Search for Standard Model Higgs Boson at LEP

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LCWS2000

- Introduction
- SM Higgs Production and Decay
- Search Topologies
- Results and Statistical Interpretations
- Summary

Preliminary Remarks

I will focus on results obtained with the LEP data, taken during 2000 at $\sqrt{s}$ = 200 - 209 GeV.

All results are very preliminary.

Introduction

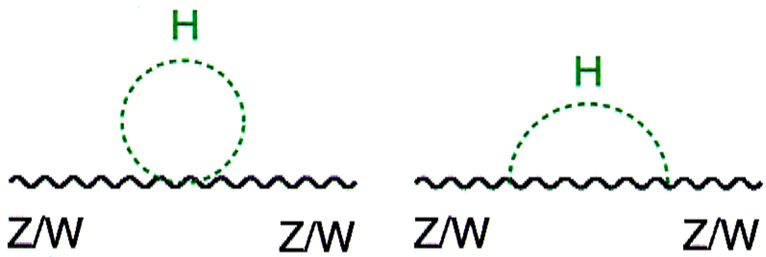
- **Why do we need Higgs boson ?**
  - $W^{\pm}$, Z^0 obtain masses via Higgs mechanism (Spontaneous Symmetric Breaking)
  - Fermions obtain masses via Yukawa coupling to Higgs boson

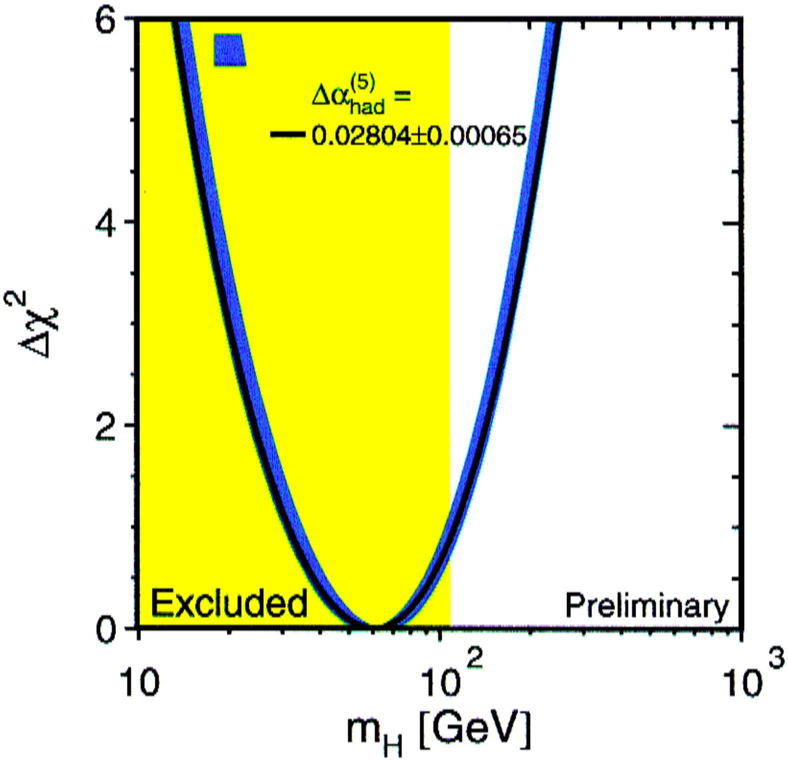
- **Higgs boson is the only particle not discovered in the Standard Model**

- **EW fit favors light Higgs boson**

Indirect Higgs Limits

Electroweak precise measurements are sensitive to Higgs mass via loops:





Results from ICHEP 2000

$m_H = 62^{+53}_{-30}$ GeV/c^2

$m_H < 170$ GeV/c^2 at 95% C.L.

With BES R measurements, minimum moves to 90 GeV/c^2

Introduction

- **LEP Experiments:**

  ALEPH, DELPHI, L3, OPAL

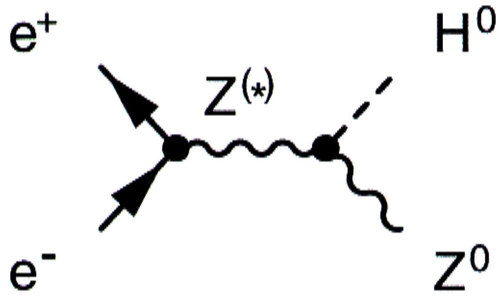
- **LEP runs:**

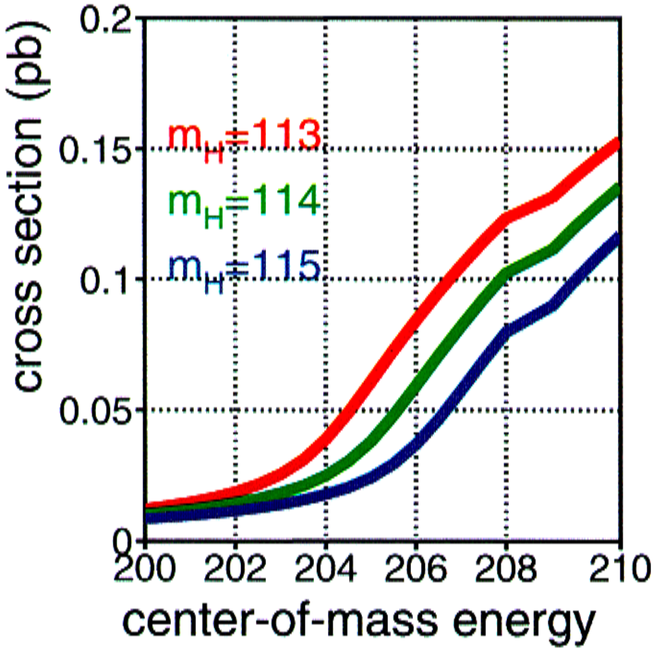
  Delivered integrated luminosity per experiment

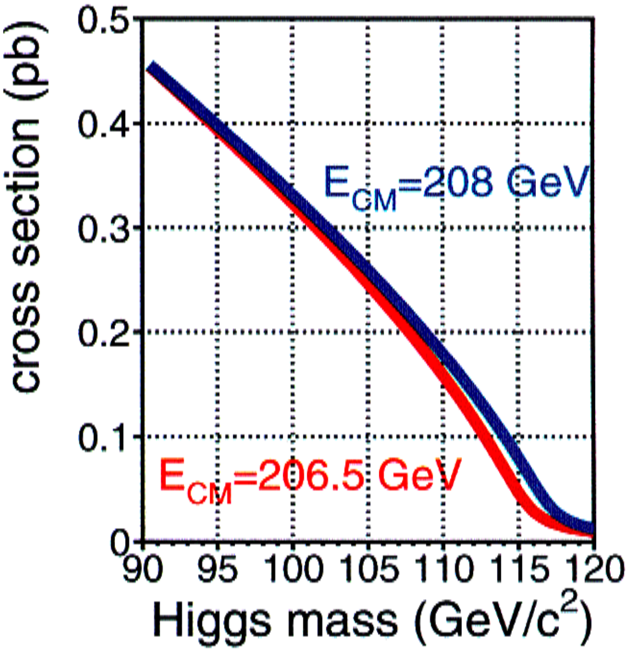
	$\sqrt{s}$ (GeV)	$\int Ldt$ (pb^{-1})
LEP 1		
1989-1995	~ 91	160
LEP 1.5		
Fall 1995&1997	130-136	12
LEP 2		
1996	161-172	20
1997	183	60
1998	189	185
1999	192-202	230
2000	200-209	175

SM Higgs Production

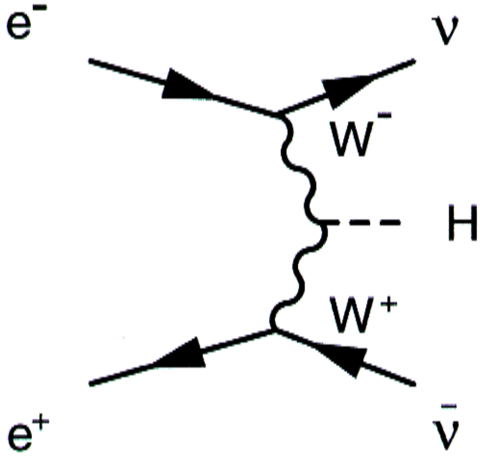
Dominant production mechanism is Higgs-strahlung.

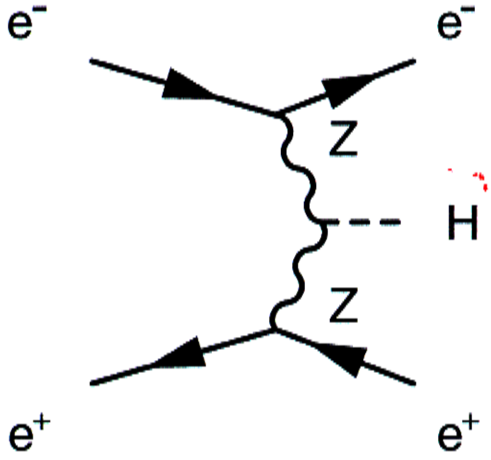






Small contributions from WW- and ZZ- fusion

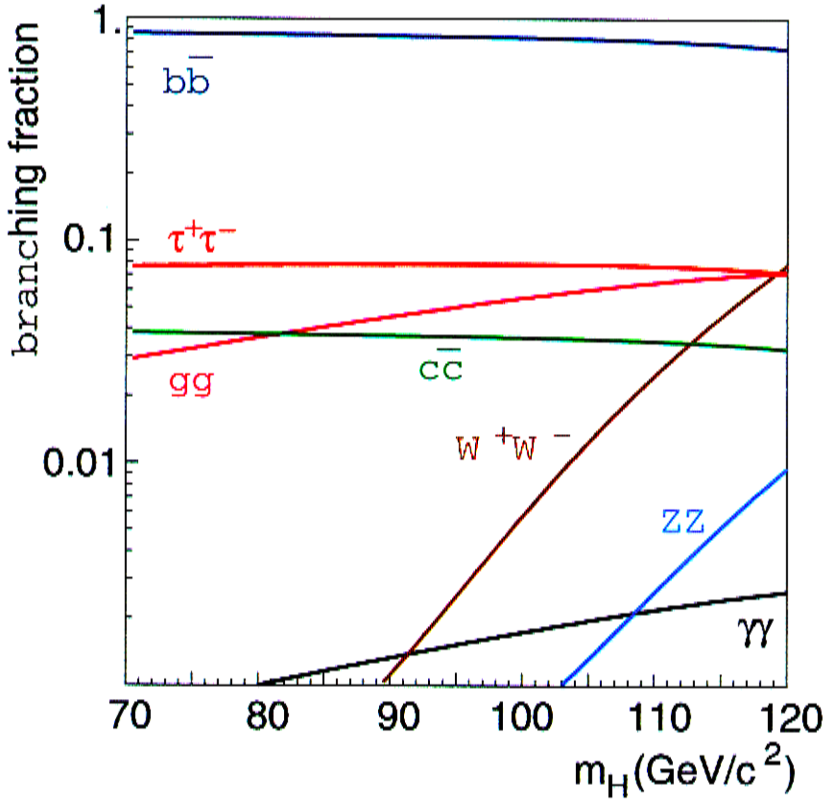




Become important if m_H is close to threshold.

SM Higgs Decay

Higgs couples most strongly to massive particles.

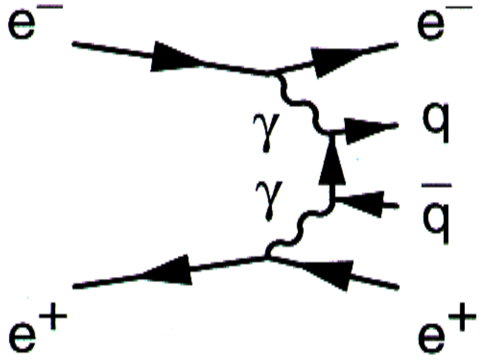


$H \rightarrow b\bar{b}$ (80~90%), $\tau^+\tau^-$ (~8%)

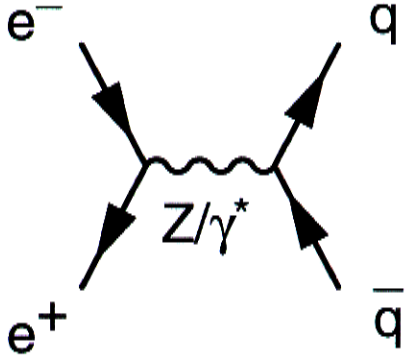
$Z \rightarrow q\bar{q}, \nu\bar{\nu}, l^+l^-, \tau^+\tau^-$

Use b-tagging to reduce background.

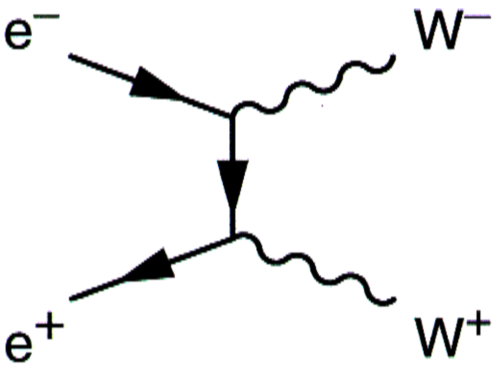
Backgrounds



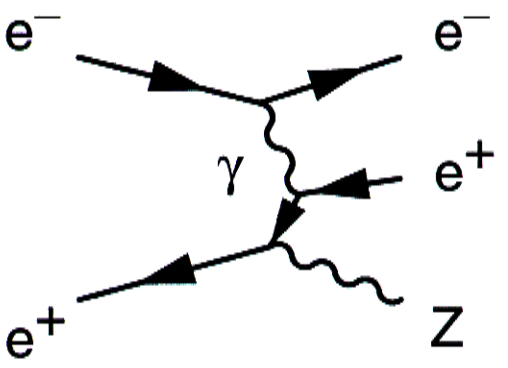
$\sigma_{\gamma\gamma} \approx 2\text{nb}$



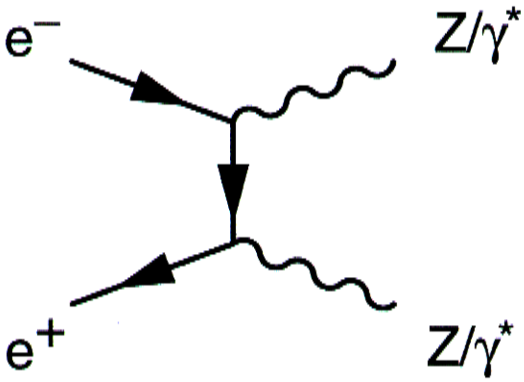
$\sigma_{q\bar{q}} \approx 80\text{pb}$



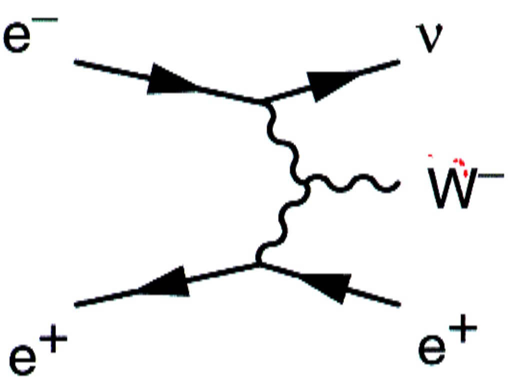
$\sigma_{WW} \approx 17\text{pb}$



$\sigma_{eeZ} \approx 7\text{pb}$

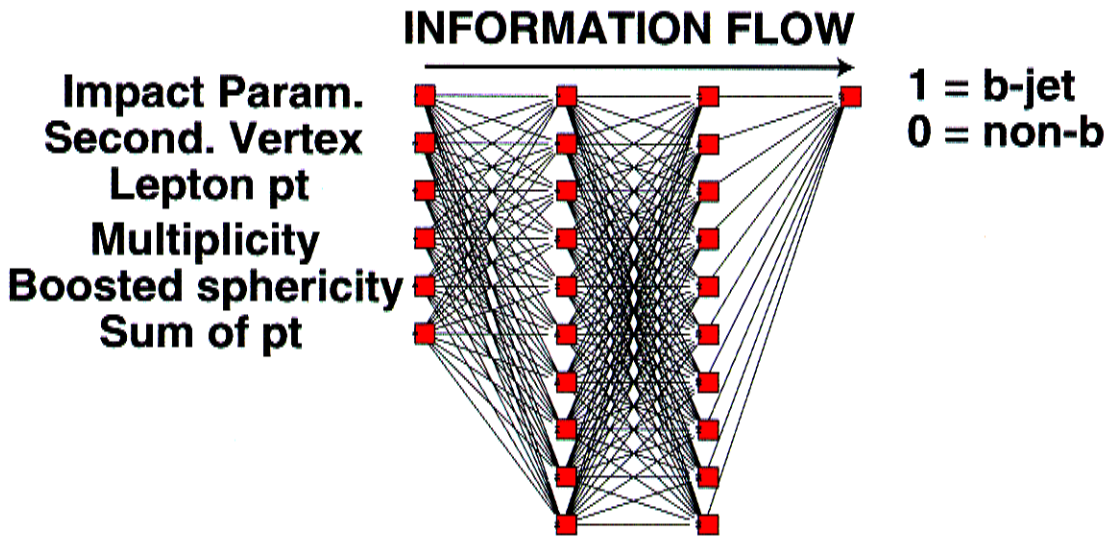


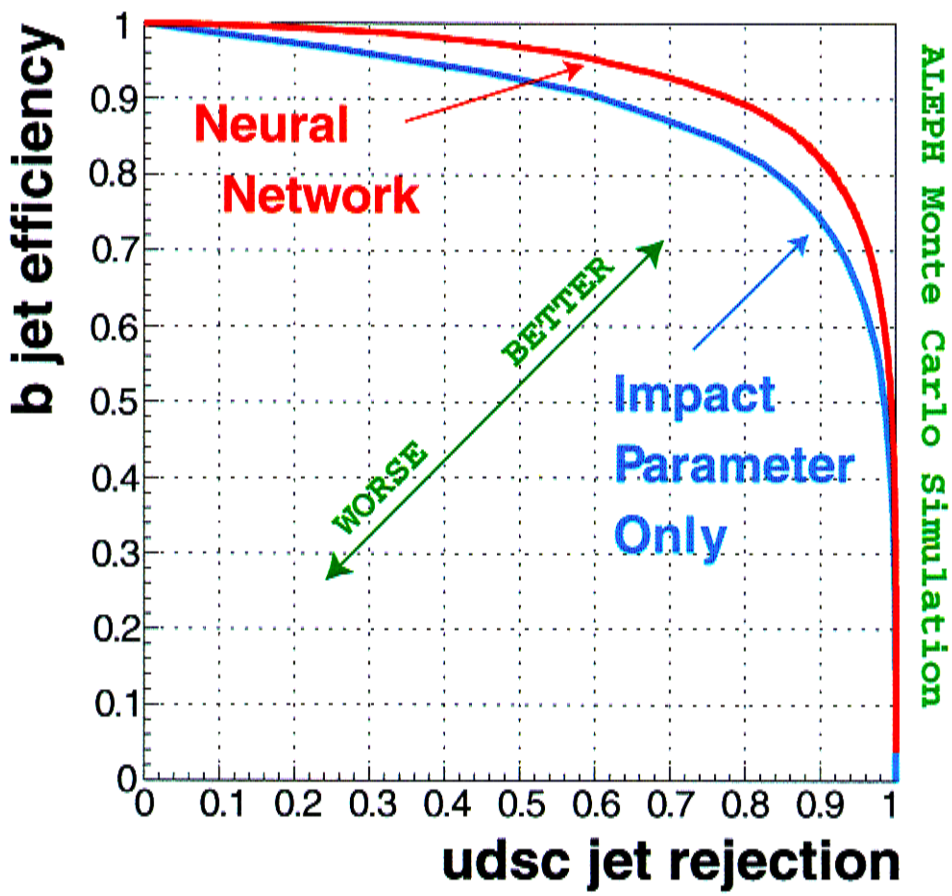
$\sigma_{ZZ} \approx 3\text{pb}$



$\sigma_{We\nu} \approx 1\text{pb}$

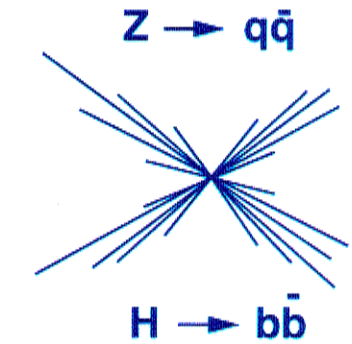
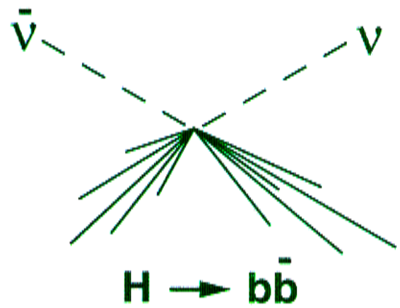
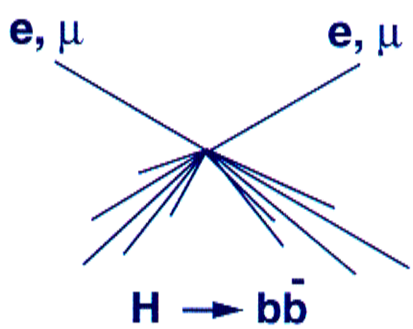
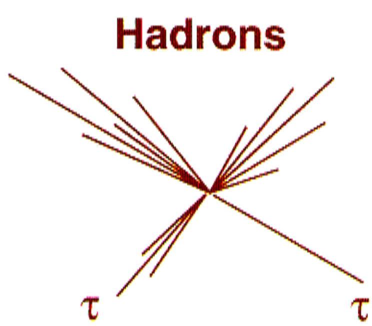
b-tagging





at 90% rejection, neural network has
~ 8% better b-jet efficiency

Search for HZ Final States

Channel	BR	Topology
$Hq\bar{q}$	64.6%	
$H\nu\bar{\nu}$	20.0%	
He^+e^-, $H\mu^+\mu^-$	6.7%	
$H\tau^+\tau^-$, $\tau^+\tau^- q\bar{q}$	8.7%	

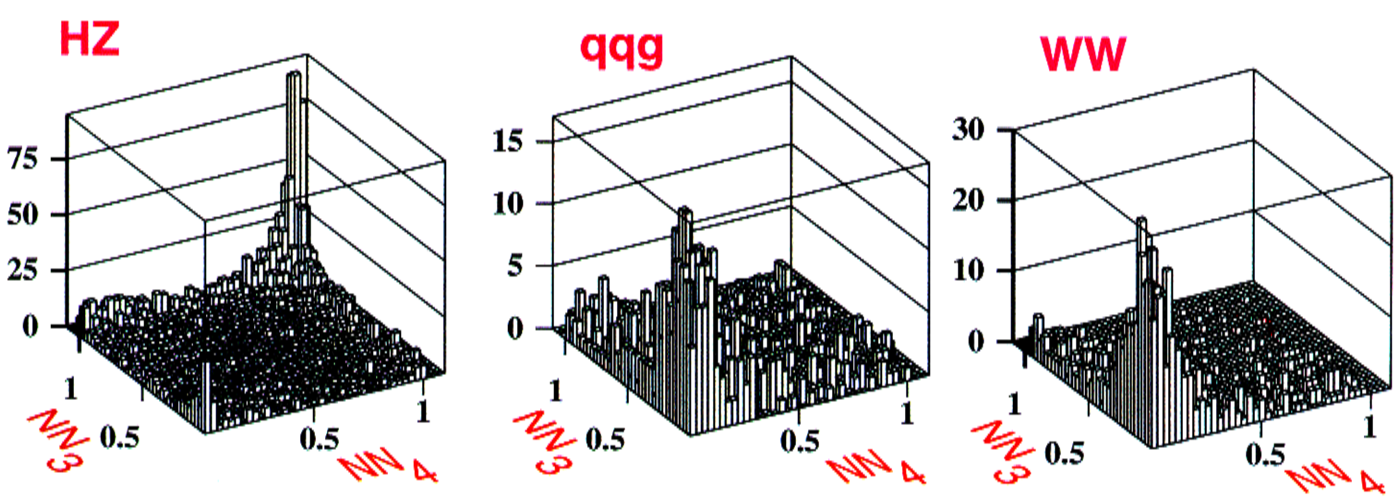
ALEPH HZ → 4 jet Analyses

Two analyses: NN and CUT

- **4 jet events**
- **One pair compatible with M_Z**

  4C or 5C fit to improve energy and mass resolutions

- **2 b jets or 4 b jets**
- **Treatment of HZ/hA overlap**



Neural Net btagging Output of 'Higgs Jets'

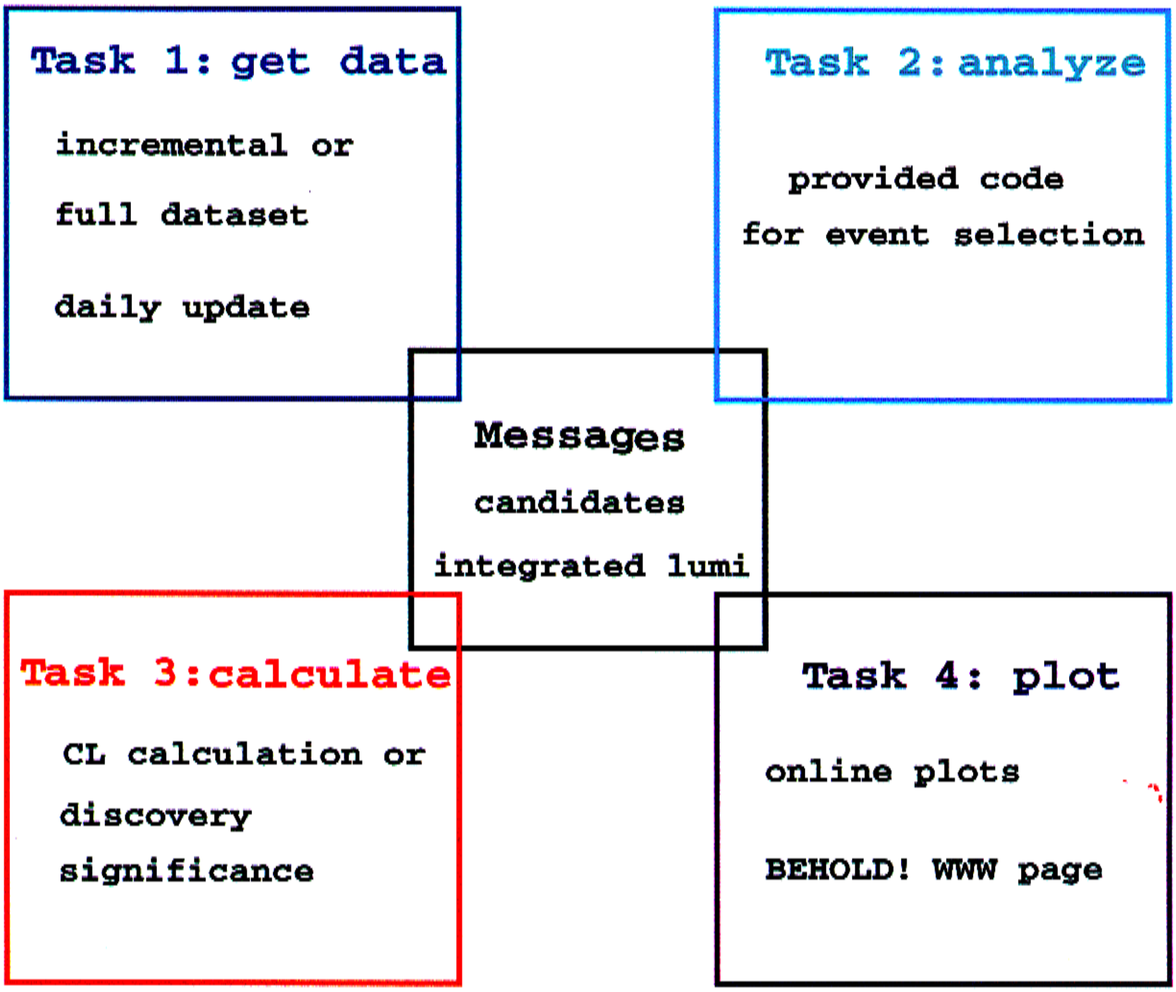
BEHOLD!

For example, ALEPH has developed

BEhold, Higgs Online Limit and Discovery !

(don't miss the Higgs...)

- early warning system for Higgs discovery
- "fast track" solution for conference results



Analyses were frozen before data taking started:
Statistically unbiased results

ALEPH 3 'Golden' 4 jet Candidates

- **Run 54698/Event 4881 @ $\sqrt{s}$ = 206.7 GeV**

  2b event

  Reconstructed Higgs Mass = 114.3 GeV

  NN19V = 0.996

- **Run 56065/Event 3253 @ $\sqrt{s}$ = 206.7 GeV**

  4b event

  Reconstructed Higgs Mass = 112.9 GeV

  NN19V = 0.997

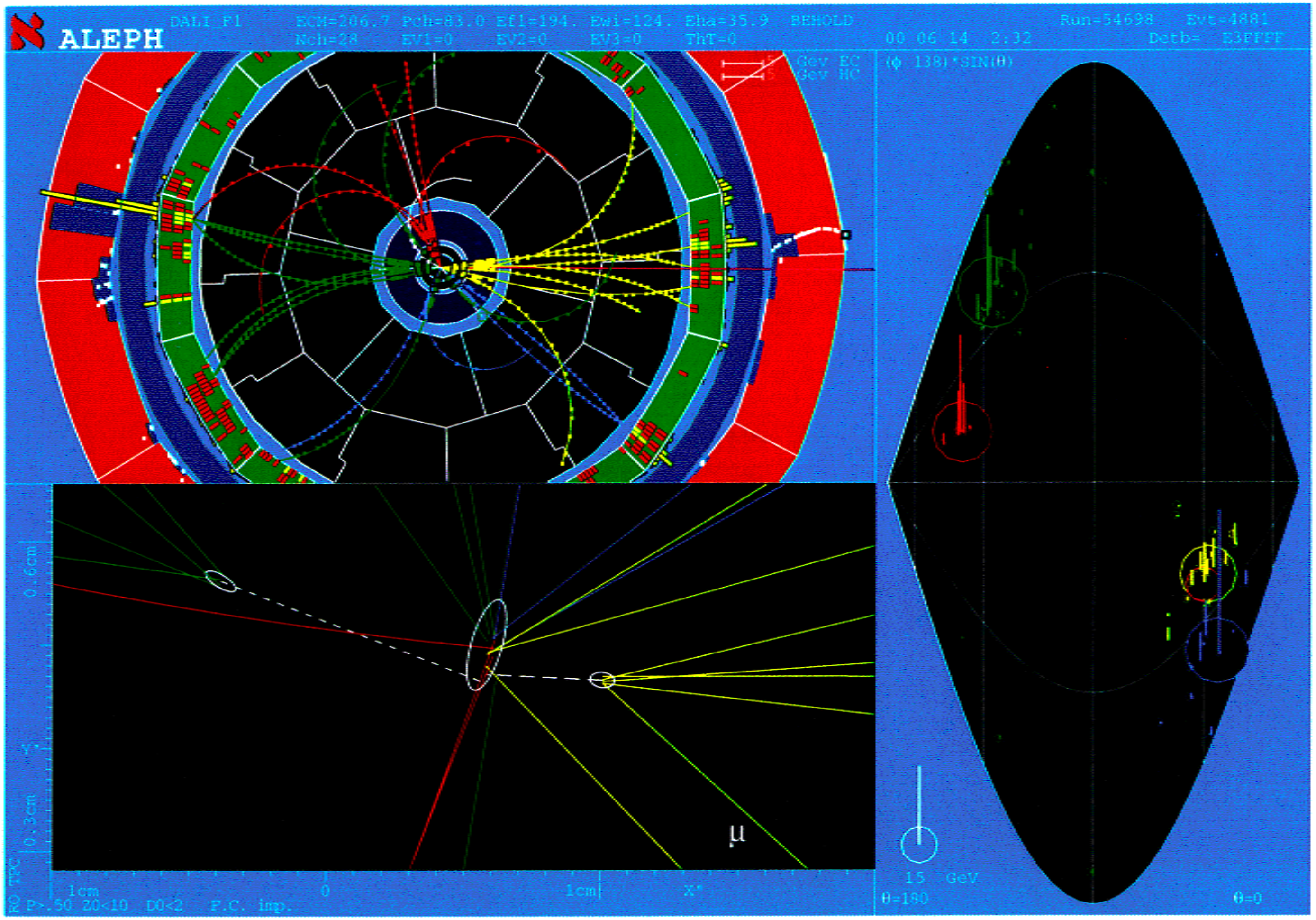
- **Run 56698/Event 7455 @ $\sqrt{s}$ = 206.7 GeV**

  4b event

  Reconstructed Higgs = 110.0 GeV

  NN19V = 0.999

ALEPH 4 jet Candidate



E_{CM} = 206.7 GeV

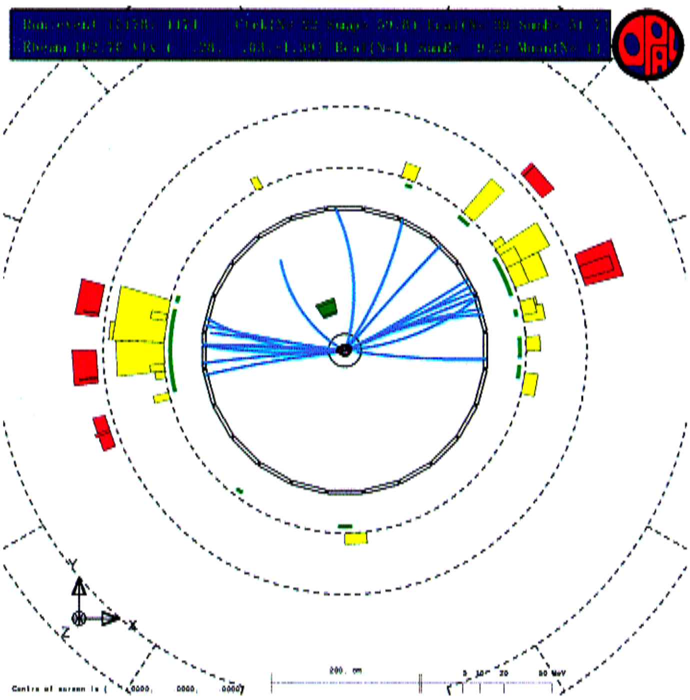
M_H = 114.3 GeV

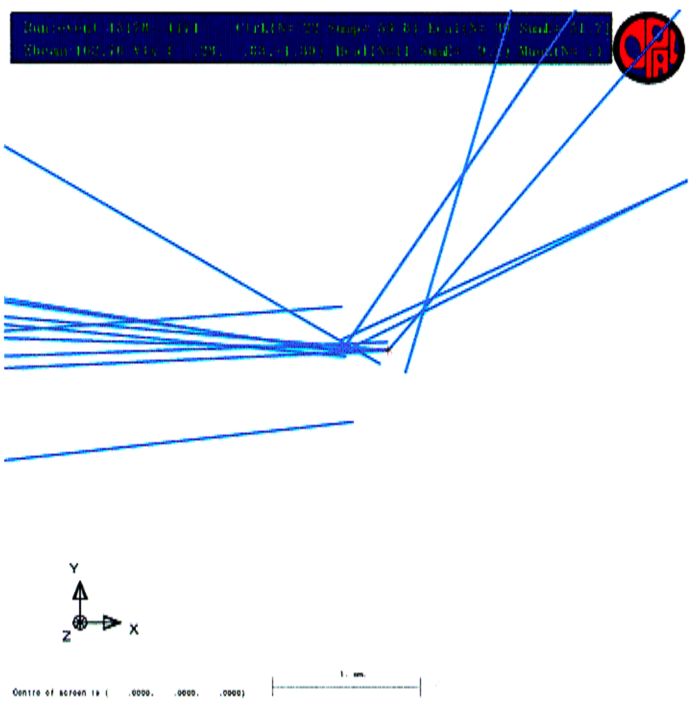
NN = 0.996

$BTAG_3$ = 0.99

$BTAG_4$ = 0.99

OPAL H$\nu\bar{\nu}$ Candidate





Mass = 104.0 GeV; NN = 0.9994

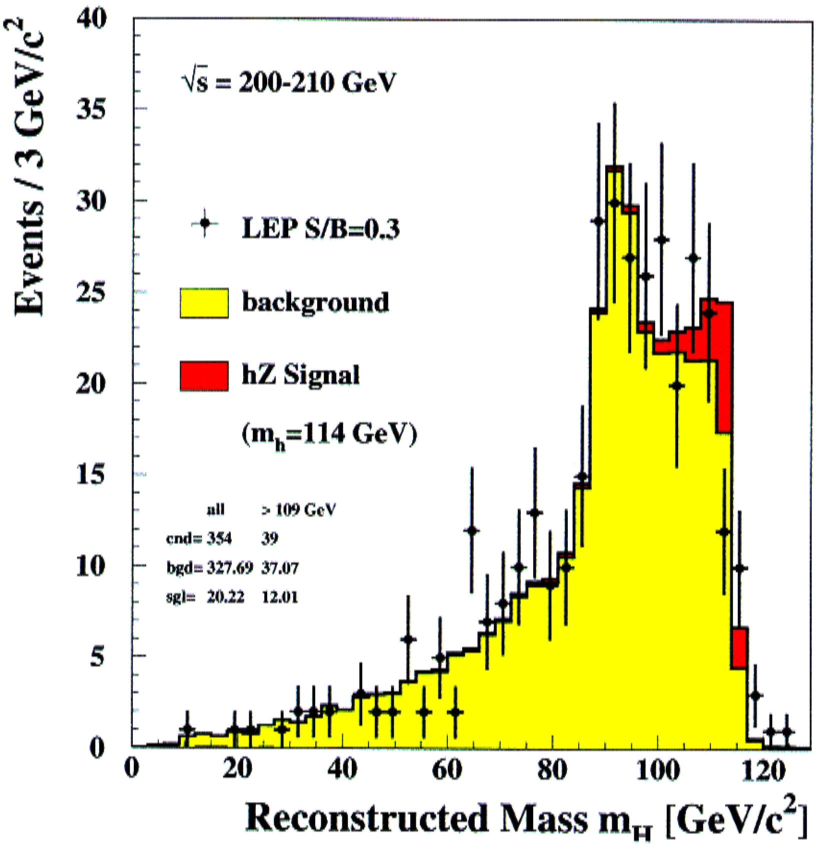
LEP Combined Mass Plot — Loose Cut

For illustration only

Cut on mass independent variables (like b-tag)

so that $\frac{s_{expected}}{b_{expected}} \sim 0.3$ For m_{rec}>109GeV

for a 114GeV Higgs



All
2000
Data

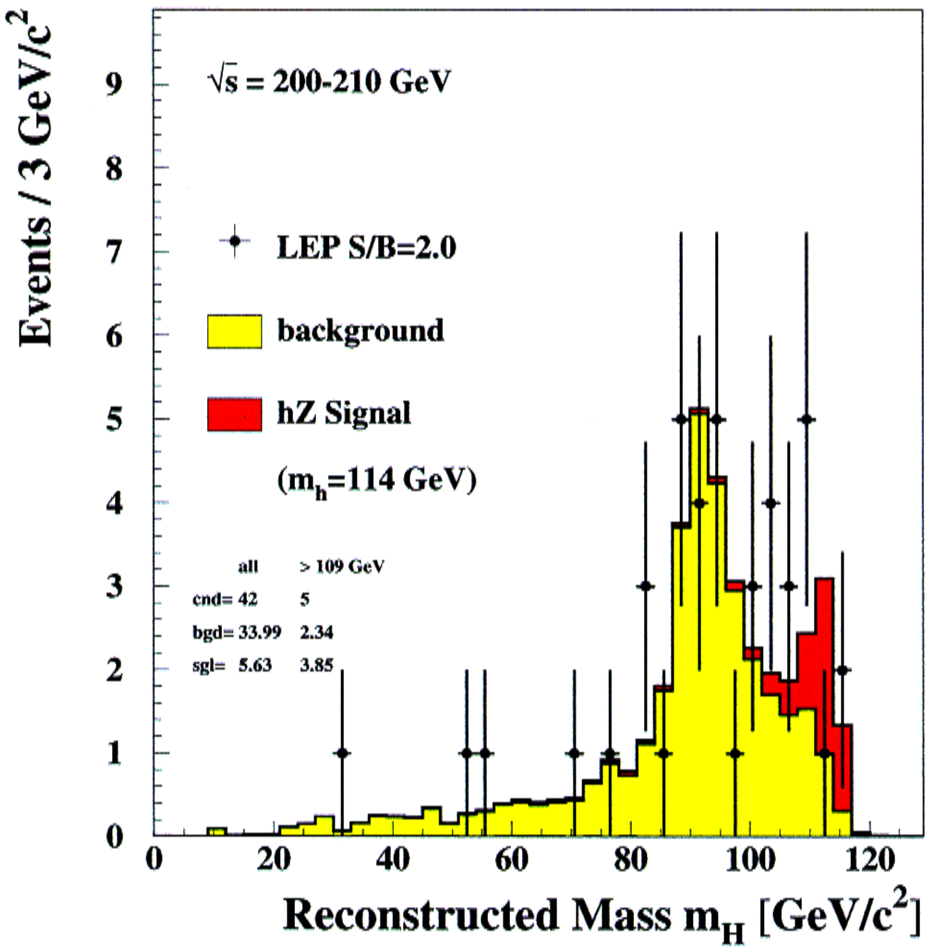
	Data	Backg	Signal
ALL m_{rec}	354	328	20.2
m_{rec} > 109GeV	39	37.1	12.0

LEP Combined Mass Plot — Tight Cut

$$\frac{s_{expected}}{b_{expected}} \sim 2$$

For m_{rec}>109GeV

for a 114GeV Higgs



Losing Efficiency -- but "really good" events kept

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

Why Cut at All ?

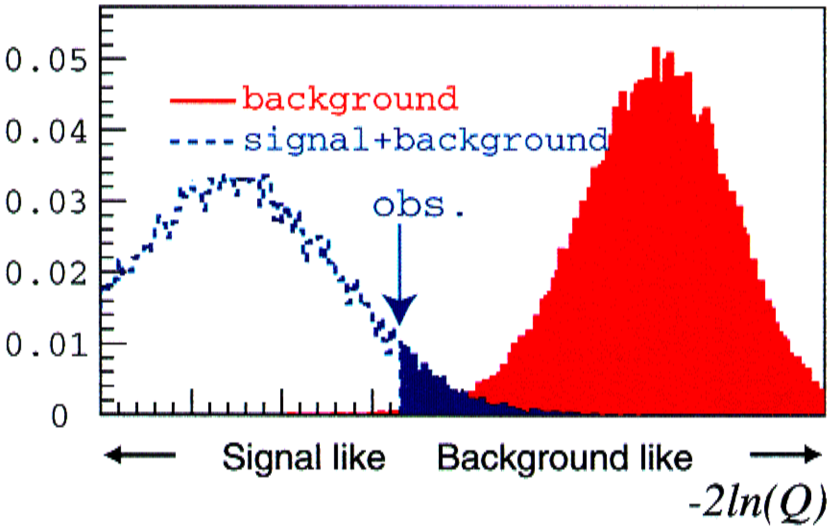
- **Pick good variables to optimize the separation between signal and background**
  - reconstructed m_H
  - b-tags or NN output

- **We do not need to cut on discriminant variables**

- **Express in bins (Combined Using Likelihood)**
  - Experimental Data
  - Monte Carlo Signal Expectation
  - Monte Carlo Background Expectation

Need a language: classical confidence levels

Confidence Levels



- **Estimator (Test-statistic):**

An Estimator is a value to quantify the "signal-ness" of an observation

$$X = -2ln(Q)$$

where $Q = L(s+b) \,/\, L(b)$

- **Definition of CL_{s+b} and CL_b :**

Given an observed value of the estimator $X_{observed}$, calculate confidence levels on the Signal+Background and Background-only hypotheses —

$$CL_{s+b} = P\,(\,X_{s+b} \geq X_{observed}\,)$$

$$CL_b = P\,(\,X_b \geq X_{observed}\,)$$

CL_b and Significance

- **How do we understand CL_b**

  Example: Simple event counting

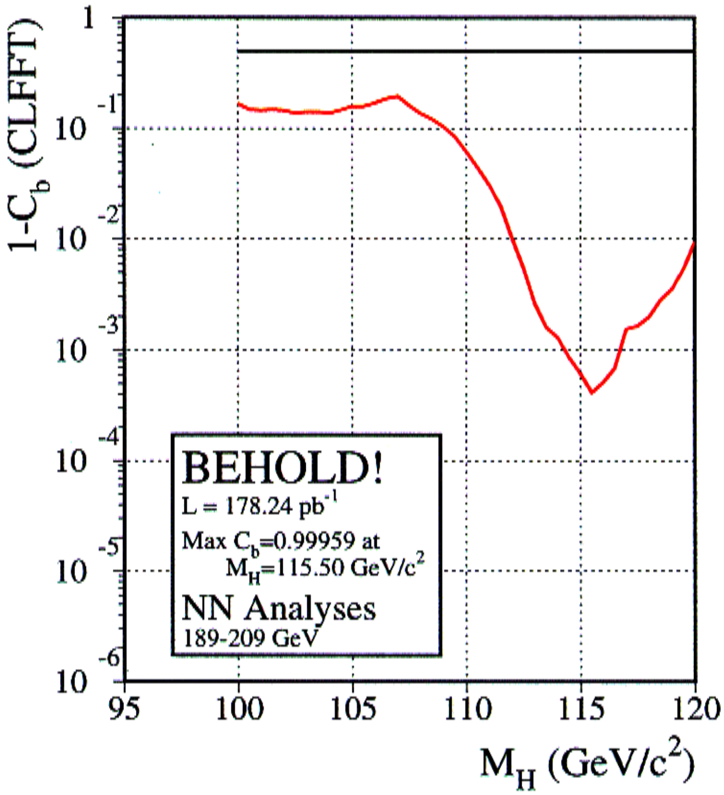
$$CL_b = P_b (N \leq N_{obs})$$

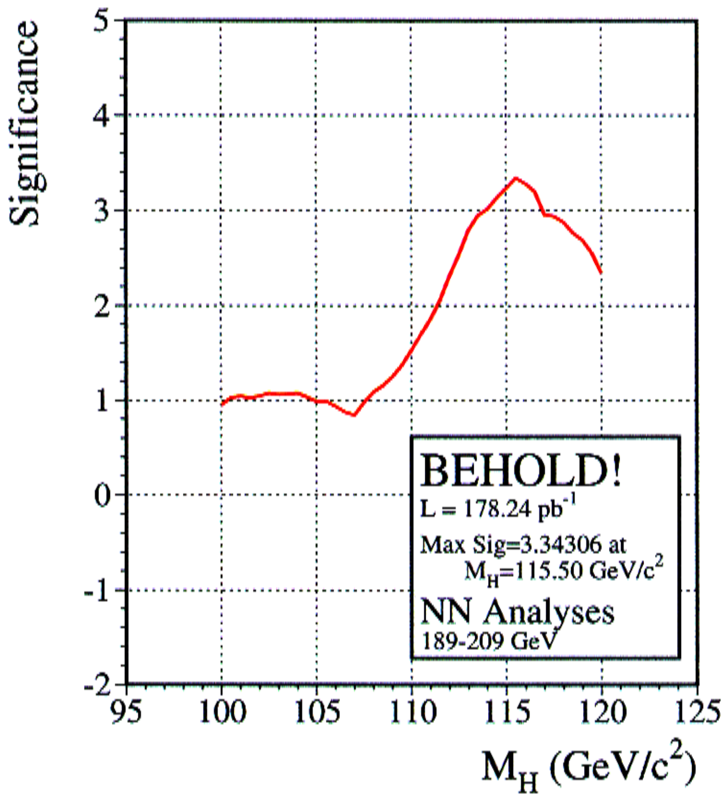
$$1\text{-}CL_b = P_b (N > N_{obs})$$

- **Significance ξ of CL_b is defined by:**

$$CL_b = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\xi} \exp\left(-\frac{x^2}{2}\right) dx$$

ALEPH CL_b and Significance





3.3 σ at 115.5 GeV/c²

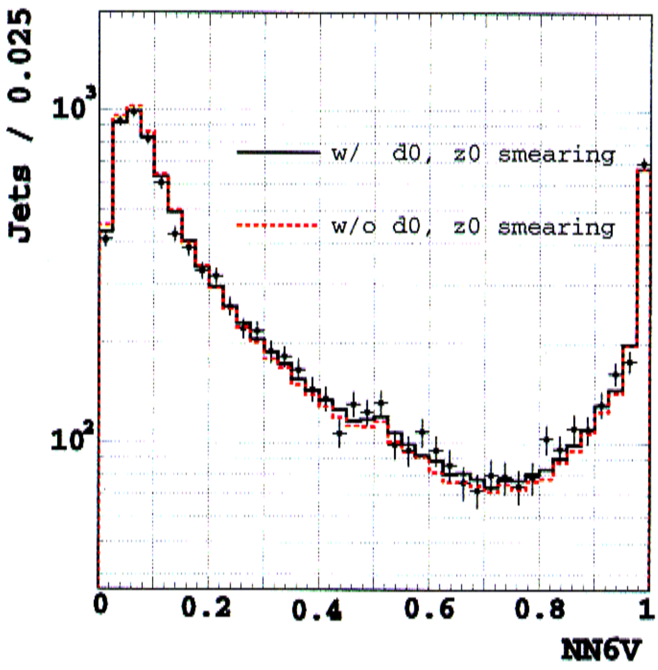
ALEPH Systematic Checks

Potential sources of bias in the 4 jet search

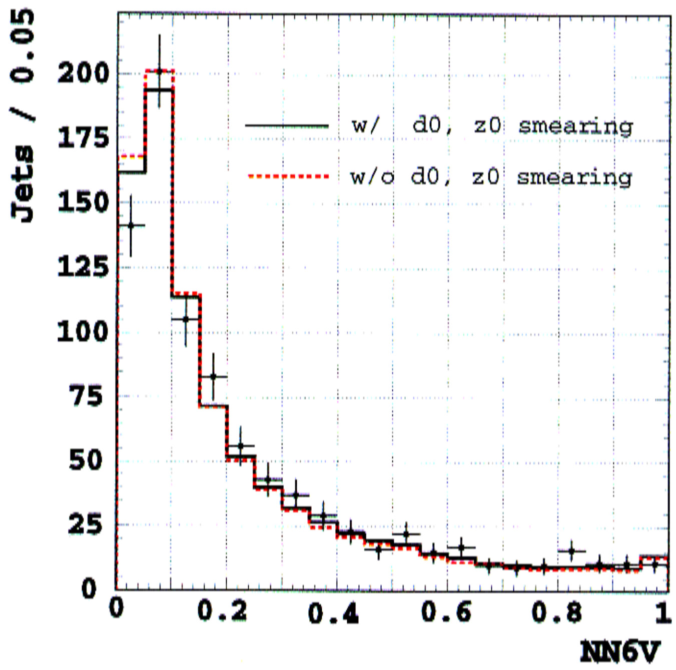
- Reliability of b taggings
- Stability of Higgs mass fit
- Jet pairing variables
- Stability of results at high-purity
- Systematic uncertainties on background levels
- Shape parameterizations of discriminant variables

B-tagging Checks in High-energy Data

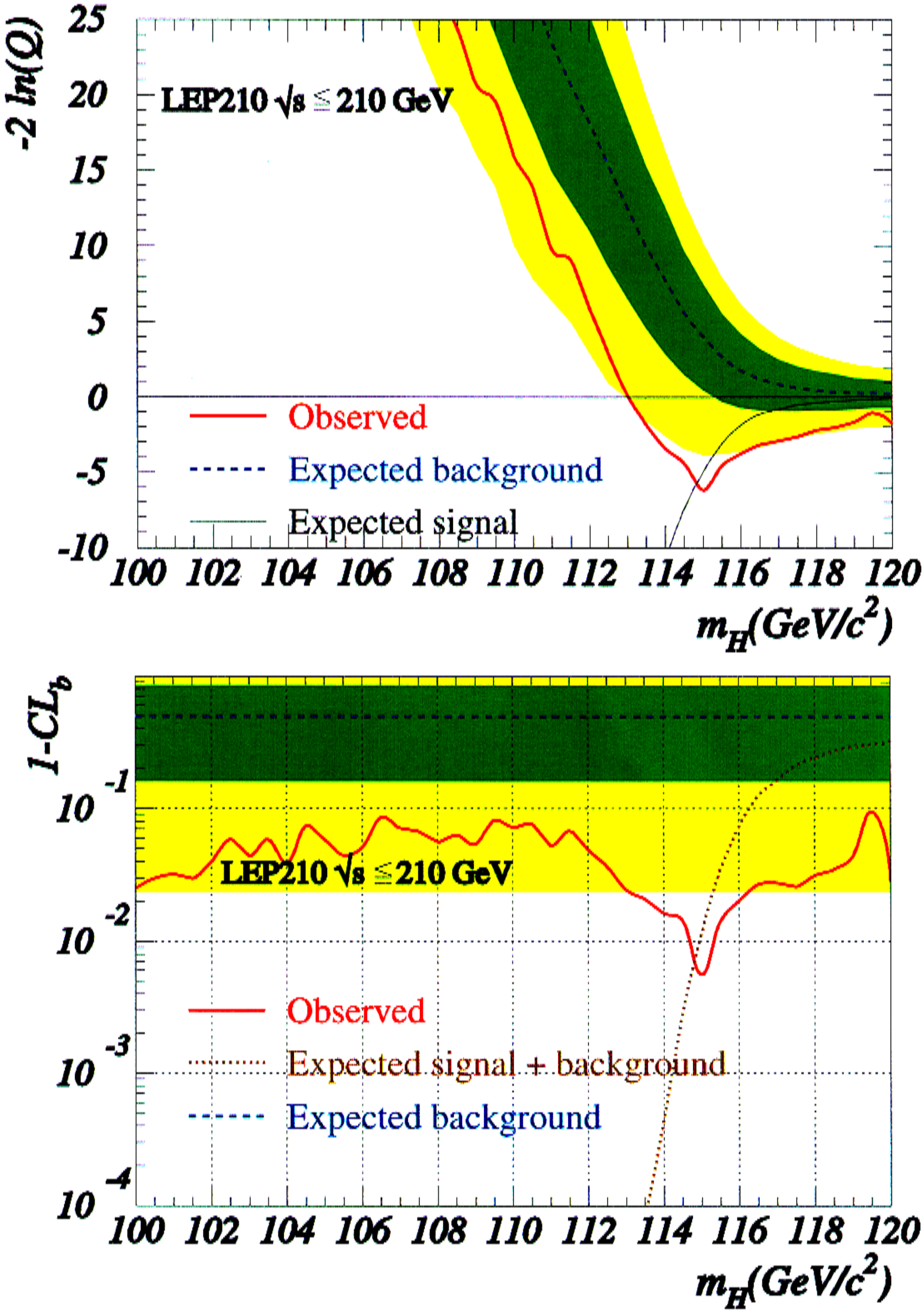
B-tagging checks performed on Z-return events



and semileptonic WW deays



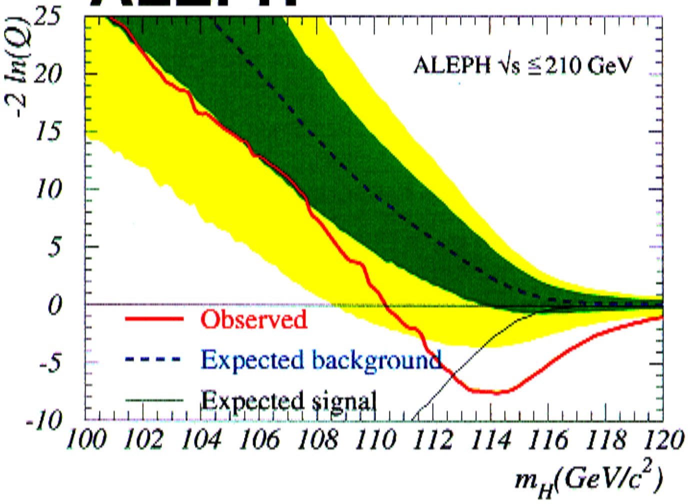
Likelihood Ratio and CL_b of LEP



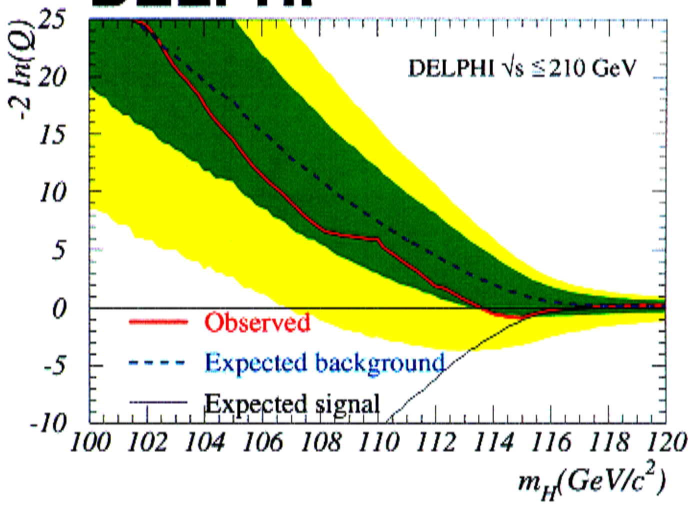
2.5 σ excess at m_H = 115 GeV/c^2

Likelihood Ratio of 4 Experiments

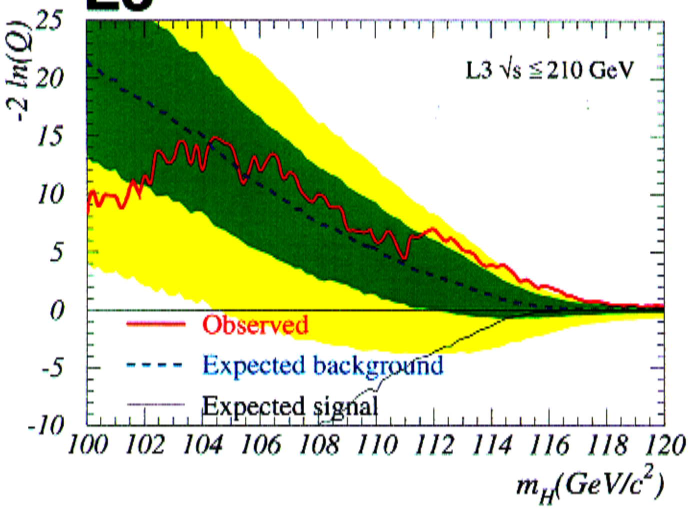
ALEPH



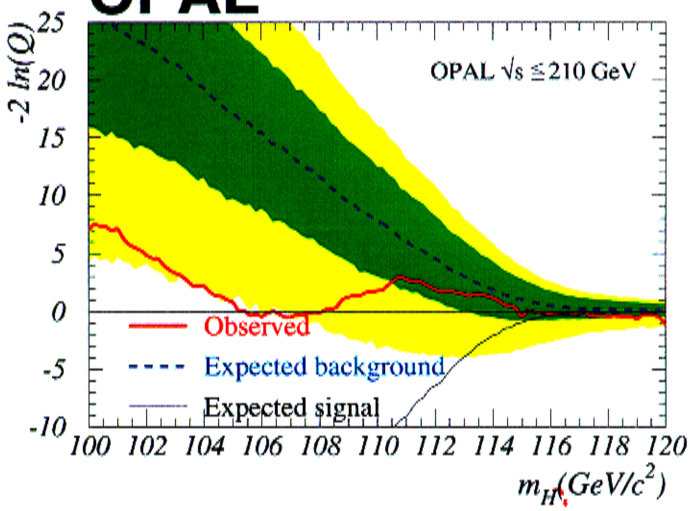
DELPHI



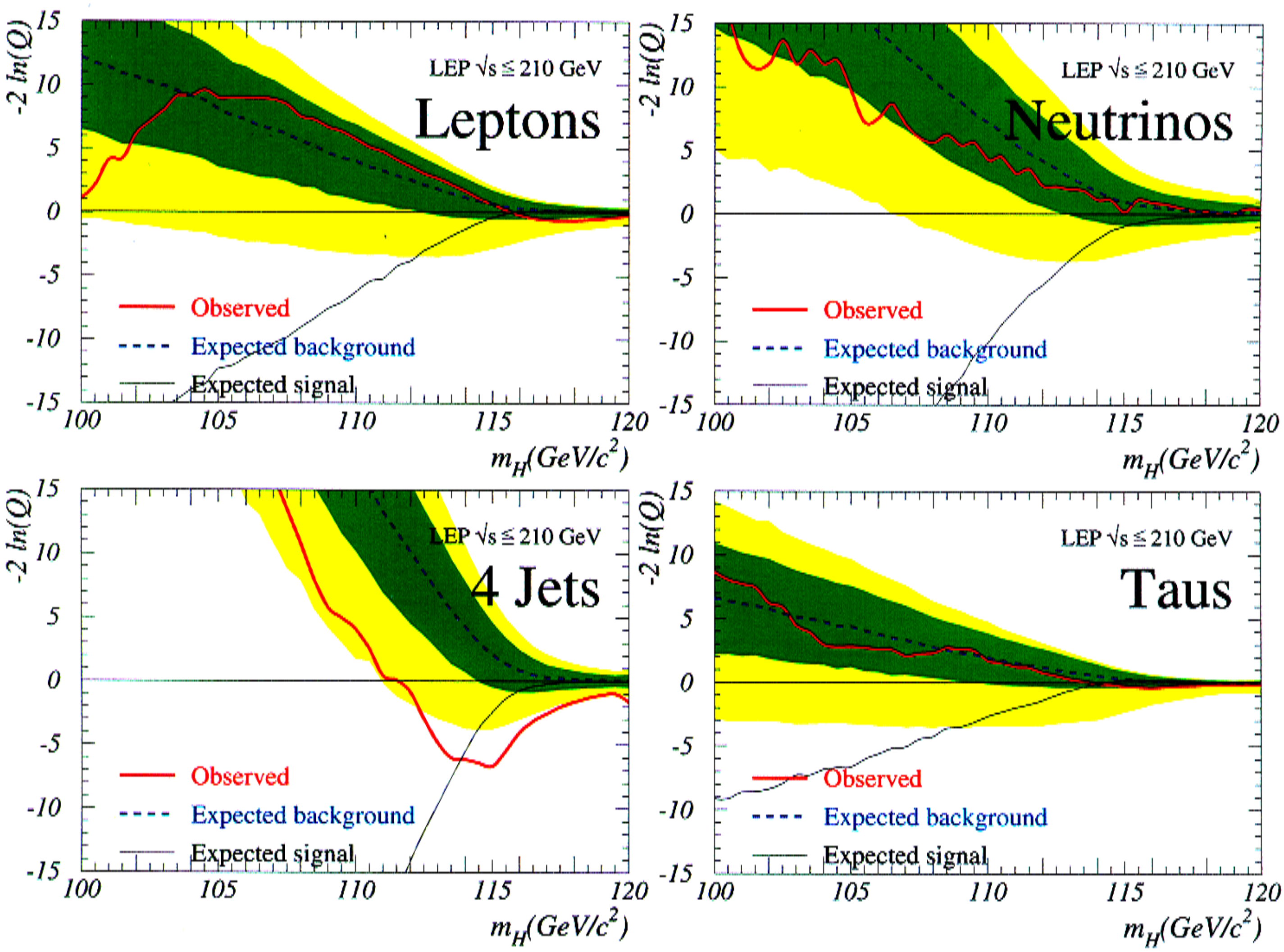
L3



OPAL



Observations by Channel



Combined lepton, neutrino and tau channels are as sensitive as the 4-jet channels

CL_s Calculation

Two methods to define CL_s

(A) Generalized Bayesian Method:

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

Used in DELPHI, L3, OPAL and LEP combined results
(See A. Read, CERN 2000-005)

(B) Signal Estimator Method:

$$CL_s = CL_{s+b} + (1-CL_b)\, e^{-s}$$

Used in ALEPH results
(See S. Jin and P. MCNamara, Physics/9812030, CERN 2000-005)

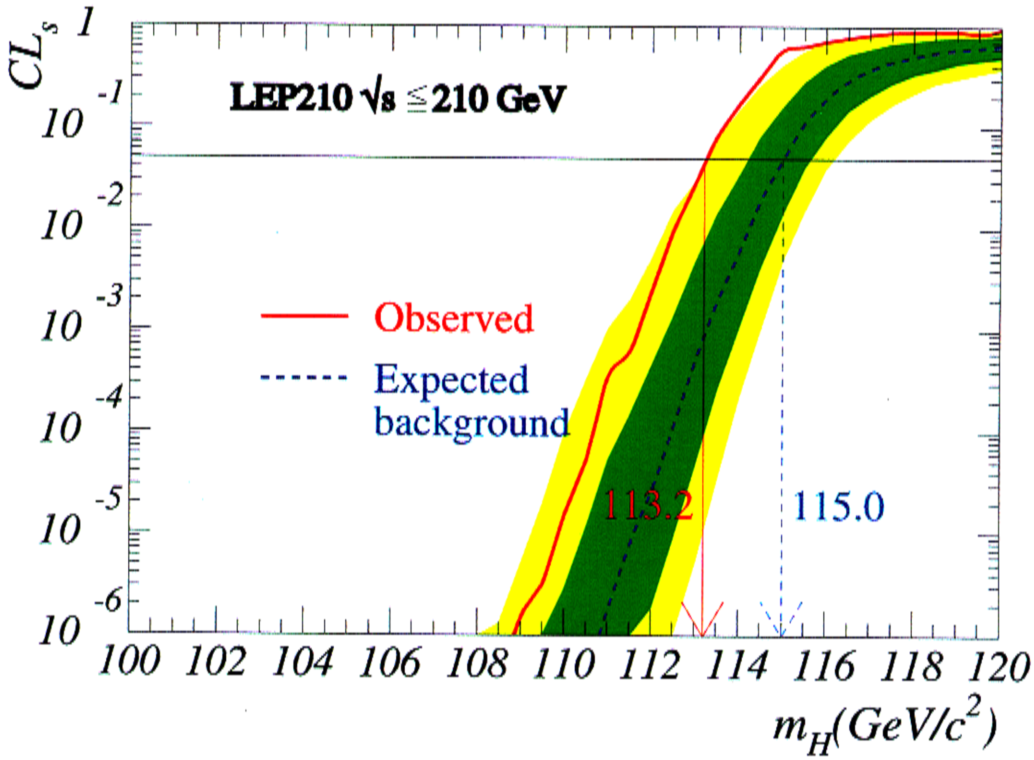
— Both methods satisfy:

$$CL_s = e^{-s} \quad \textit{for 0 event observed}$$

which is independent of background expectation

— Signal Estimator method gives ~0.5 GeV better sensitivity for the exclusion on m_H than Generalized Bayesian method.

Lower Limits on m_H



- **LEP Combined Limits at 95% CL :**

  Observed : $m_H \geq 113.2$ GeV/c^2

  Expected : $m_H \geq 115.0$ GeV/c^2

- **95% CL limits on m_H (GeV/c^2) from each experiment**

	ALEPH	DELPHI	L3	OPAL
Observed	110.5	111.2	113.0	109.3
Expected	113.8	112.3	110.9	112.2

* The expected limit is calculated from background-only hypotheses.

Summary

- $2.5\ \sigma$ excess at $m_H = 115\ GeV/c^2$ is observed in the combined LEP Standard Model Higgs searches; $3.3\ \sigma$ in ALEPH experiment.

- LEP Combined Limits on m_H at 95% CL :

  Observed : $m_H \geq 113.2\ GeV/c^2$

  Expected : $m_H \geq 115.0\ GeV/c^2$

- More data will be included and further systematic study is going on ...

Current Status of 1-CL_b on the Roadmap