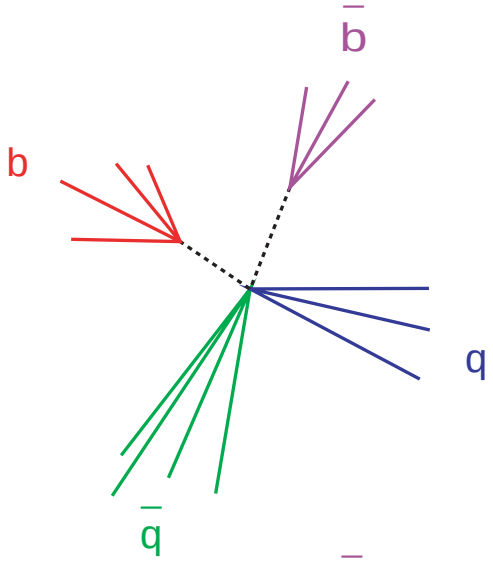



| BR(%) | Higgs 115 GeV | Z boson |
|---|---|---|
| $q\bar{q}$ | | 70 |
| $b\bar{b}$ | 74 | 15 |
| $c\bar{c}$ | 4 | 12 |
| gg | 6 | 0 |
| $\ell^+\ell^-$ | | 10 |
| $\tau^+\tau^-$ | 7 | 3 |
| $\nu\bar{\nu}$ | | 20 |
| $W^*W^*$ | 8 | |
| $Z^*Z^*$ | 1 | |

# HZ decays

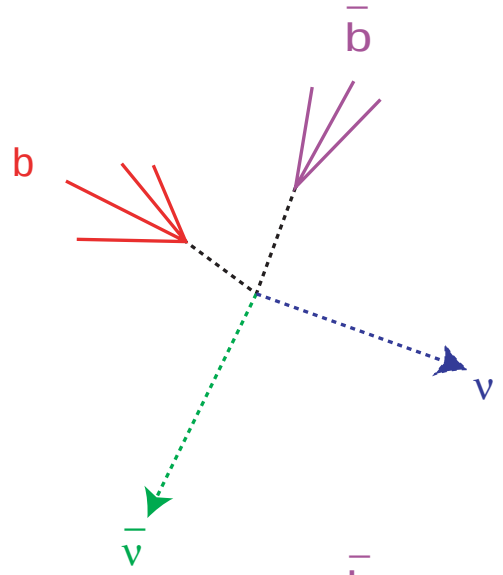
Four jets, 60%

$H \to b\bar{b}$, $Z \to q\bar{q}$



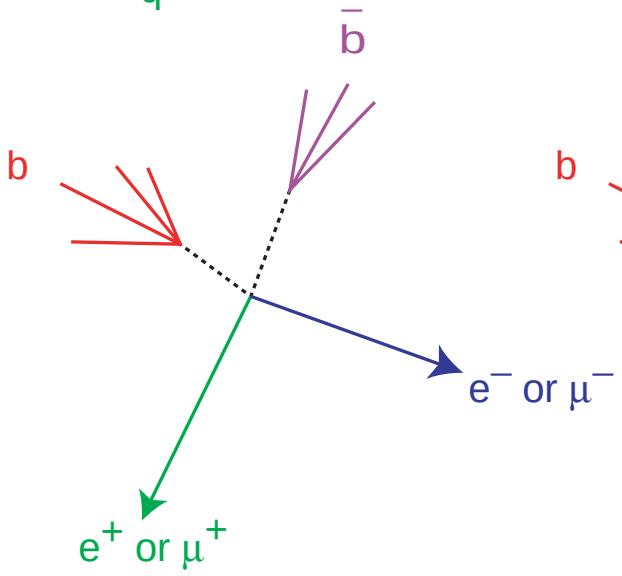

Missing energy, 18%

$H \to b\bar{b}$, $Z \to \nu\bar{\nu}$



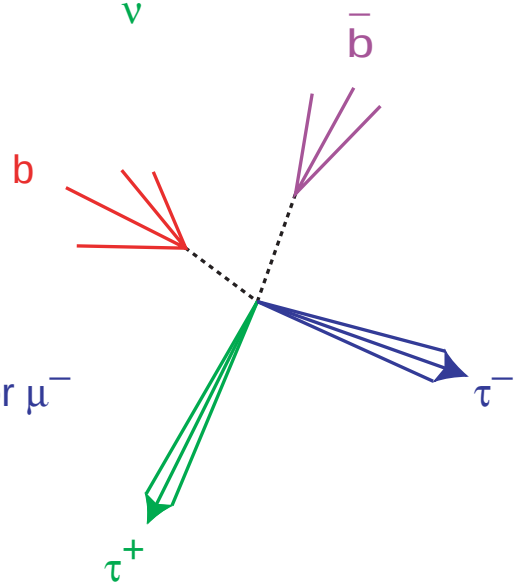

Leptonic, 6%

$H \to b\bar{b}$, $Z \to \ell^+\ell^-$




Tau channels, 9%

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

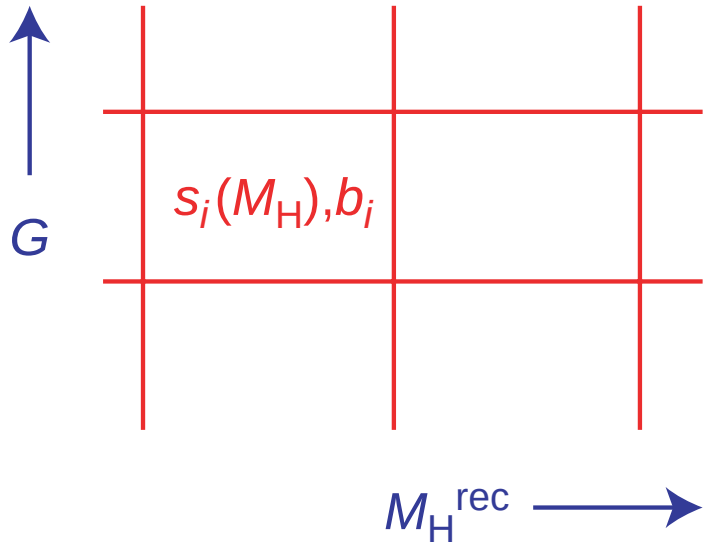


# *Got some candidates? Are they significant?*

$b_i$ expected number of background

$s_i(m_H)$ expected signal, function of "test mass" $m_H$

Count these in bins of reconstructed Higgs mass $m_H^{rec}$ and a global discriminating variable $G$




Discriminant $G$ takes into account b-tagging, $\tau$-id, kinematic variables that distinguish signal and background.

"How Higgs-like is the event?"

Expectations account for luminosity, $E_{cm}$, resolution, efficiency...

Compare likelihoods of "$s + b$" and "$b$ only".

# *Likelihood comparison*

Likelihoods of $s + b$ and $b$ from Poisson probabilities of observing $n_i$ data events in each bin:

$$Q(m_H) = \frac{L_{s+b}}{L_b} = \prod_i \frac{(s_i + b_i)^{n_i} e^{-(s_i+b_i)}/n_i}{b_i^{n_i} e^{-b_i}/n_i}$$

More convenient to work with log likelihood:

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

Sum is over all bins, channels (four jet, missing energy...), and experiments.

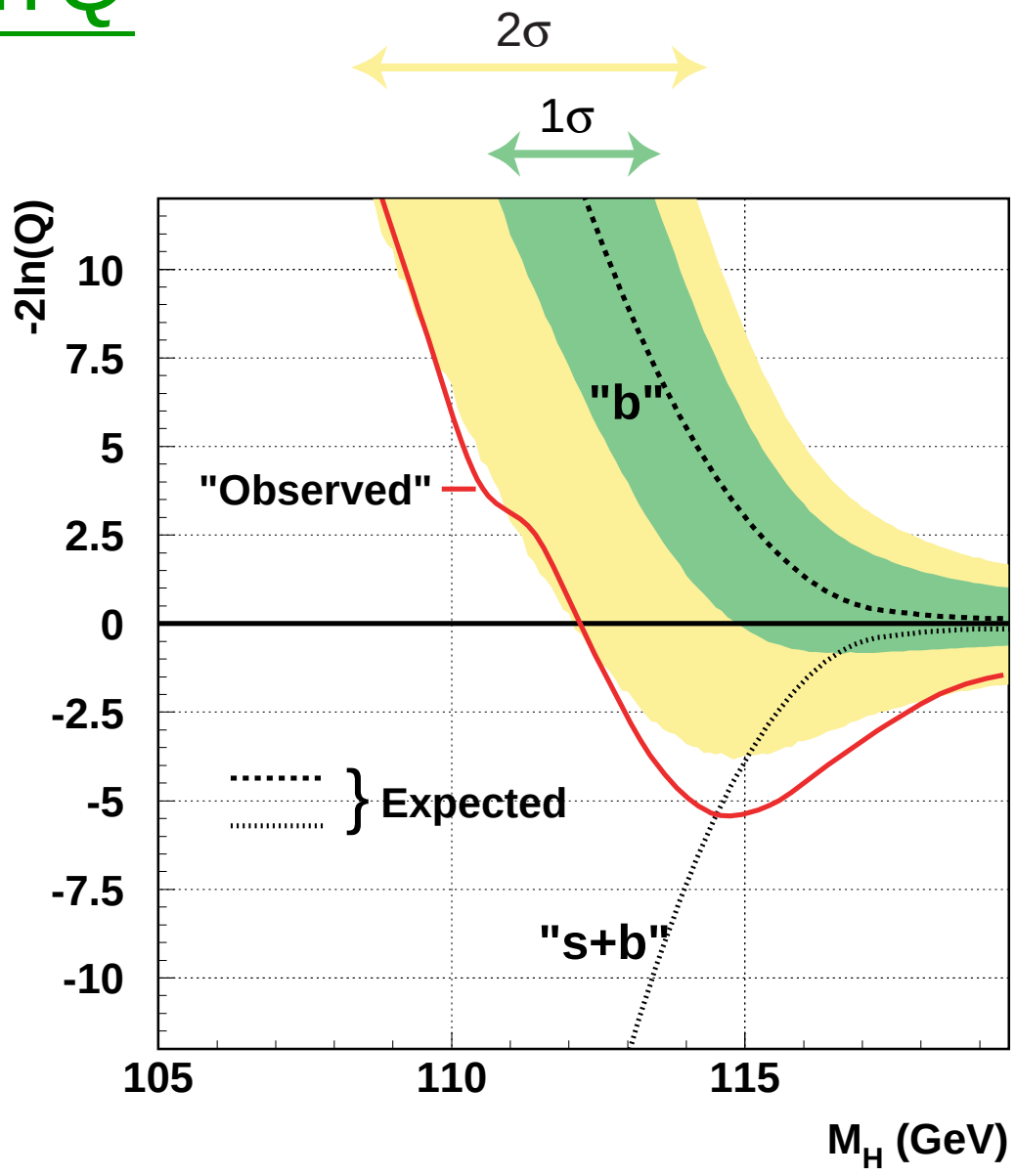
# *Likelihood ratio,* $-2 \ln Q$

$-2 \ln Q$ vs. test mass $m_H$.

Find expected (median) curves and statistical spread from a set of ficticious MC samples of the same luminosity/$E_{cm}$ mix as the data.

Compare with the observation - here's an example of what you might hope to see in the real data!

Taking slices at different test masses - separation of b and s+b decreases as mass increases.



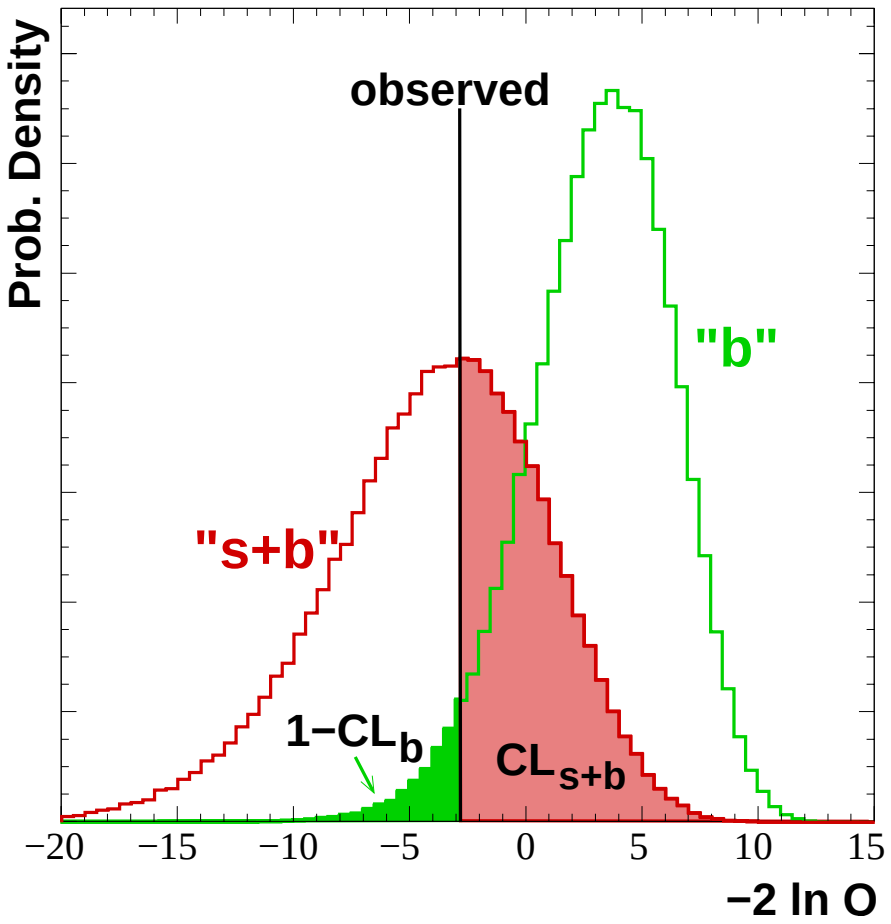
# Confidence levels

This is a slice through the previous plot at one test mass, showing the distributions for MC experiments, and the data observation.

Separation of b and s+b curves

indicates sensitivity of analysis.

For EACH test mass, $m_H$, define confidence levels




| | |
|---|---|
| $1 - CL_b$ | Measure of inconsistency with “b” |
| $CL_{s+b}$ | Measure of inconsistency with “s + b” |
| $CL_s = CL_{s+b}/CL_b$ | Lower bound on Higgs mass |

# *5 September 2000 LEPC*

LEPC - The CERN Committee in charge of the LEP physics programme

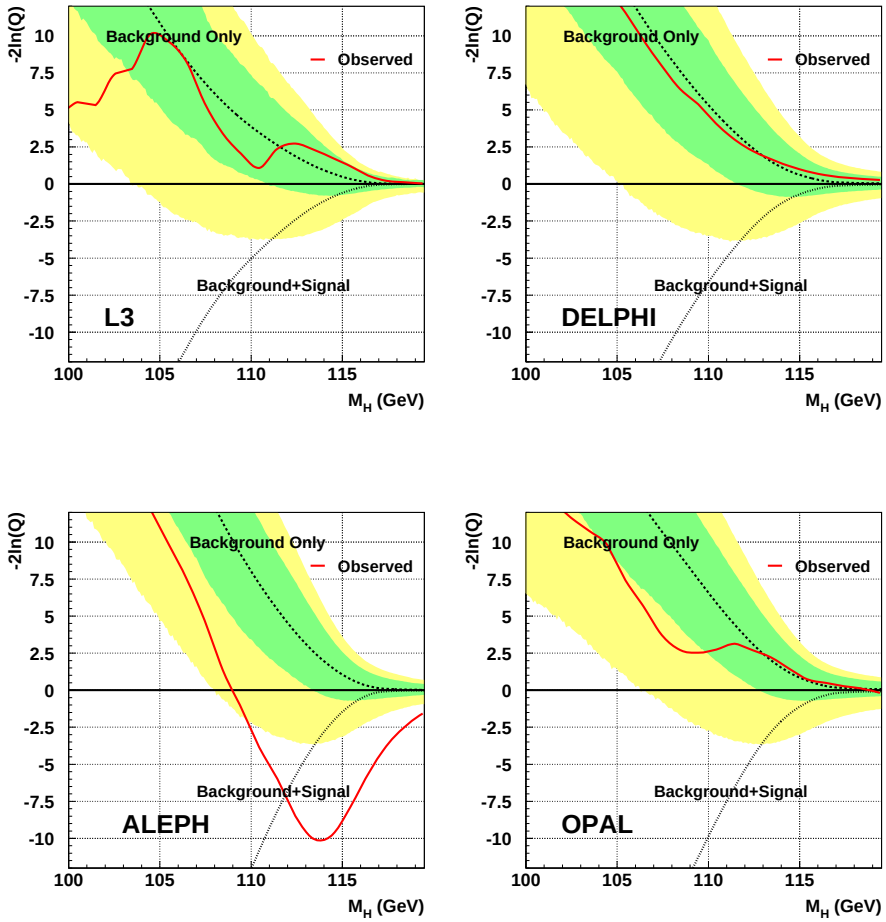
One of a planned series of presentations of results from the four experiments during 2000 in case something new came up during the last year of LEP running at higher energy than ever before...

150pb$^{-1}$ per experiment with $E_{cm} > 200$ GeV

of which 75pb$^{-1}$ per experiment with $E_{cm} > 206$ GeV

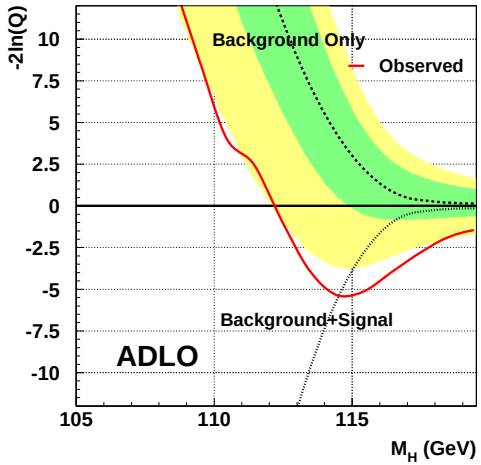
Here are some slides shown in that meeting...

# SM Results from All Experiments

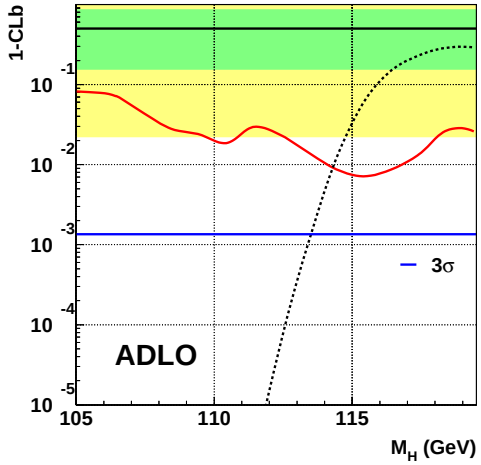



$3.9\sigma$ Excess in ALEPH Data $(1 - \mathrm{CL_b} = 6 \cdot 10^{-5})$

# Combined SM Results



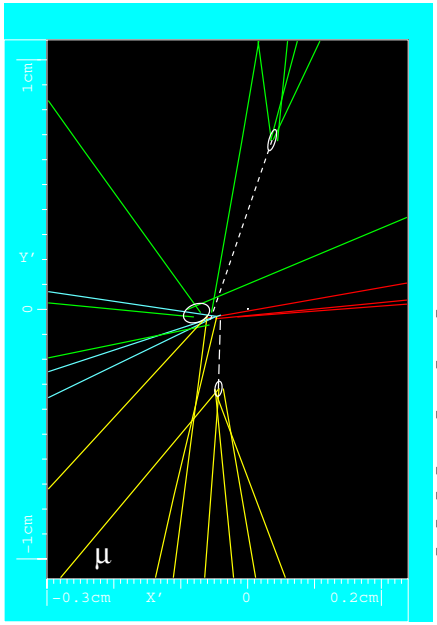

$-2\ln(Q)$ Minimum
at 114.9 GeV

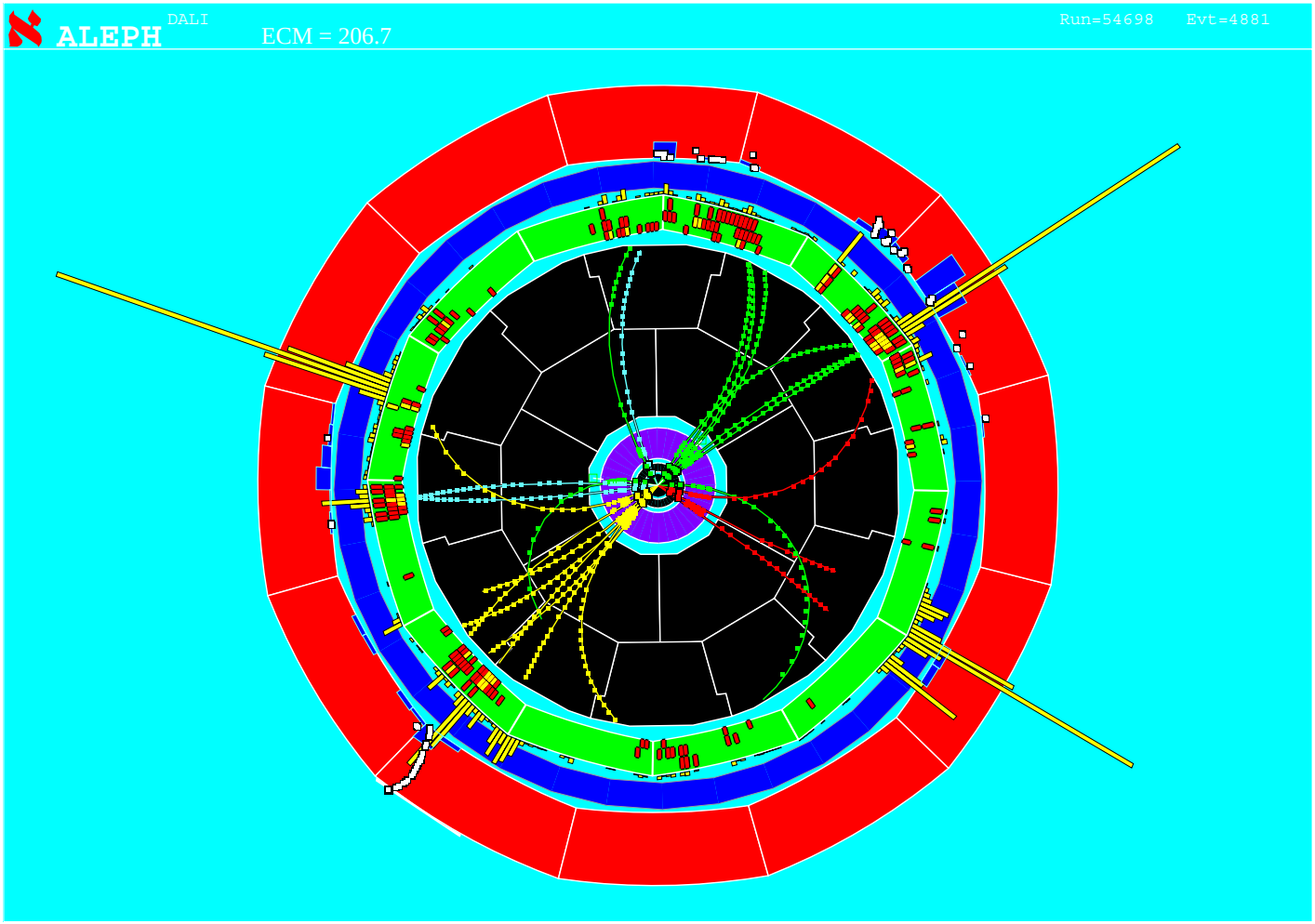



$1 - CL_b$ Minimum
at $2.6\sigma$
Significance

# ALEPH Events - four jets with b tags

Zoom right inside the beam pipe:



# *5 September Decision*

Approve 1 month extension of LEP running from scheduled stop on 1 October to 2 November 2000.

Hope that this will allow time to double the luminosity above 206 GeV (add 75pb$^{-1}$ per experiment)

(Big end-of-LEP celebration on 11 October had to go ahead!)

Slides from the 3 November meeting...

# Data Sets

- **REFERENCE data set ... where it all begun ...**

  **data set combined for the Sept 5 LEP seminar ...**

  **Revisited ... changes within the experiments**

  - $\Rightarrow$ **Recalibration of data**
  - $\Rightarrow$ **Revision of procedures (corrections)**
  - $\Rightarrow$ **Improvements ... better sensitivity**

- **DELTA set ... data collected since "REF"**

  **(... until the "cutoff date" ... Oct 18-25)**

- **TOTAL = REF + DELTA**

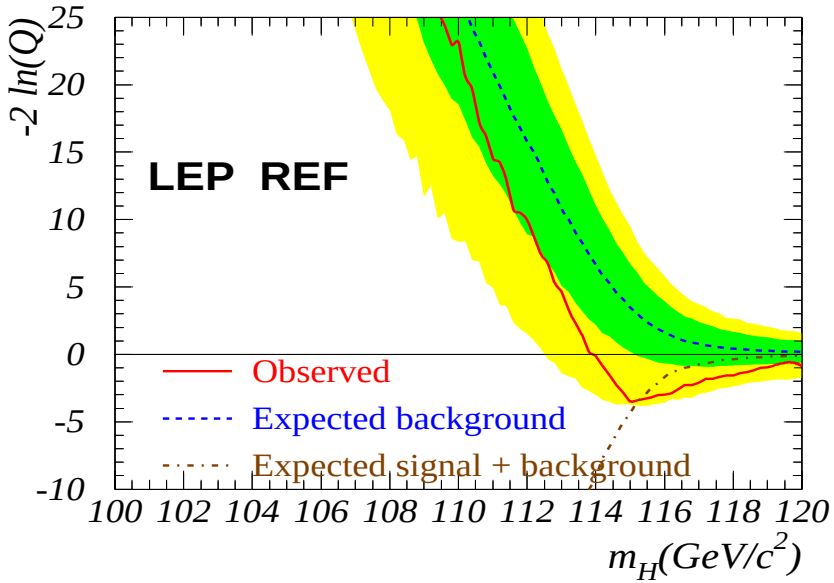
**Integrated luminosities ... A+D+L+O = "ADLO"**

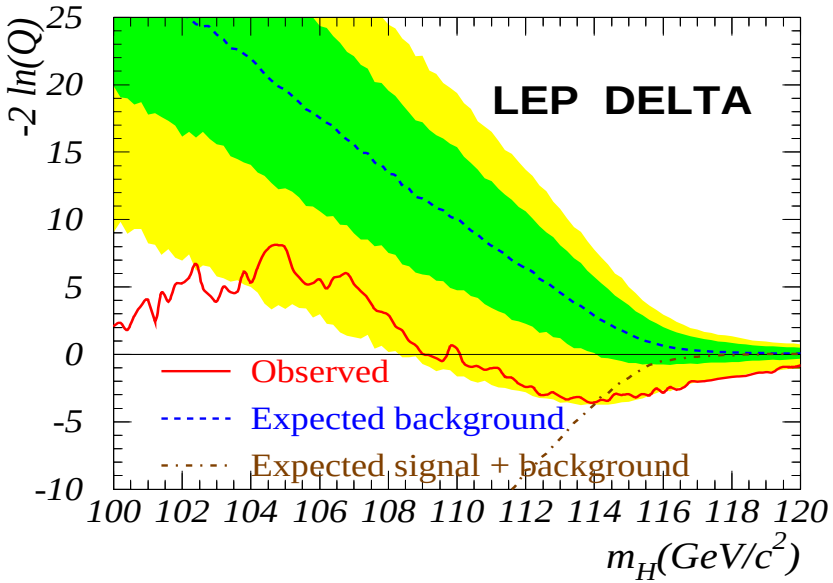
**(contributions from single experiments ... within $\pm$5%)**

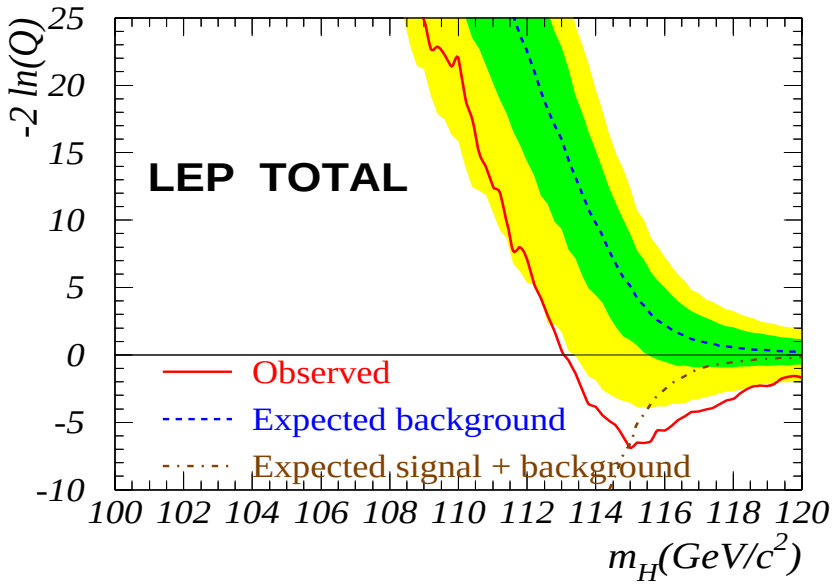
**Not included ... latest data ... $\approx$30 pb$^{-1}$**

| $\mathcal{L}$ (pb$^{-1}$) | REF | DELTA | TOTAL |
|---|---|---|---|
| $E_{cm} > 200$ GeV | 596.6 | 213.7 | 810.3 |
| $E_{cm} > 206$ GeV | 303.5 | 184.5 | 488.0 |

# $-2\ln(Q)$ ... REF, DELTA, TOTAL




$\Leftarrow$

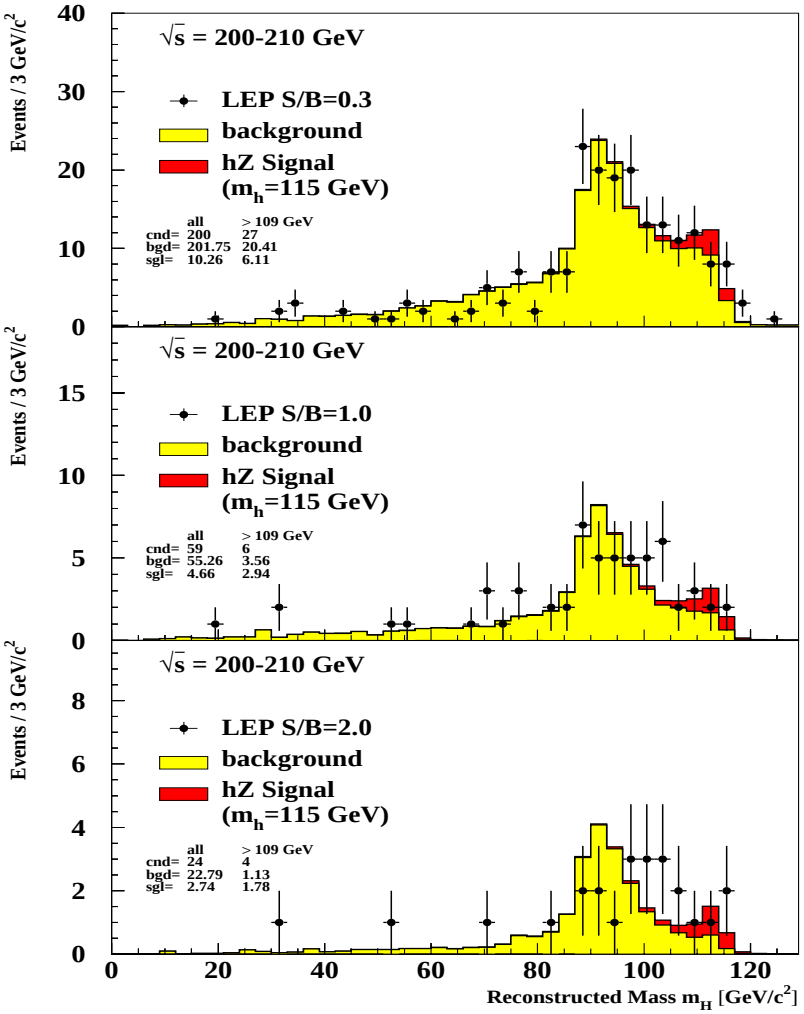
**Minimum @$m_H \approx 115$ GeV**

**Agreement with SM Higgs cross-sect. for**

$$m_H = 115.0^{+1.3}_{-0.9}\ \text{GeV}$$

# Distributions of Reconstructed Mass

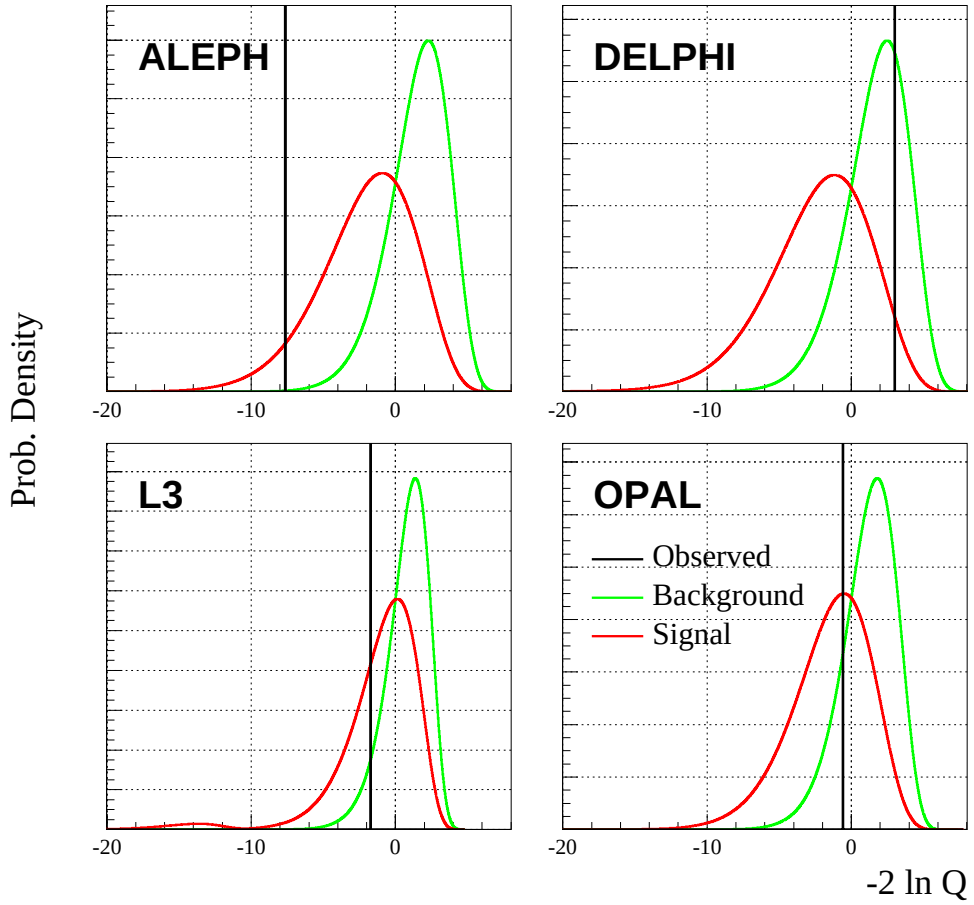
**Sequence: “Loose”, “Medium” and “Tight” selection (*)**




(*) **Special selection ... not biasing the mass distribution**

# Results by Experiments

**for TOTAL data set, @ $m_H = 115$ GeV**



# SUMMARY

| REFERENCE | $\Rightarrow$ | TOTAL |
|---|---|---|
| $2.2\sigma$ | $\Rightarrow$ | $2.9\sigma$ |
| One expt "s+b"-like | $\Rightarrow$ | Three expt "s+b"-like |
| 4-jet "s+b"-like | $\Rightarrow$ | 4-jet, E-miss "s+b"-like |

**Perfect compatibility with SM Higgs cross section**

**for**

$$m_H = 115.0^{+1.3}_{-0.9} \text{ GeV}$$

**! ALL THIS IS VERY EXCITING !**

**Current bound on Higgs boson mass**

$m_H > 113.5$ **GeV @95% c.l.**

**for 115.3 GeV expected**

# *Run LEP in 2001?*

Evidence was consistent with a hint of Higgs production at 115 GeV

- 3/4 experiments somewhat more “s+b” than “b”
- Two channels more “s+b” than “b”
- Spread of s/b and $m_H^{rec}$ for significant candidates consistent with Higgs

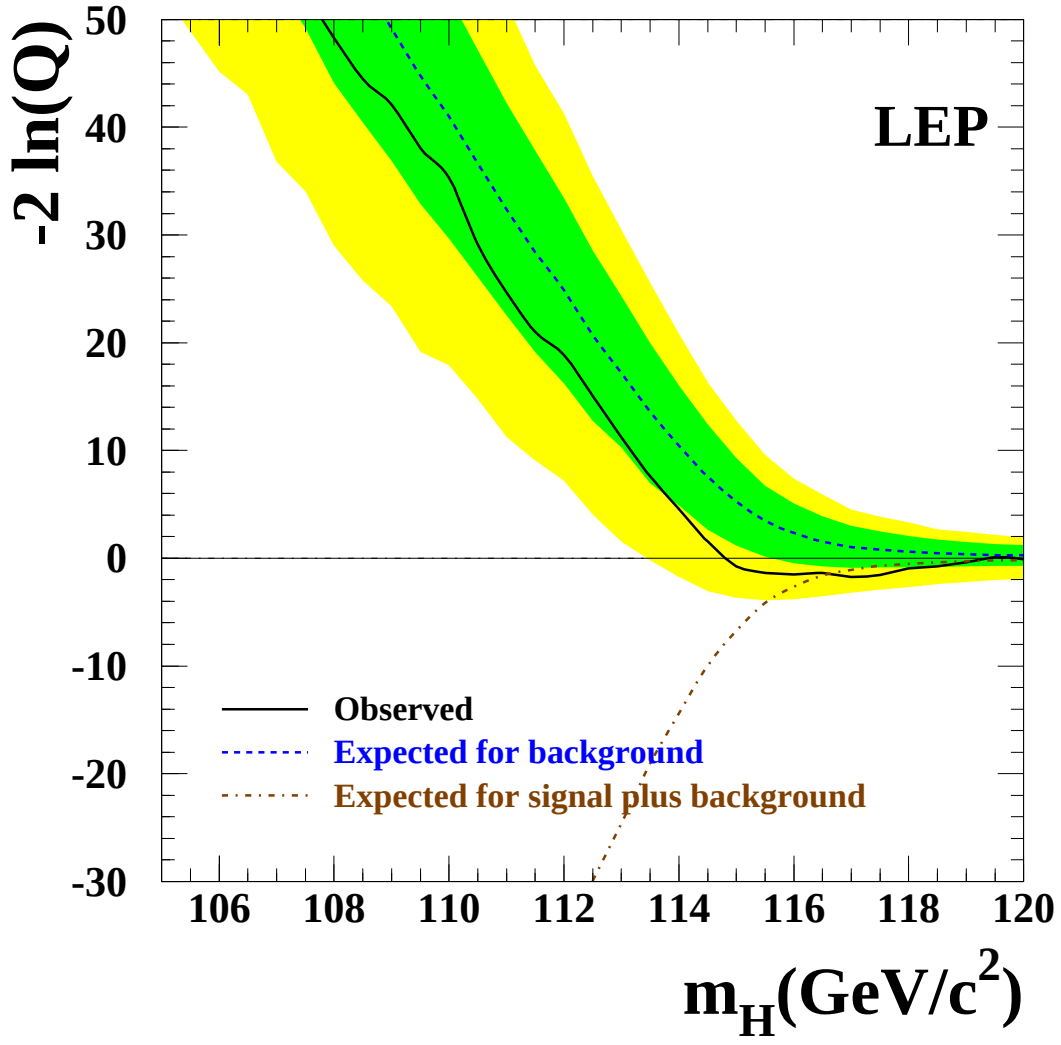
BUT

- Evidence still weak ($< 3\sigma$ - a “discovery” is usually considered to be $5\sigma$. Fluctuations happen.)
- No guarantee that extra running would confirm a discovery
- Big impact on LHC schedule and resources (civil engineering directly delayed by LEP extension)
- LHC could see this Higgs boson, and if it’s a light SUSY Higgs could simultaneously investigate other SUSY particles...

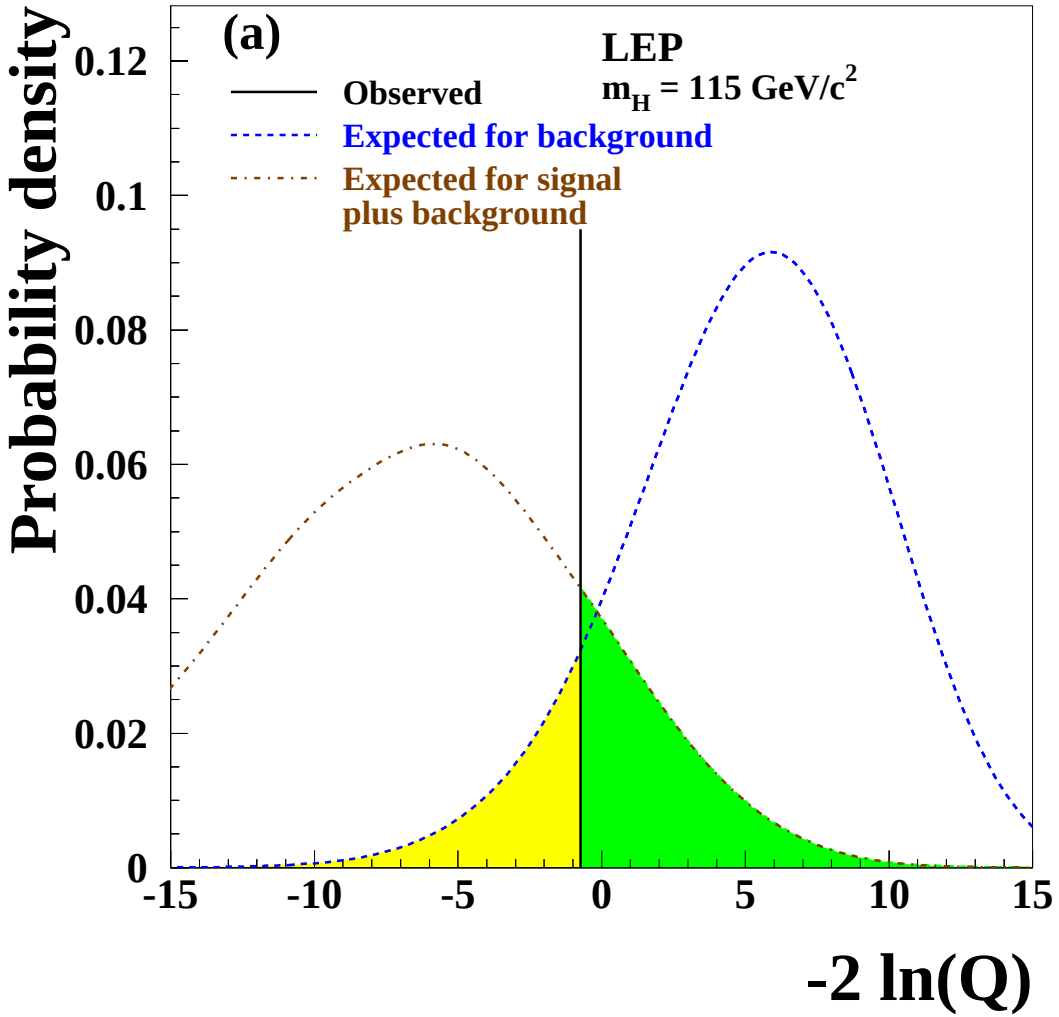
LEP SHUTDOWN DEFINITIVELY AT THE END OF 2000

# *The final word on the SM Higgs (April 2003)*

Full dataset, calibration updates, some improvements to analyses.



# *The final word on the SM Higgs (April 2003)*




Higgs boson excluded up to 114.4 GeV at 95% CL

# *The End*

The LEP experiements have published more than 1000 papers on many topics.

High precision tests of the Standard Model have been made, and are sensitive to radiative corrections.

The electroweak data prefer a light Higgs boson.

The SM Higgs boson search gives a limit at 114.4 GeV, with an inconclusive hint of a signal at around 115 GeV.

Pass the baton to the Tevatron (Run II - CDF, D0 in progress) and the LHC (ATLAS, CMS first data in 2007).