LEP Higgs Search Results

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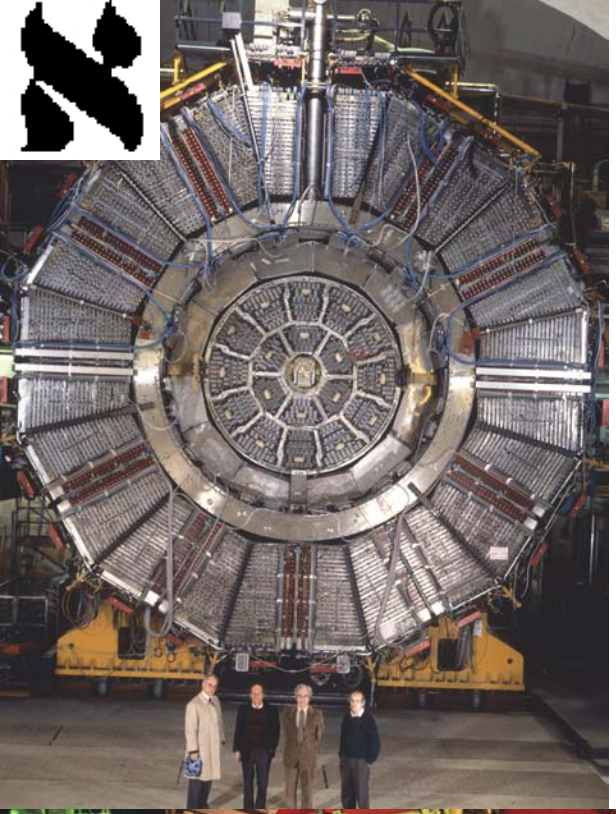
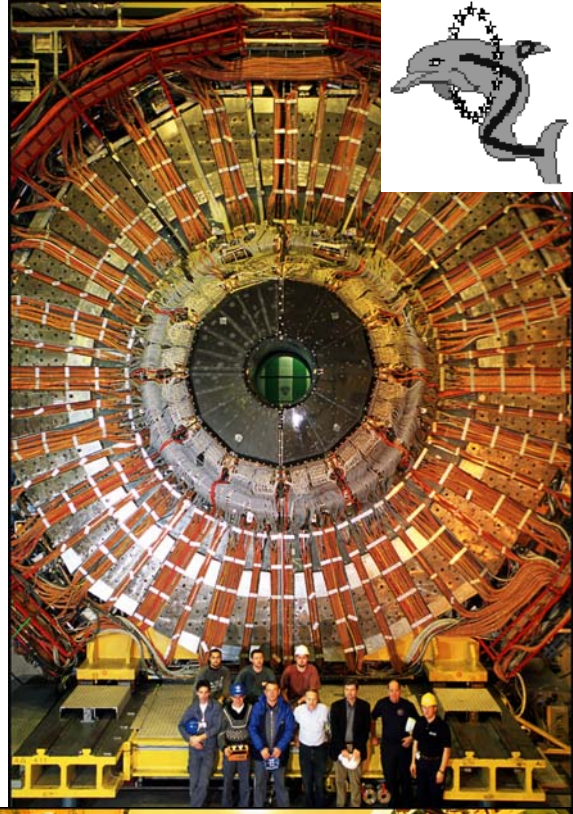
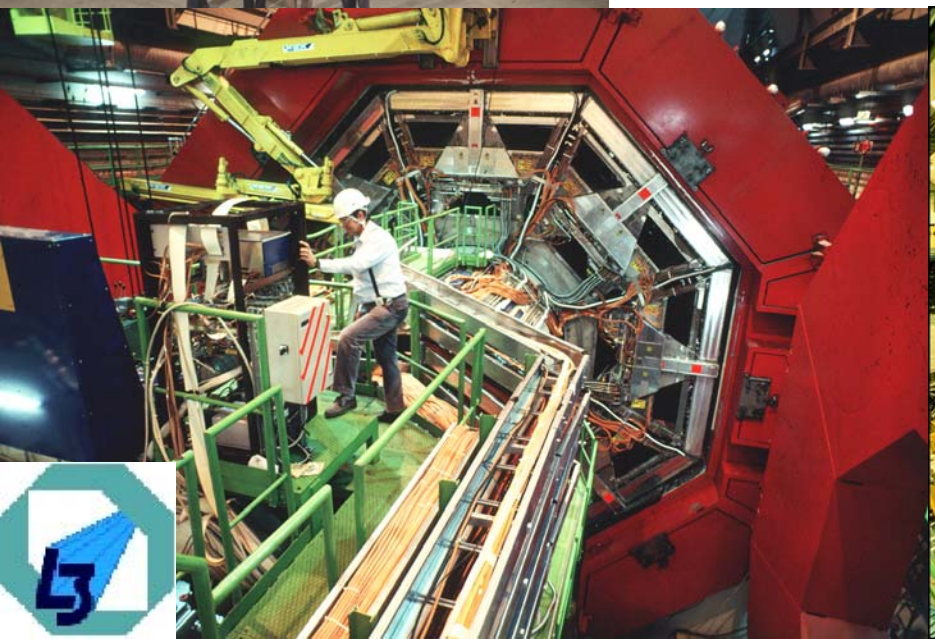
Weak Interactions and Neutrinos Workshop

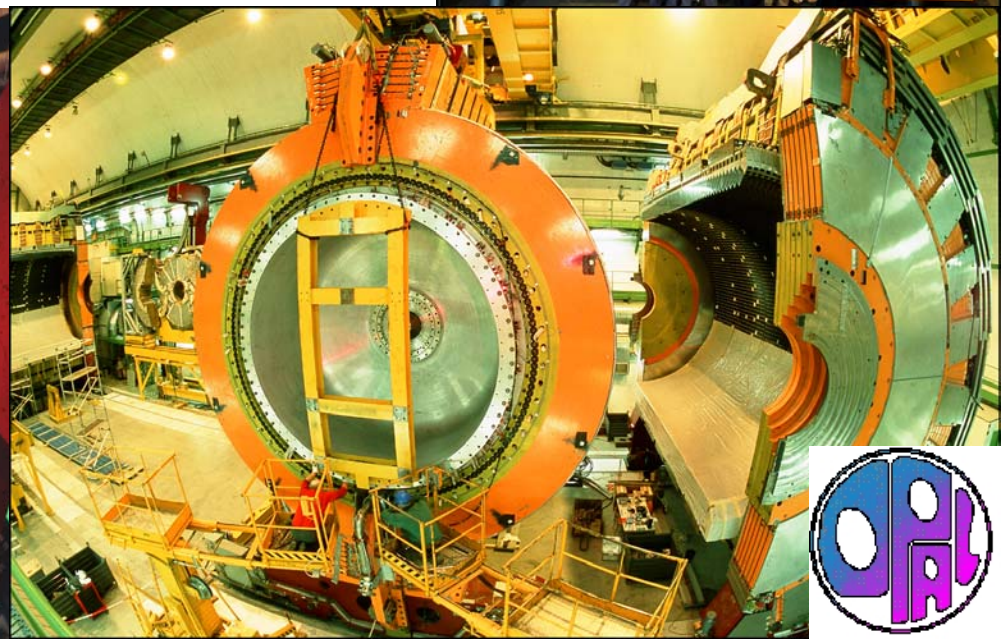
January 21-26, 2002



View of LEP Experiments







Spontaneous Symmetry Breaking

Two Primordial Gauge Interactions:

$$\partial_\mu \rightarrow \partial_\mu + ig'\frac{Y}{2}B_\mu + igT_iW_\mu^i$$

Hypercharge(Y)
$U(1)_Y$ Symmetry

$$T = 0 \qquad Y = 0$$

$$B_\mu$$

Y

Left-Handed Isospin(T)
$SU(2)_L$ Symmetry

$$T = 1 \qquad Y = 0$$

$$\begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix}$$

T

Higgs Field
1-complex doublet

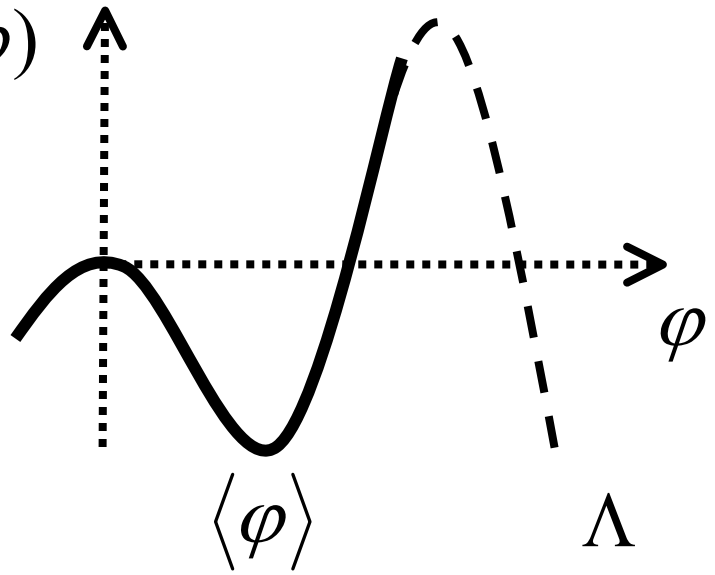
$$T = \tfrac{1}{2} \qquad Y = 1$$

$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \xrightarrow{C} \begin{pmatrix} \overline{\varphi}^0 \\ -\varphi^- \end{pmatrix}$$

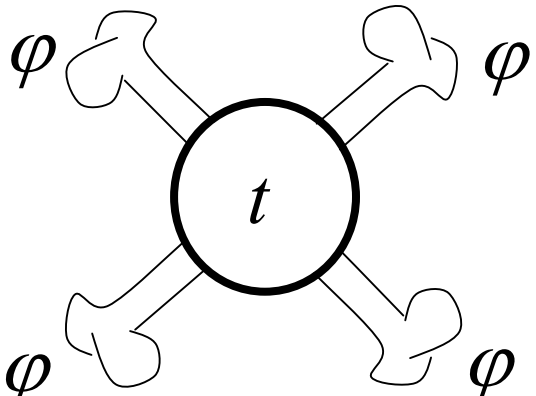
Properties of the Physical Vacuum

Self-Interacting Effective Potential:

$$V(\varphi) = -\mu^2\varphi^2 + \lambda\varphi^4 \qquad \text{(tree-level)}$$



$$\lambda(\Lambda) \to \text{negative}$$



(top-loop)

$$T_3\langle\varphi\rangle = -\tfrac{1}{2}$$

$$Y\langle\varphi\rangle = 1$$

$$(Q = T_3 + \frac{Y}{2})\langle\varphi\rangle = 0$$

Electric Charge(Q)
$U(1)_{EM}$ Symmetry

$$\boxed{Q = 0} \qquad A_\mu$$

$$\varphi^{\pm}, \text{Im}\{\varphi^0\} \Rightarrow W_L^{\pm}, Z_L$$

$$\text{Re}\{\varphi^0\} \Rightarrow \langle\varphi\rangle + H$$

missing link

Is the Z just a massive W^0?

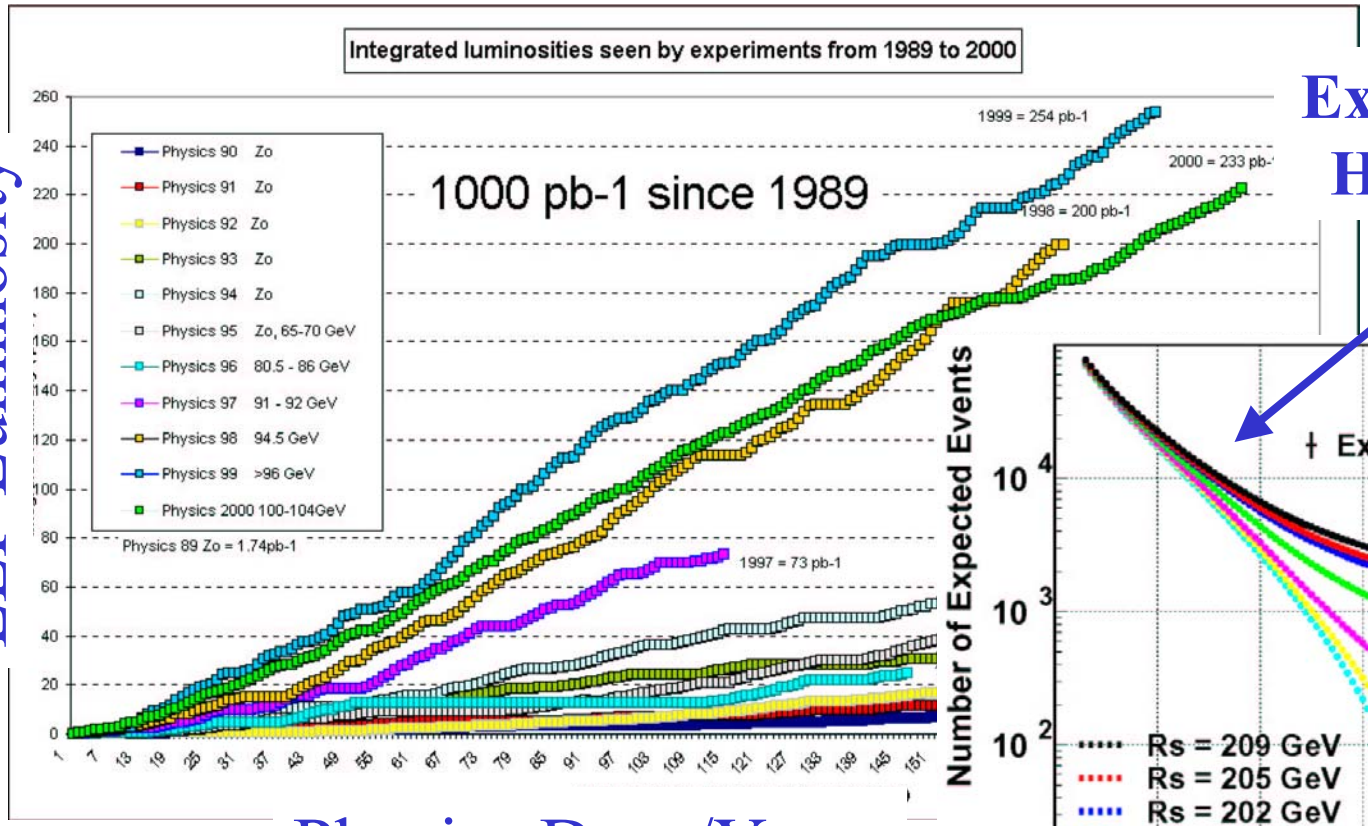
If isospin ($\boldsymbol{T}$) were an unbroken symmetry,

$$T = \tfrac{1}{2} \quad e_L^- \qquad \xrightarrow{\textit{allowed}} \qquad T = 1 \quad W^0$$
$$T = \tfrac{1}{2} \quad e_R^+$$

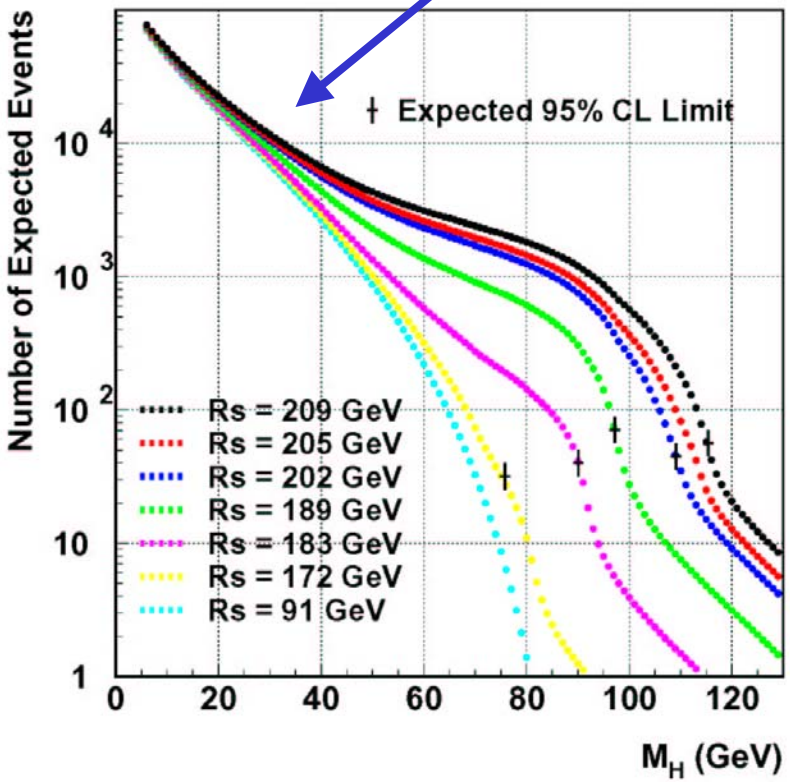
$$T = 0 \quad e_R^- \qquad \xrightarrow{\textit{not allowed}} \qquad T = 1 \quad W^0$$
$$T = 0 \quad e_L^+$$

The measurement of $e_R^- e_L^+ \to Z$ **gives us** $\sin^2\theta_W$

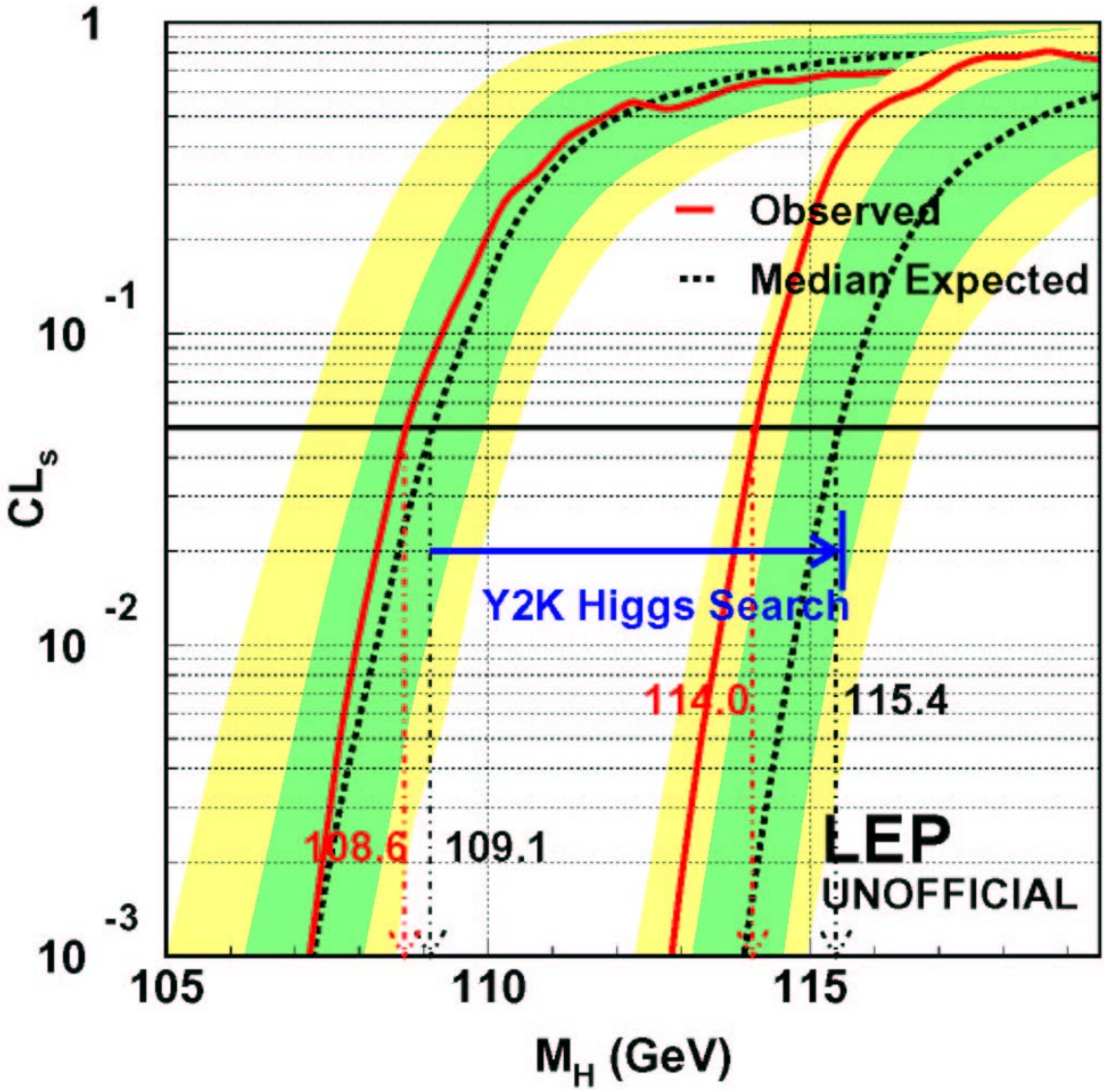
LEP Luminosity → Higgs Search



Expected #'s of Higgs Events

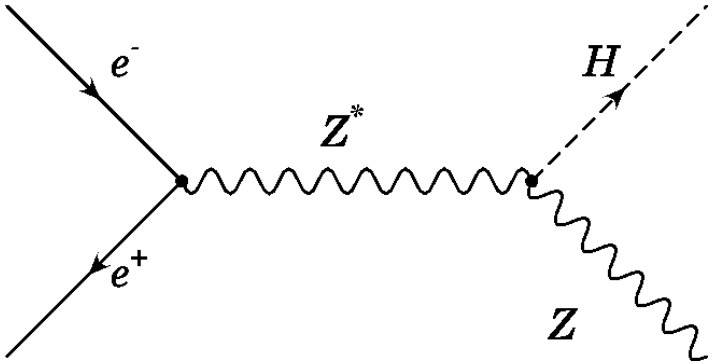


Pushing LEP to its Limit

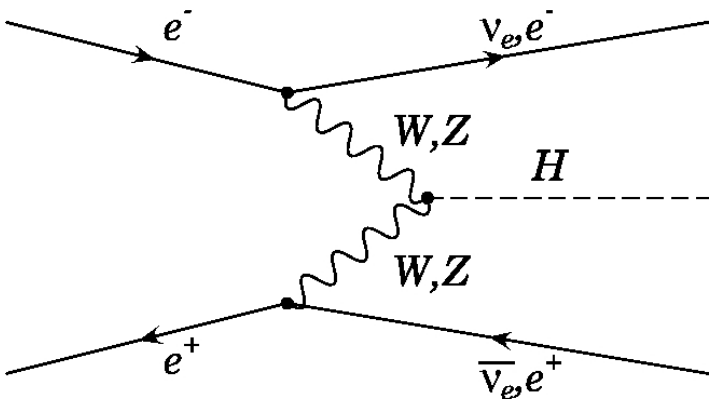


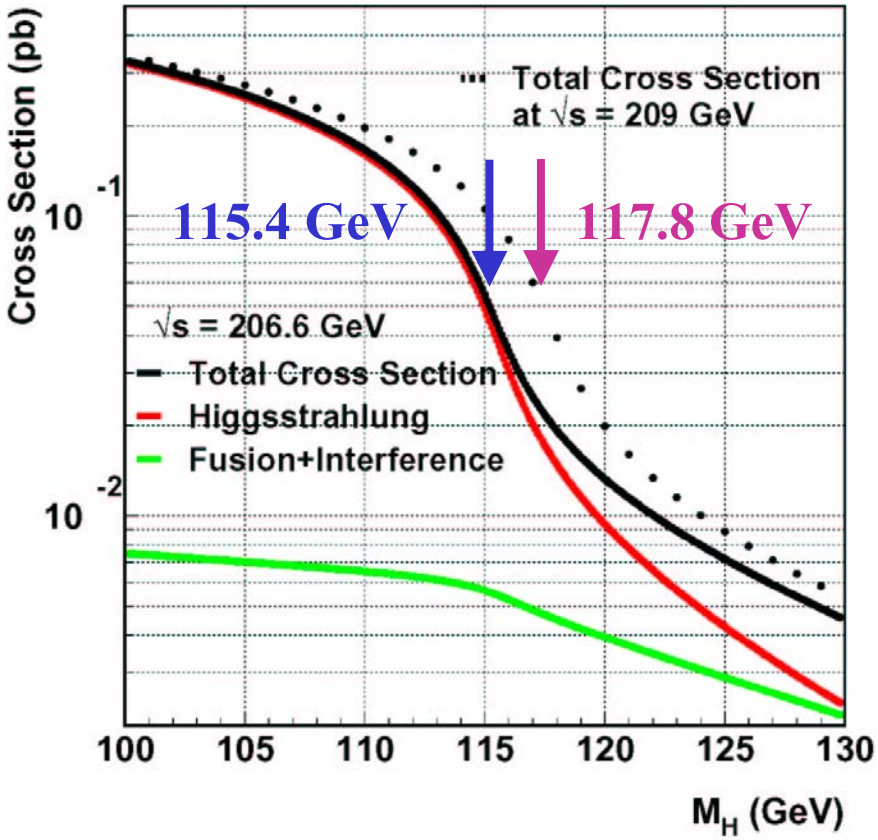
Standard Model Higgs Production

Higgsstrahlung Diagram

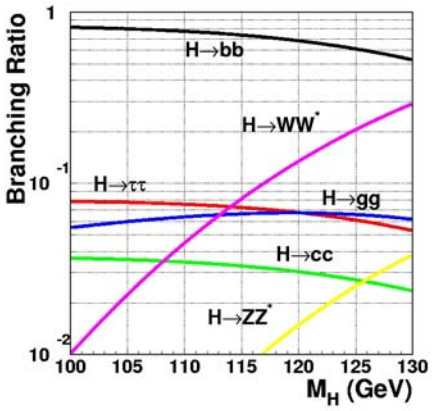


Fusion Diagrams





Physical Search Channels



Higgs Decay Mode @ m_H=115 GeV

$b\bar{b}(74\%)$ $gg(7\%)$ $c\bar{c}(3\%)$

$\tau^+\tau^-(7\%)$

Production Fermions

$Z \to q\bar{q}$

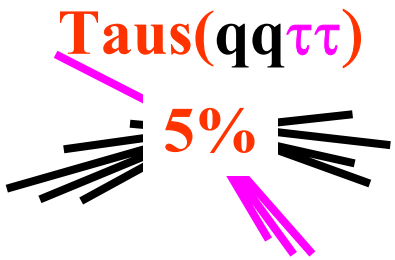
$Z \to \nu\bar{\nu}$,

$e^+e^-WW \to \nu_e\bar{\nu}_e H$

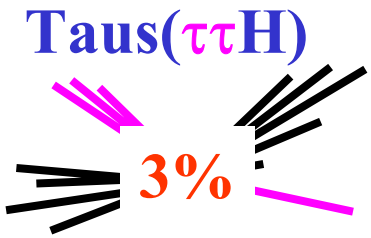
$Z \to e^+e^-$ or $\mu^+\mu^-$,

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

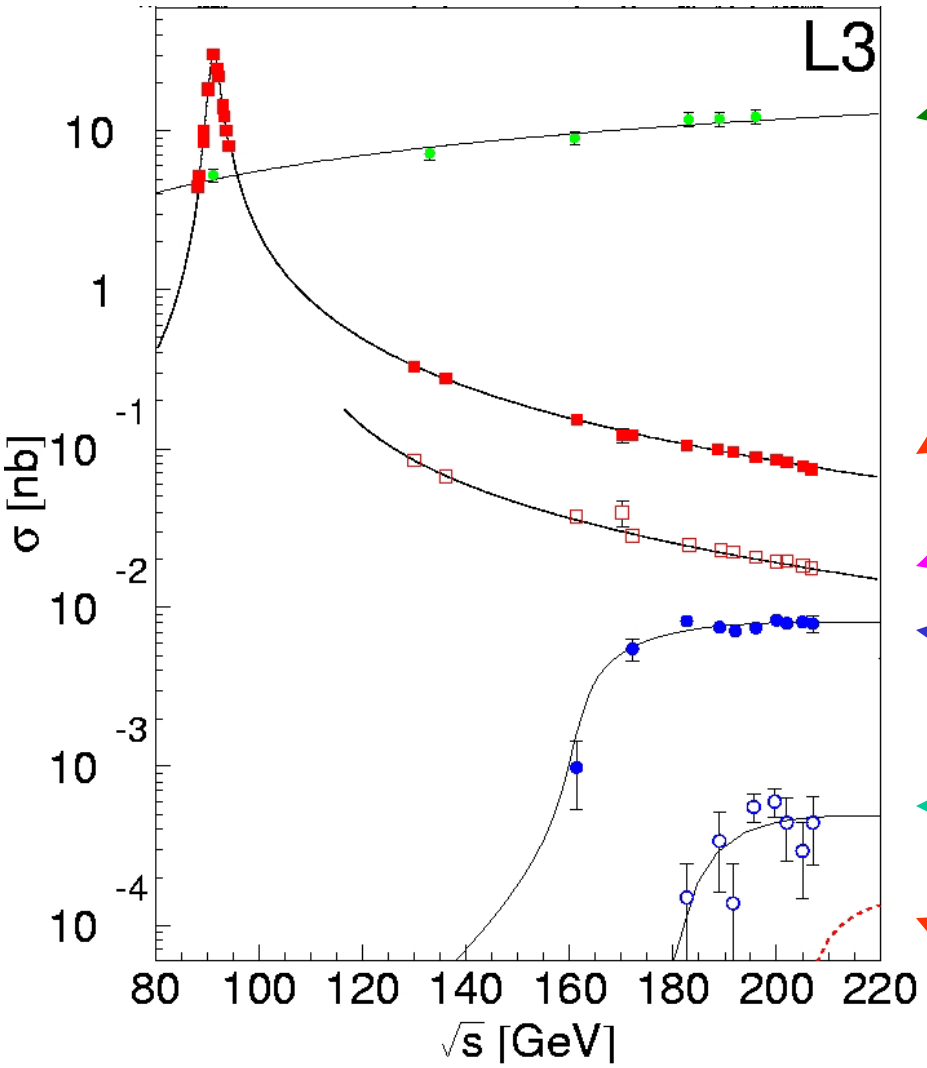
$Z \to \tau^+\tau^-$



10% missing



Standard Model Processes at LEP



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

Two-Photon Interaction

$e^+e^- \to q\bar{q}(\gamma)$

Full Energy

$q\bar{q}\ \left(\sqrt{s'/s} > 0.85\right)$

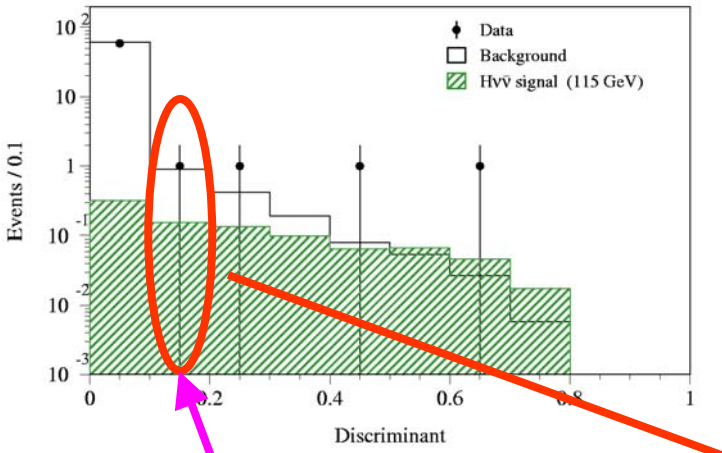
$e^+e^- \to W^+W^- \to q'\bar{q}q'\bar{q}$

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

$e^+e^- \to HZ \to b\bar{b}\,q\bar{q}$

$m_H = 114$ GeV

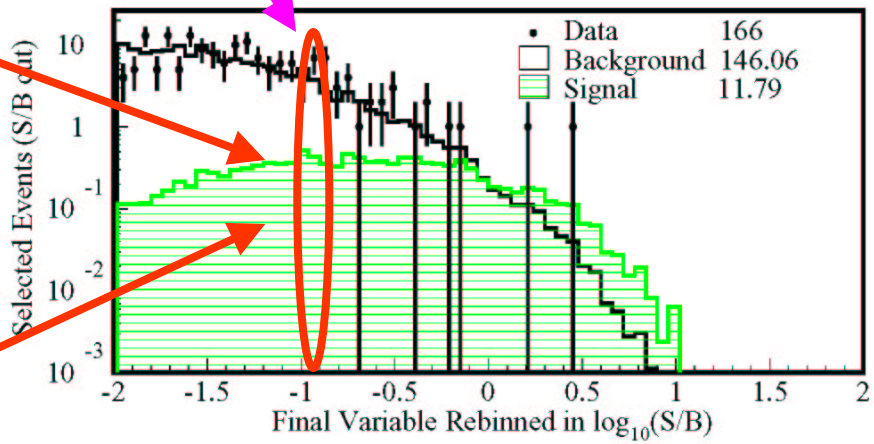
Combining Search Data

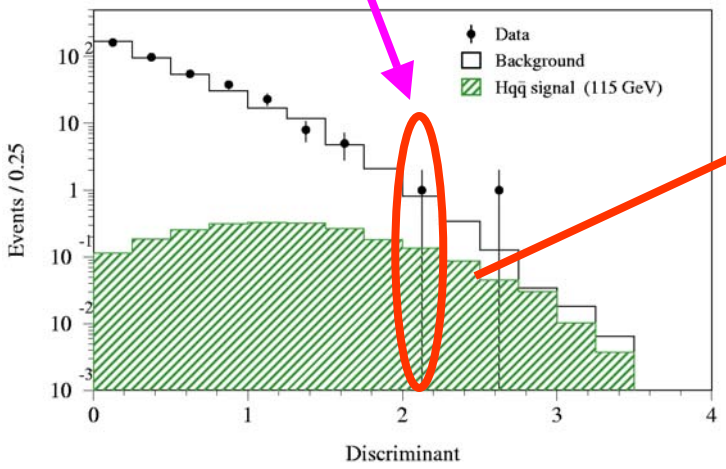


Rebinning Procedure

4 Experiments
×4 Channels
×15 Beam Energies
=240 Analyses

Equal S/B Ratio ≡ Equal Sensitivity





LEP treated as a single search analysis

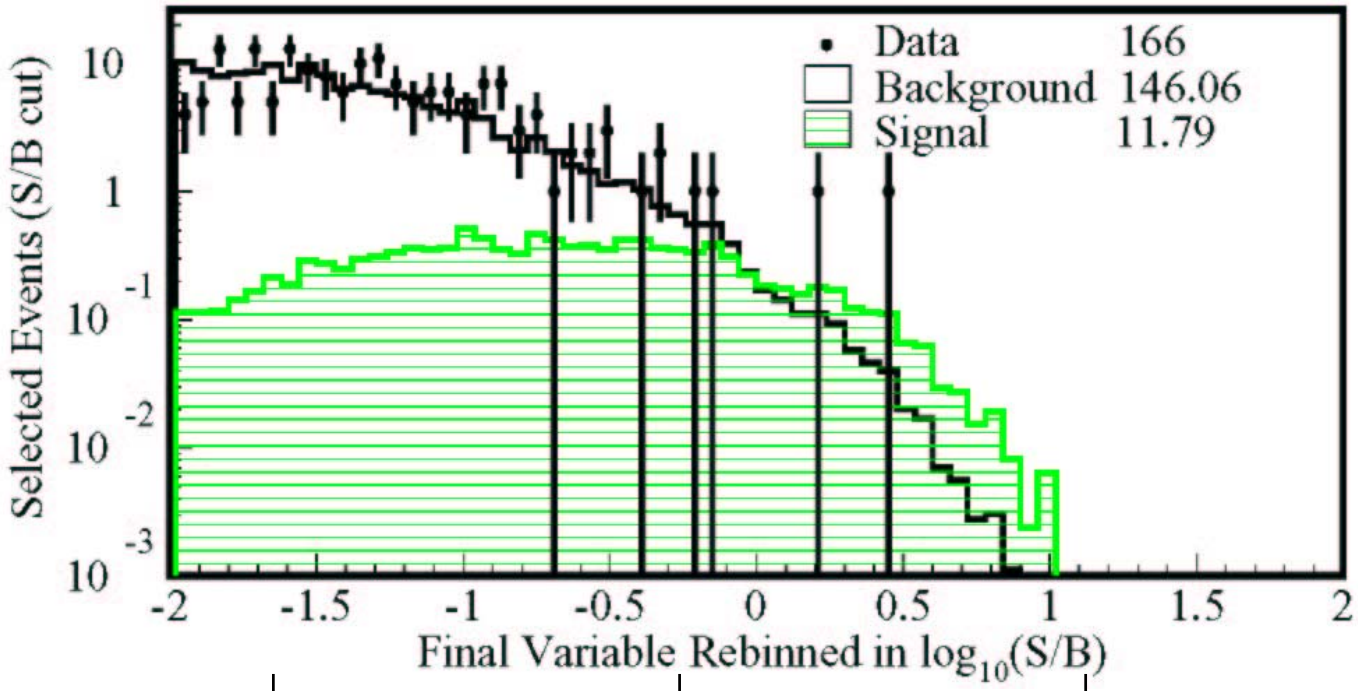
Search Channel Analyses

Average Signal/Background at m_H=115.6 GeV

Search Channel	Exp.	Expected Number of Events 1.0	0.5	0.1
4-Jet	Aleph	**0.4**	**1.0**	**2.8**
	Delphi	**0.5**	**1.1**	**2.6**
	L3	**0.2**	**0.5**	**1.1**
	Opal	**0.2**	**0.5**	**1.0**
Missing Energy	Aleph		**0.3**	**0.9**
	Delphi		**0.5**	**2.1**
	L3		**0.2**	**0.7**
	Opal		**0.3**	**0.7**
Leptons (e+μ)	Aleph			**2.5**
	Delphi			**1.9**
	L3			**1.6**
	Opal			**1.6**

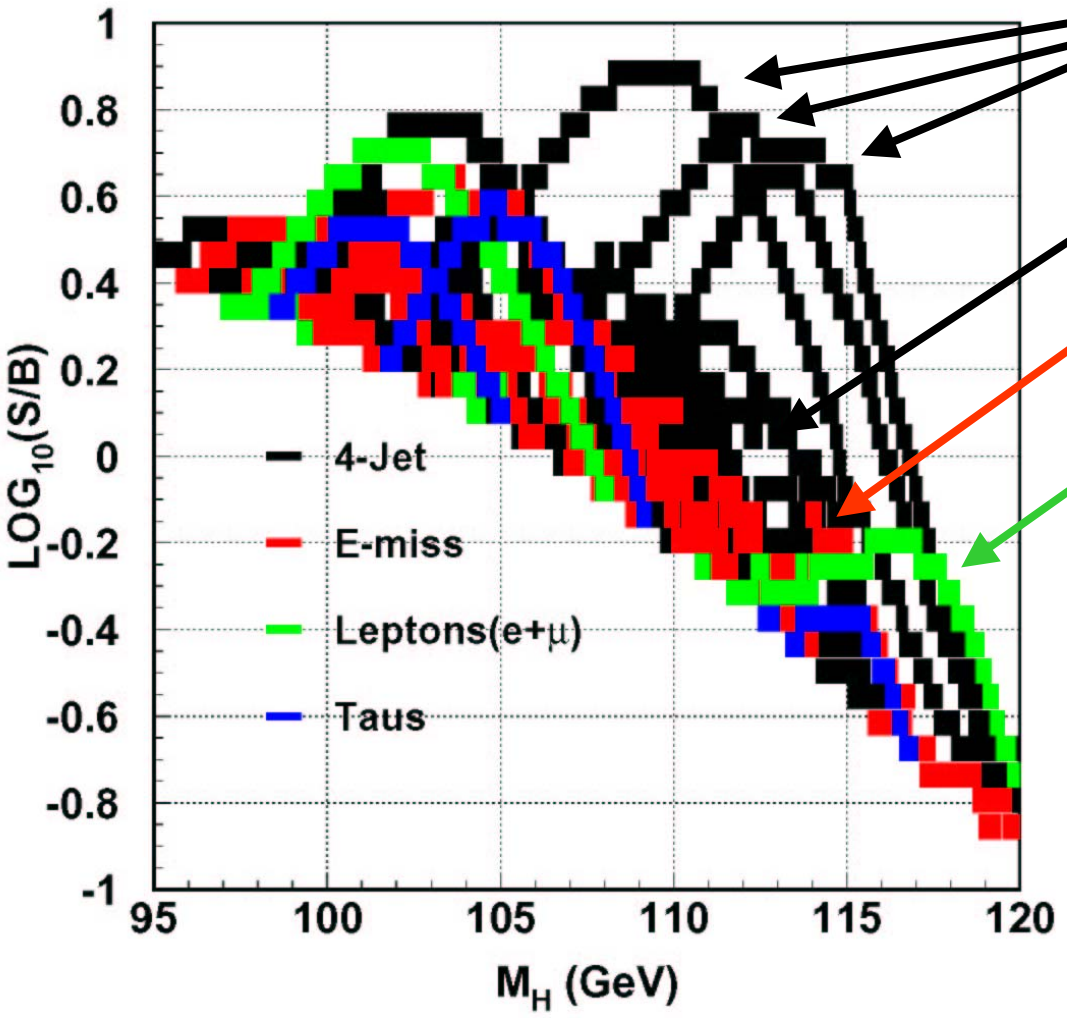
Notable Analysis Variation

LEP Higgs Data at m_H=115.6 GeV



Selection	Data	Background	Signal+ Background
All Events	1117	1143.8	1158.7
s/b>0.05	80	60.1	70.3
s/b>0.3	10	7.5	12.1
s/b>1.0	2	0.8	2.3

Candidate Evolutions in Log(s/b)



3 ALEPH 4-Jet Events

OPAL 4-Jet Event

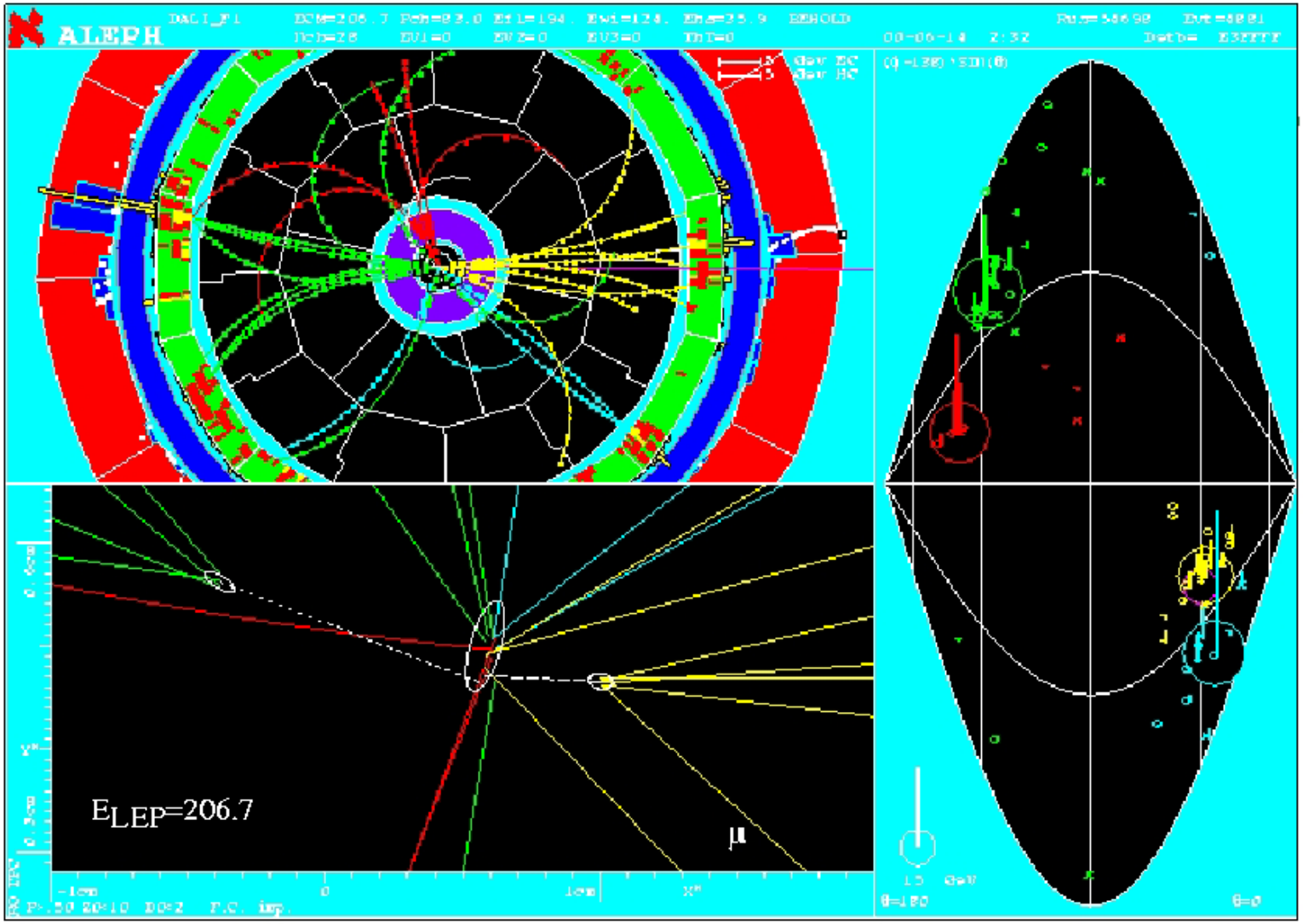
1 L3 Missing Energy

ALEPH Lepton(e) Event

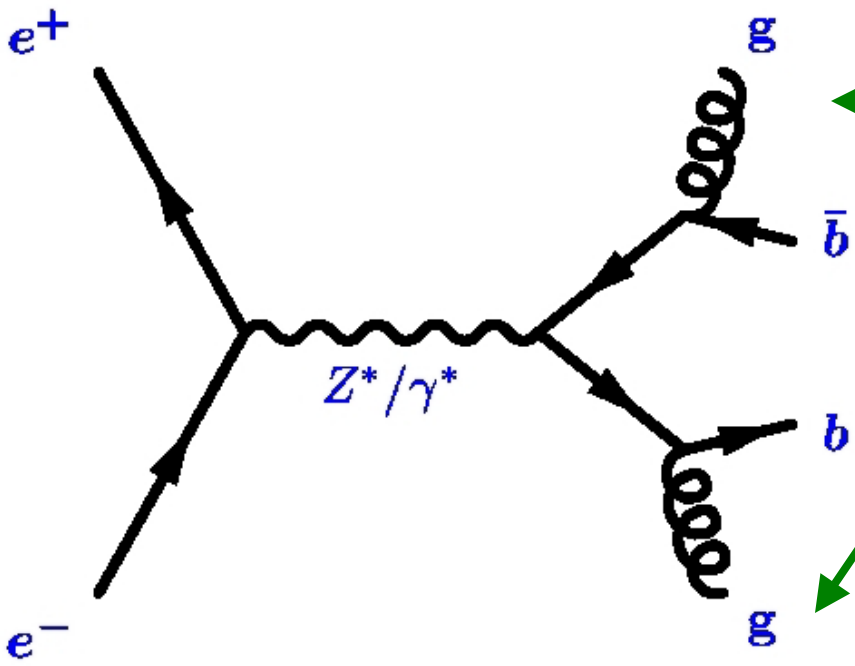
Peaks occur at Reconstructed masses

Widths come from Mass resolutions

ALEPH 4-Jet Channel



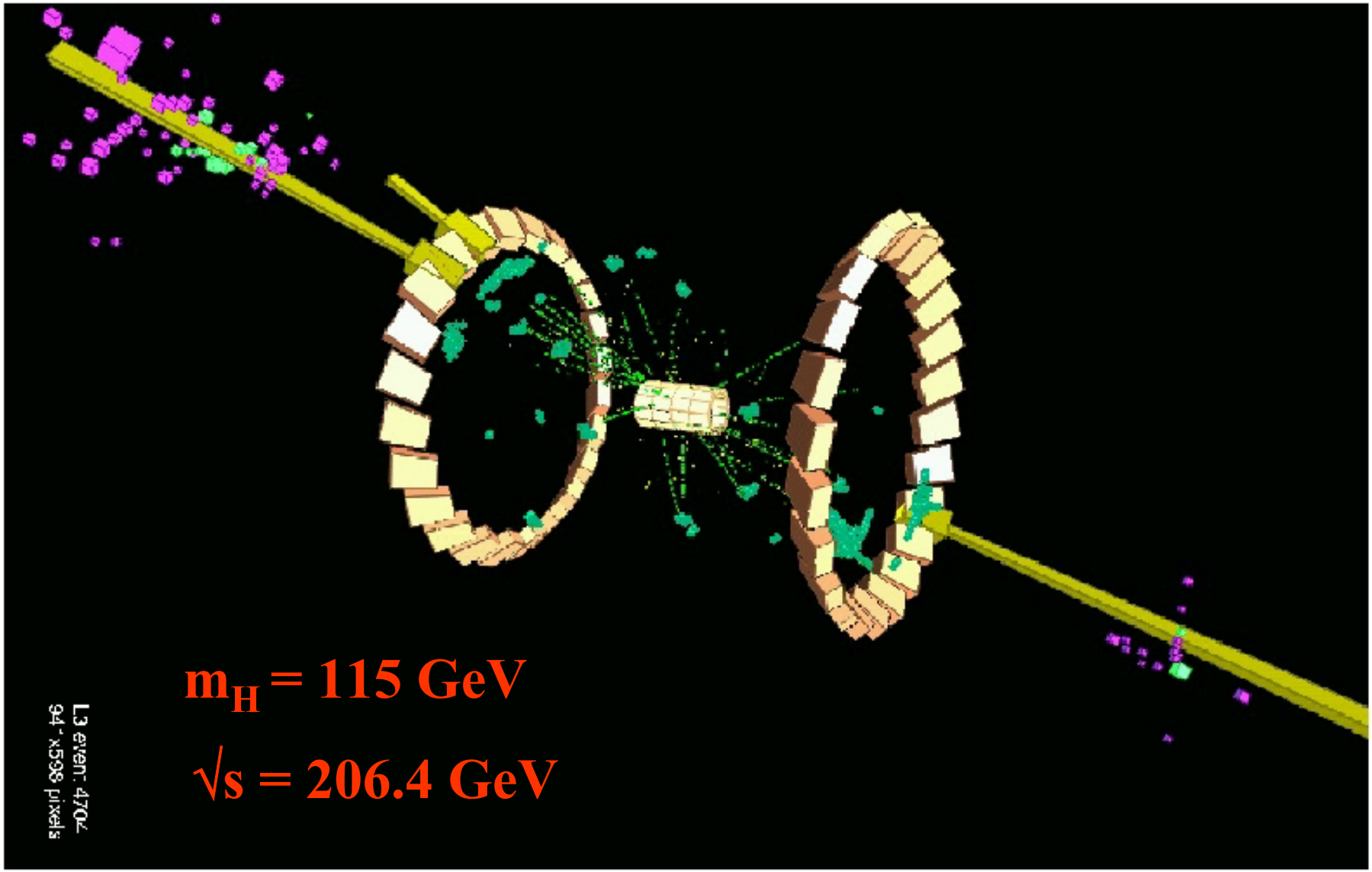
Background from Double Gluon Radiation



To mimic Z→qq decay, gluons must be:
a) back-to-back
b) separated from the quark jets, and each have
c) 45 GeV of energy

Cross section is reasonably well known in perturbative QCD (known to ≈20%)

Side View of Hνν Candidate



Composition of Background Estimate for Hνν Candidate

$e^+e^- \rightarrow ZZ$

$\rightarrow \nu\nu$

$\rightarrow b\bar{b} \rightarrow$ Two b-Jets

Dijet Mass ≈ 91 GeV but measured to be ≈115 GeV (Measurement Tails)

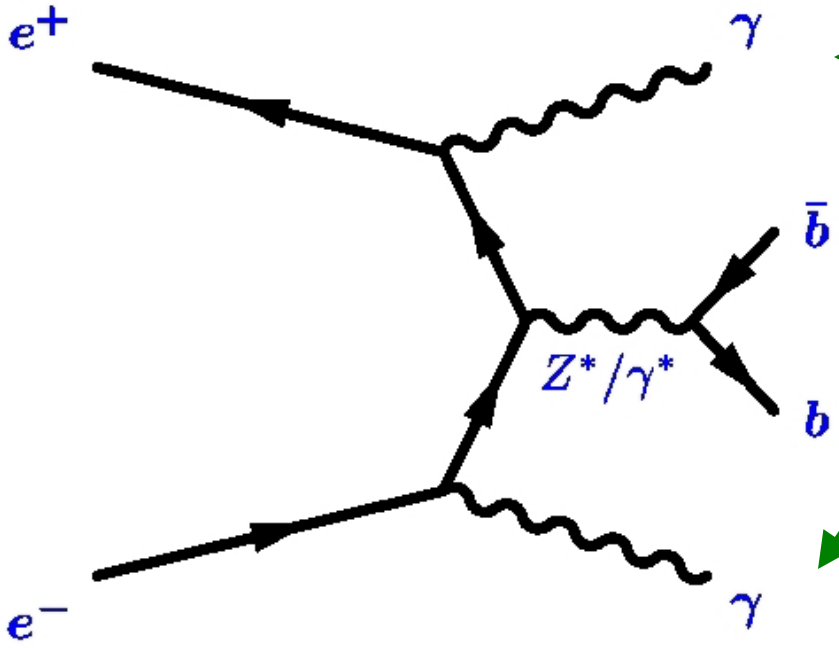
$e^+e^- \rightarrow b\bar{b}(\gamma\gamma)$

- **Fraction of Full Energy Events Extremely Small**

(Dijet Mass ≈ 206 GeV but measured to be ≈115 GeV)

- **Dominantly Double Radiative Return Rare Process that Mimics the Signal (Production Tails)**

Background from Double Radiative Return

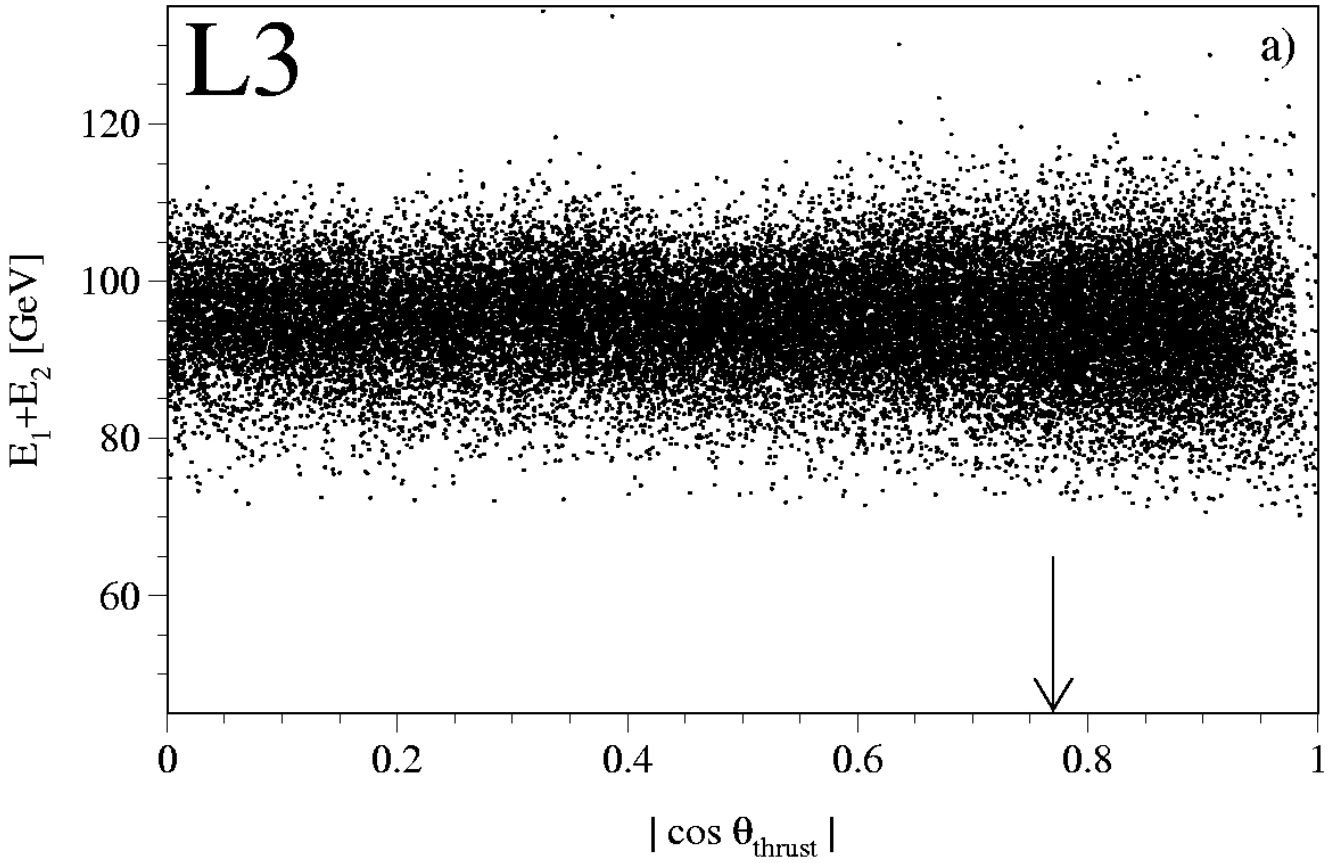


To mimic $Z \to \nu\nu$ decay, photons must be:
a) back-to-back
b) undetected (down beam pipe), and each with
c) 45 GeV of energy

Additional photon lines imply small cross sections (known to ≈15%)

Jet Measurements

Z Peak Calibration Data in Year 2000

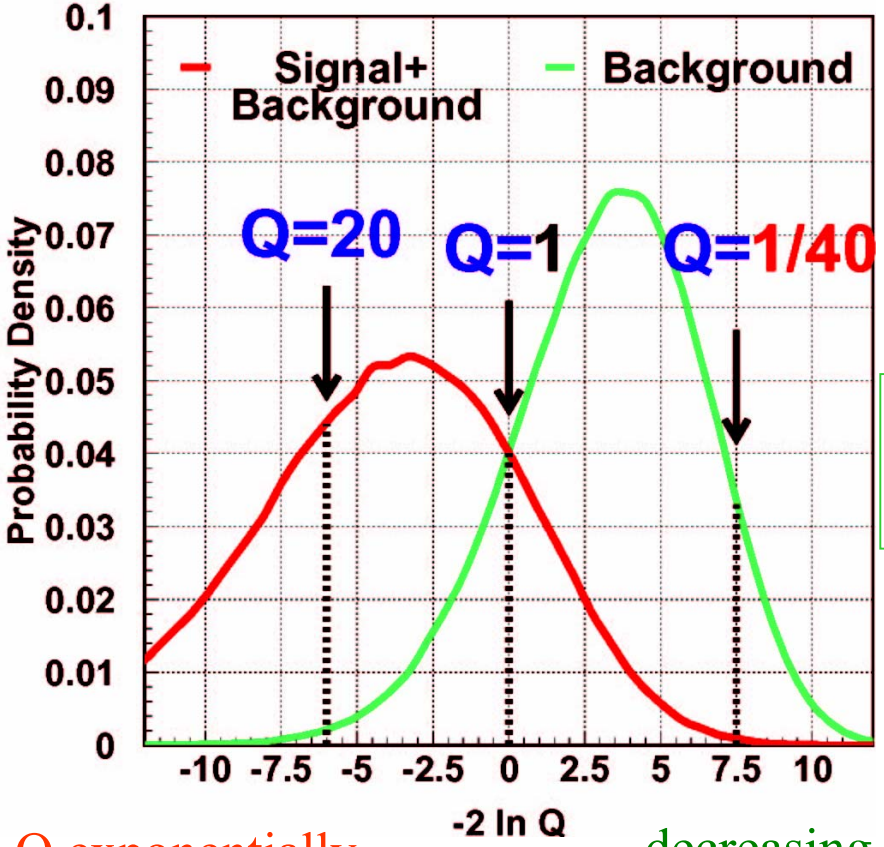


Jet Resolution
≈13%
at θ=45°

Jet Energy Sum
= 91 GeV

No Evidence
for
Large Energy Loss

Visualizing Search Sensitivity



Q exponentially increasing ← → decreasing

Treat each bin *i* as a
Poisson Counting Experiment

b_i Expected Background

s_i Expected Signal

n_i Observed Number of Events

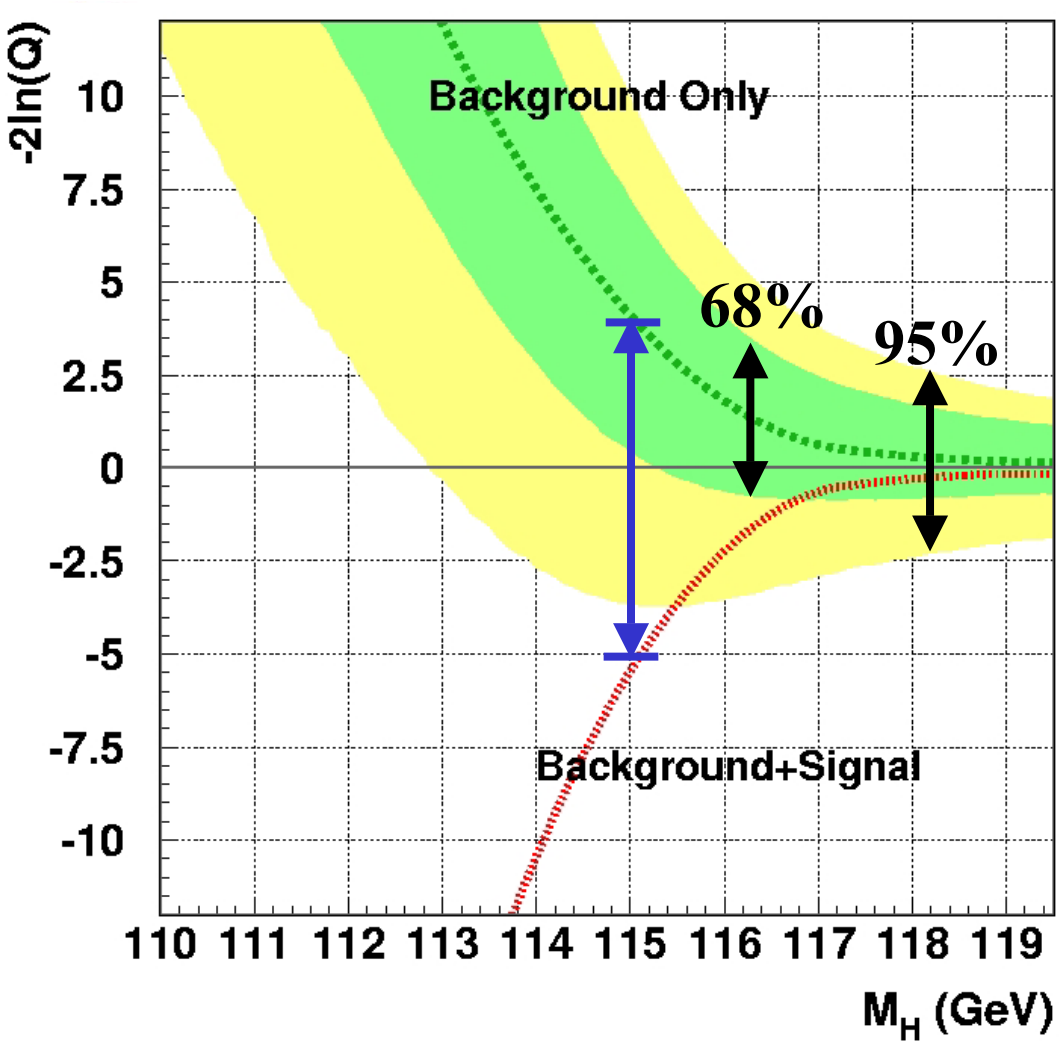
$$-2\ln(Q) = 2\sum_i s_i - n_i \ln\left(1+\frac{s_i}{b_i}\right)$$

weight

$n_i = s_i + b_i$ **(Signal+Background)**

$n_i = b_i$ **(Background Only)**

Scanning for a Higgs Boson Mass

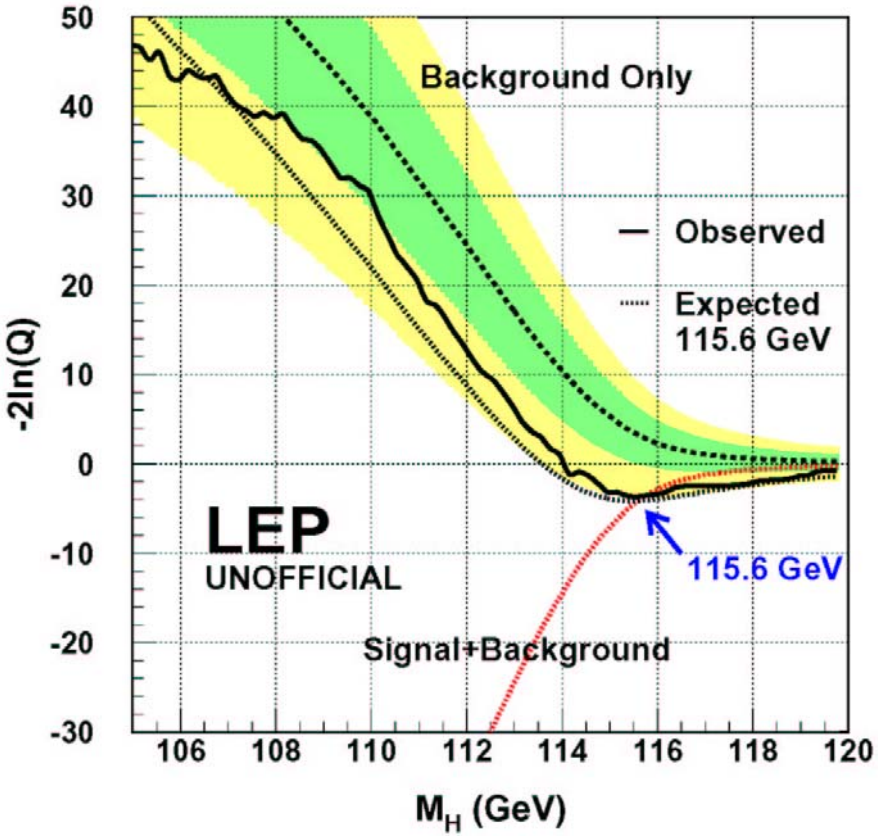


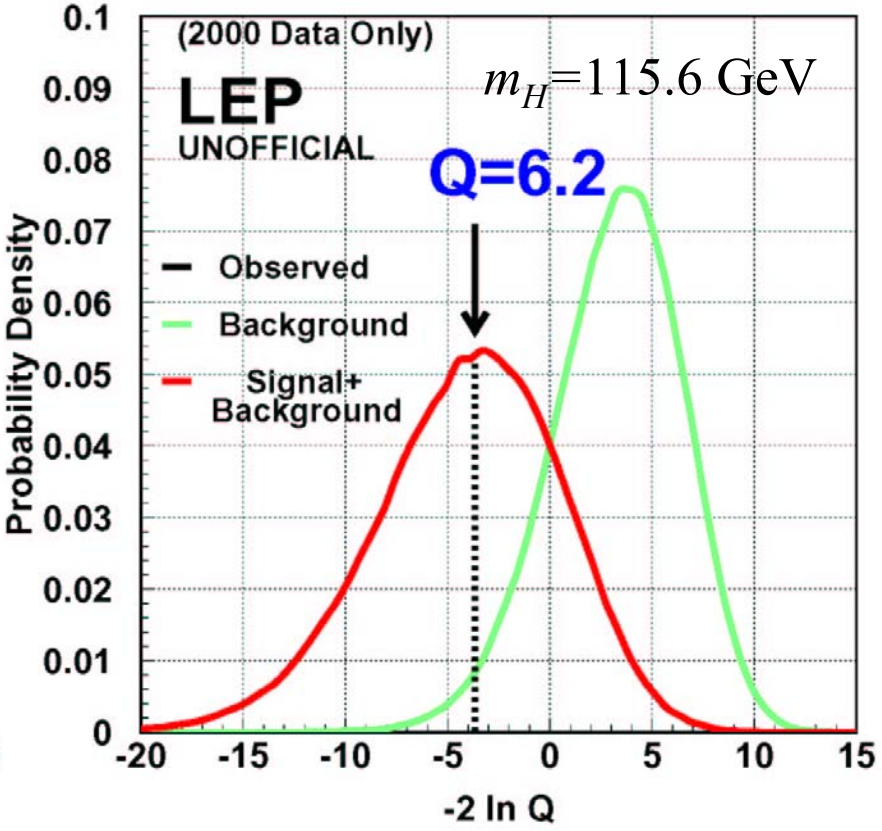
Measure median separation of hypotheses

Compare with widths of distributions

Scan versus Mass

Combined Standard Model Results



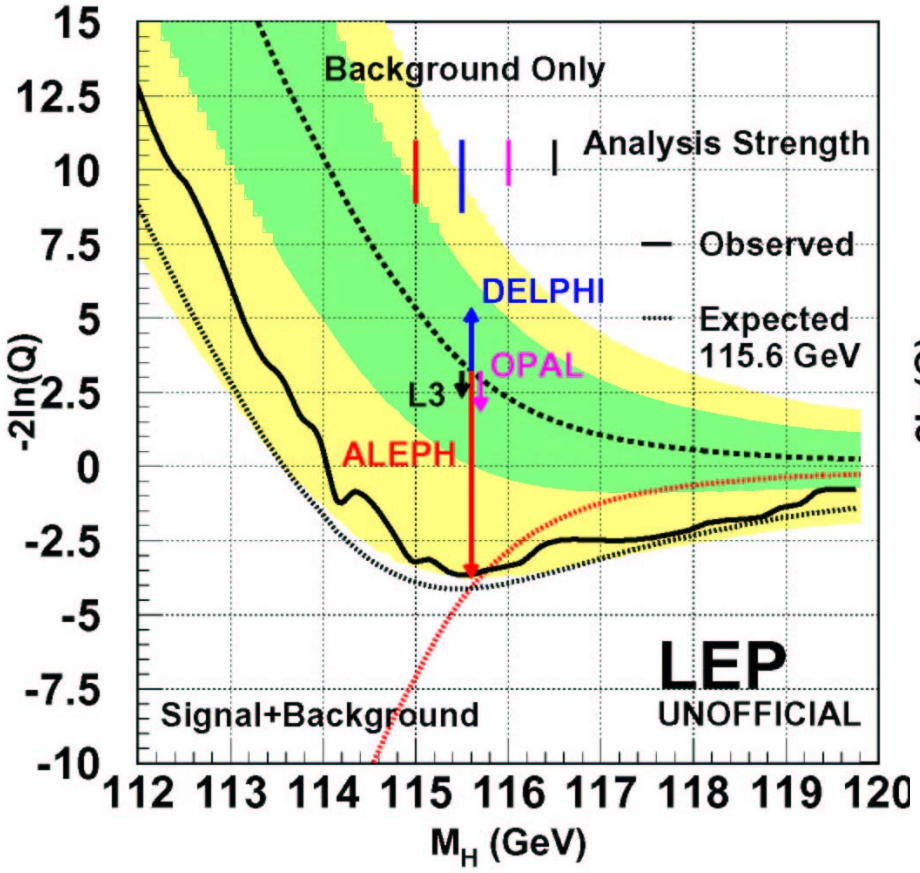


Data Excess Compatible with:

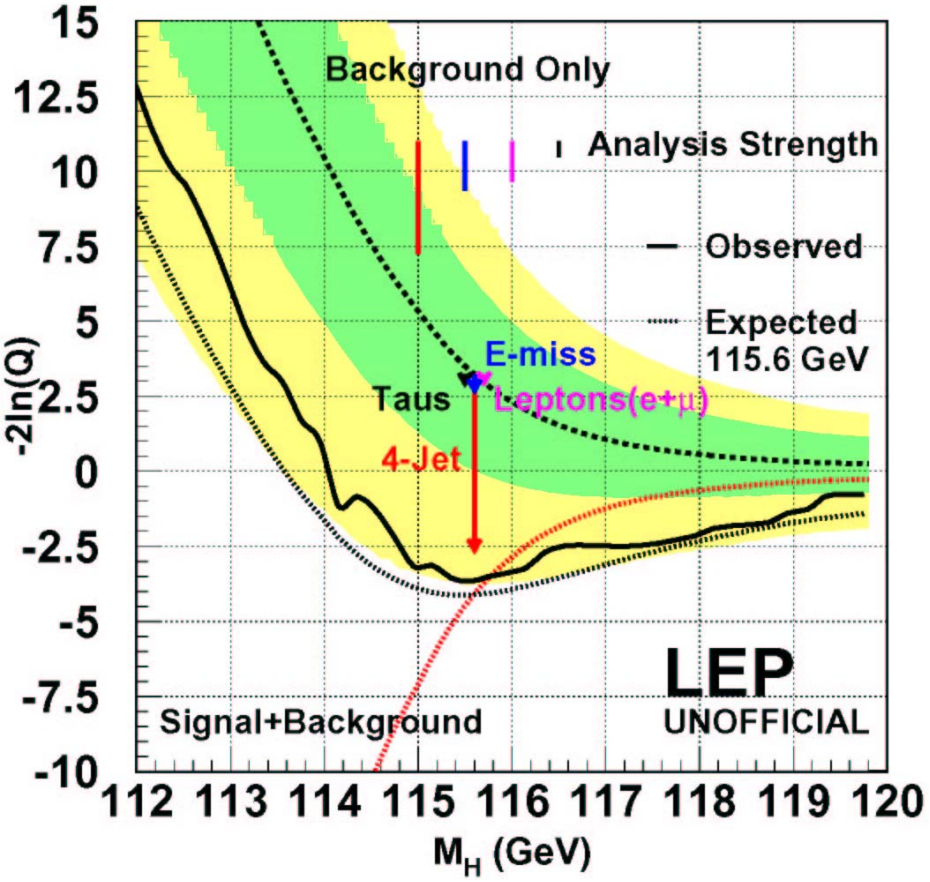
$$m_H = 115.6^{+1.4}_{-1.1}\ \text{GeV}$$

Preliminary Data
final combination expected
in February

Is it Background Only?

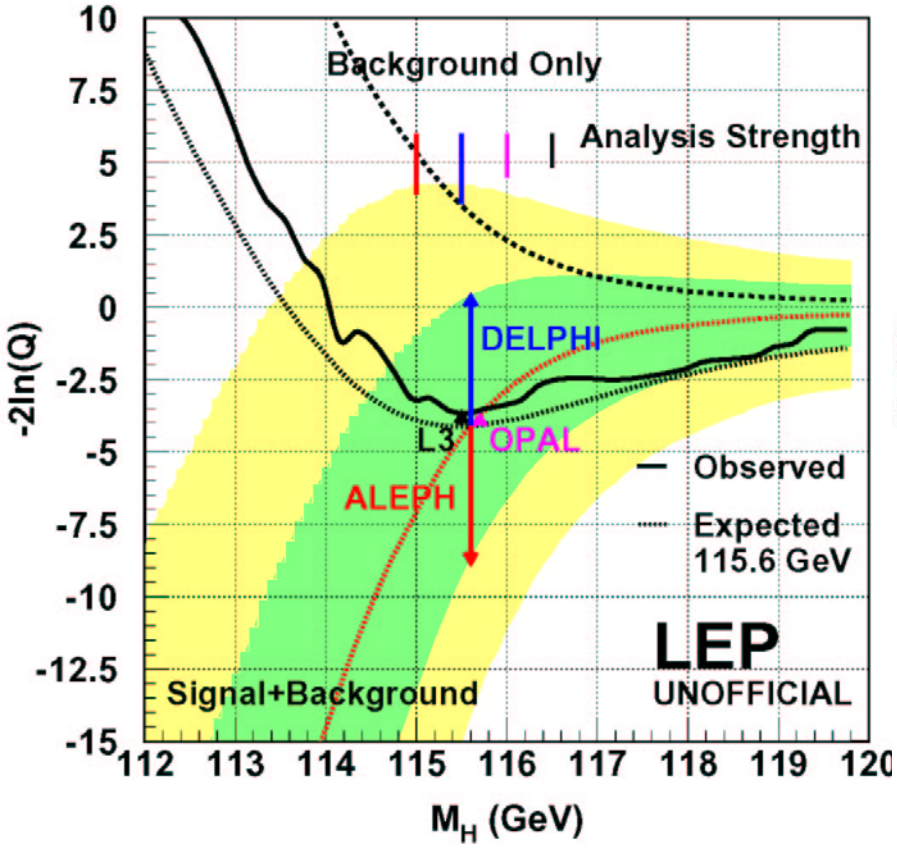


by Experiment

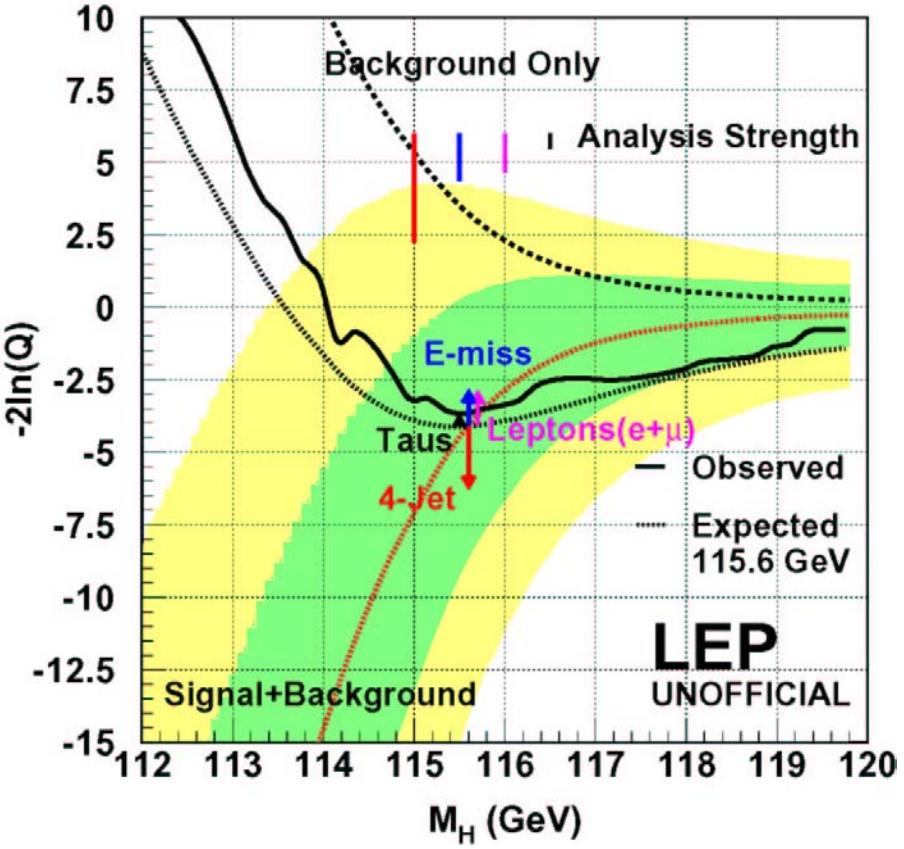


by Channel

Is it Signal + Background?

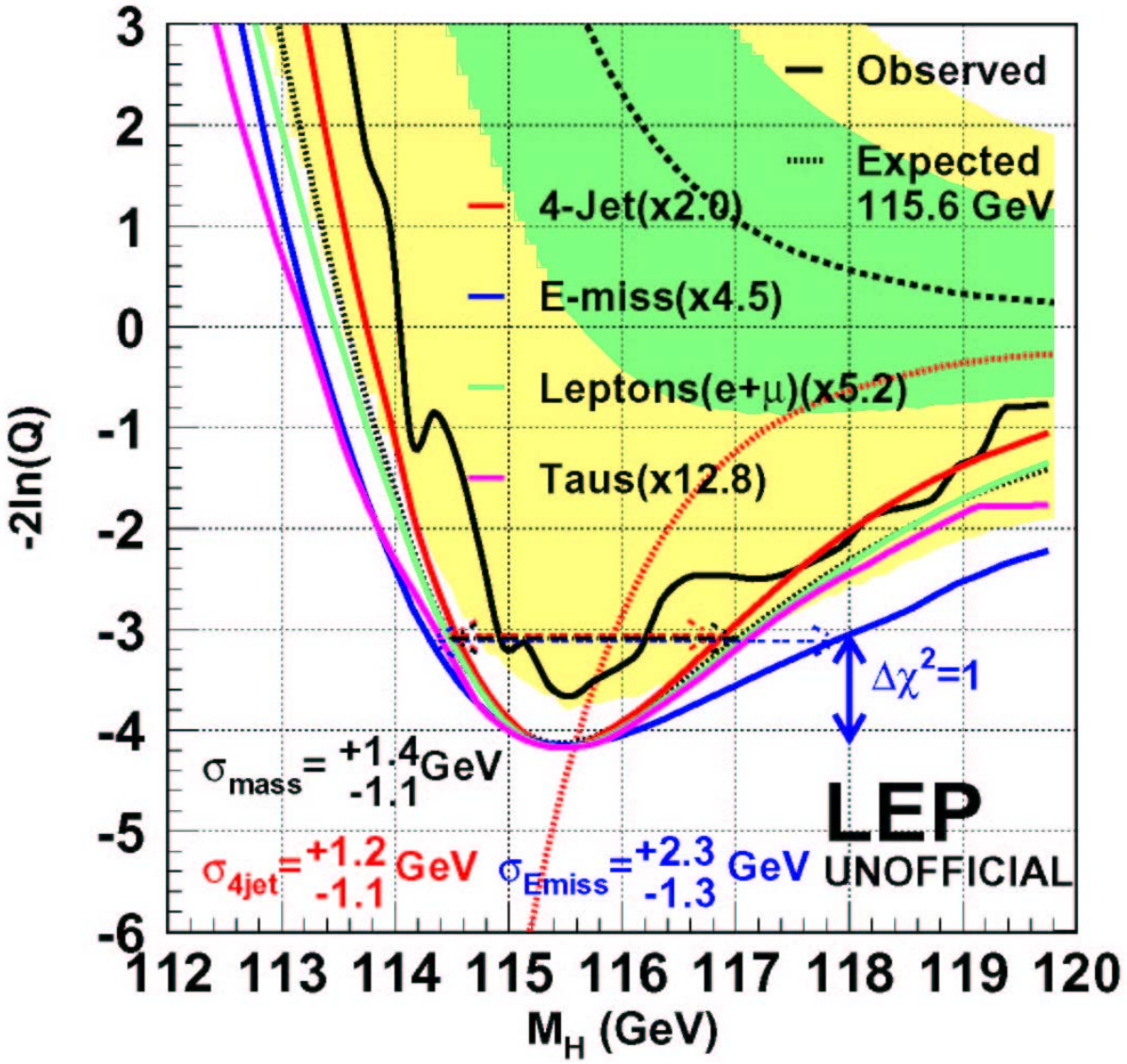


by Experiment

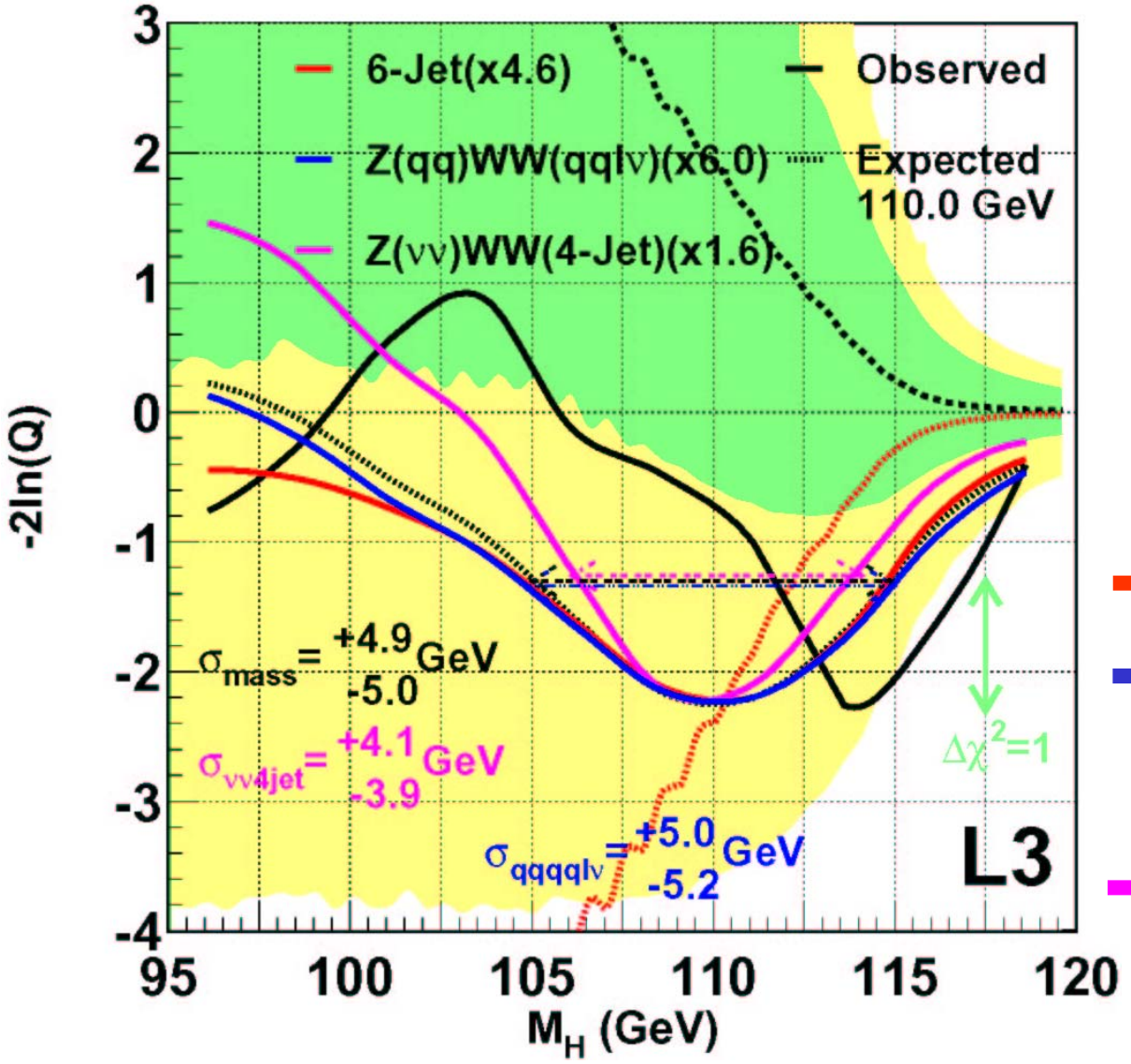


by Channel

Mass Resolution by Channel



Mass Resolution in $H \rightarrow WW^*$



Higgsstrahlung

$$ZH \rightarrow ZWW^*$$

Decay Modes

$Z \rightarrow q\bar{q}$

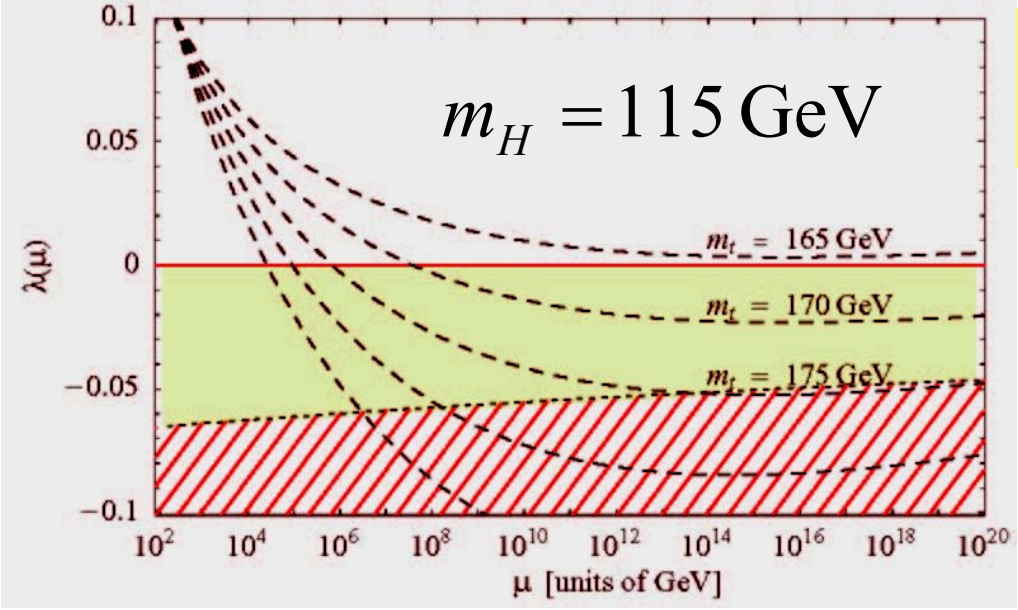
$WW^* \rightarrow 4-\text{Jet}$

$WW^* \rightarrow q\bar{q}'l\nu$

$Z \rightarrow \nu\bar{\nu}$

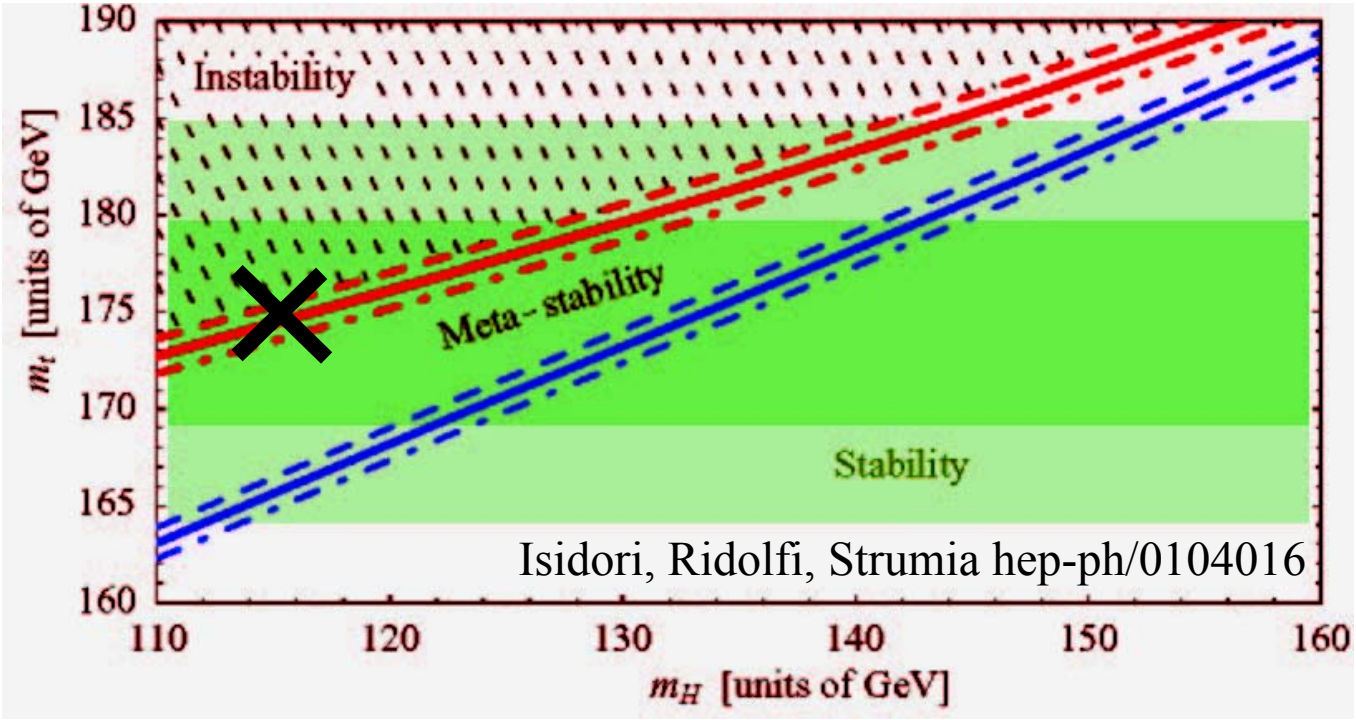
$WW^* \rightarrow 4-\text{Jet}$

Self-Coupling λ

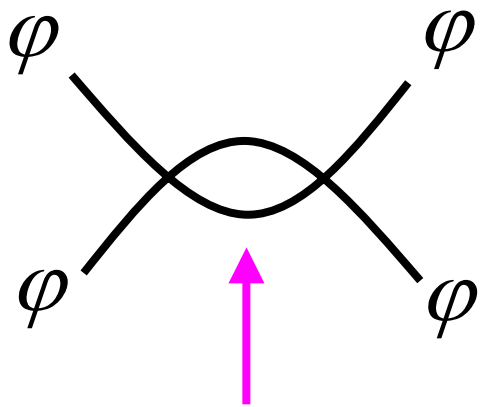


λ is negative for m_t=175 GeV at 1000 TeV

What can be done?



$\lambda(\Lambda) \rightarrow$ positive



Massive scalar or vector particles

Fermion Masses in a 1-doublet Model

1-doublet Model:

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \xrightarrow{C} \varphi_c = \begin{pmatrix} \overline{\varphi}^0 \\ -\varphi^- \end{pmatrix}$$

Down-type mass

$$\mathcal{L}_d = -G_d \begin{pmatrix} \overline{u} & \overline{d} \end{pmatrix}_L \varphi \, d_R$$

$$\langle \varphi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$m_d = \frac{G_d v}{\sqrt{2}}$$

Up-type mass

$$\mathcal{L}_u = -G_u \begin{pmatrix} \overline{u} & \overline{d} \end{pmatrix}_L \varphi_c \, u_R$$

$$\langle \varphi_c \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$m_u = \frac{G_u v}{\sqrt{2}}$$

Same *v*

Fermion Masses in a 2-doublet Model

Down-type mass

$$m_d = \frac{G_d v_1}{\sqrt{2}}$$

Up-type mass

$$m_u = \frac{G_u v_2}{\sqrt{2}}$$

$$v_1^2 + v_2^2 = v^2$$

Electroweak Energy Scale

$$\tan\beta = v_2 / v_1$$

m_{top}/m_{bottom}?

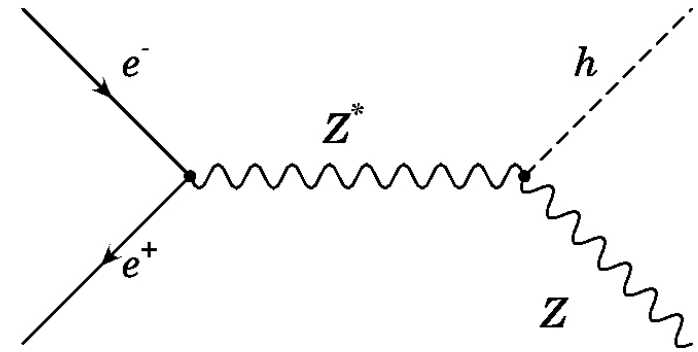
8 degrees of freedom

– 3 longitudinal polarizations ($W_L^{\pm}$,Z_L)

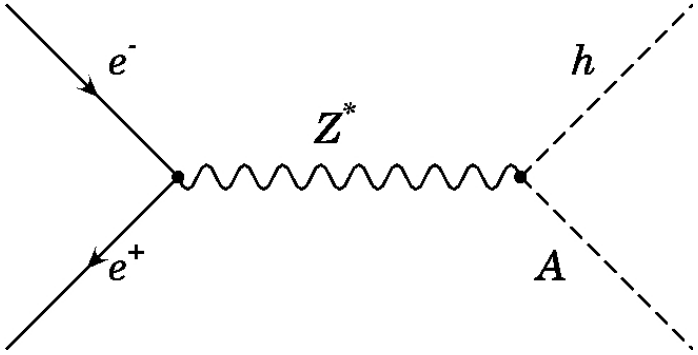
leaves 5 Higgs bosons: *h*, *H*, *A*, $H^{\pm}$

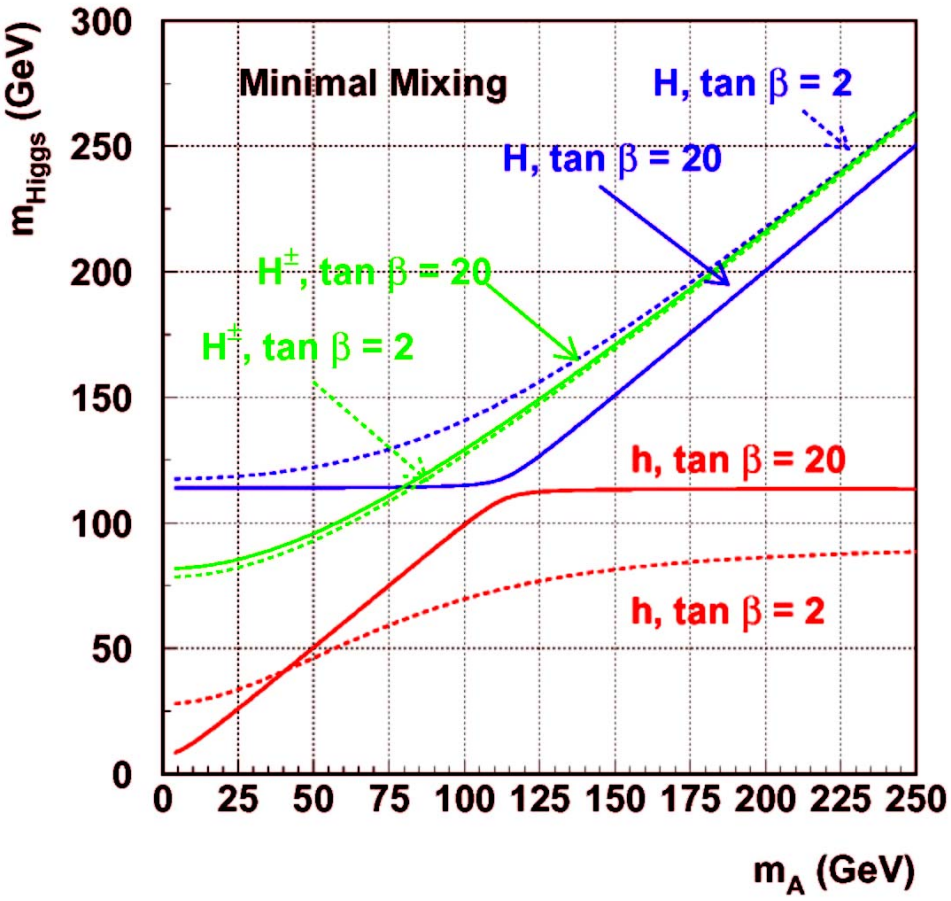
Production of Higgs Bosons in the Minimal Super Symmetric Model

$\sigma \sim \sin^2(\beta-\alpha) \cdot \sigma_{SM,hZ}$



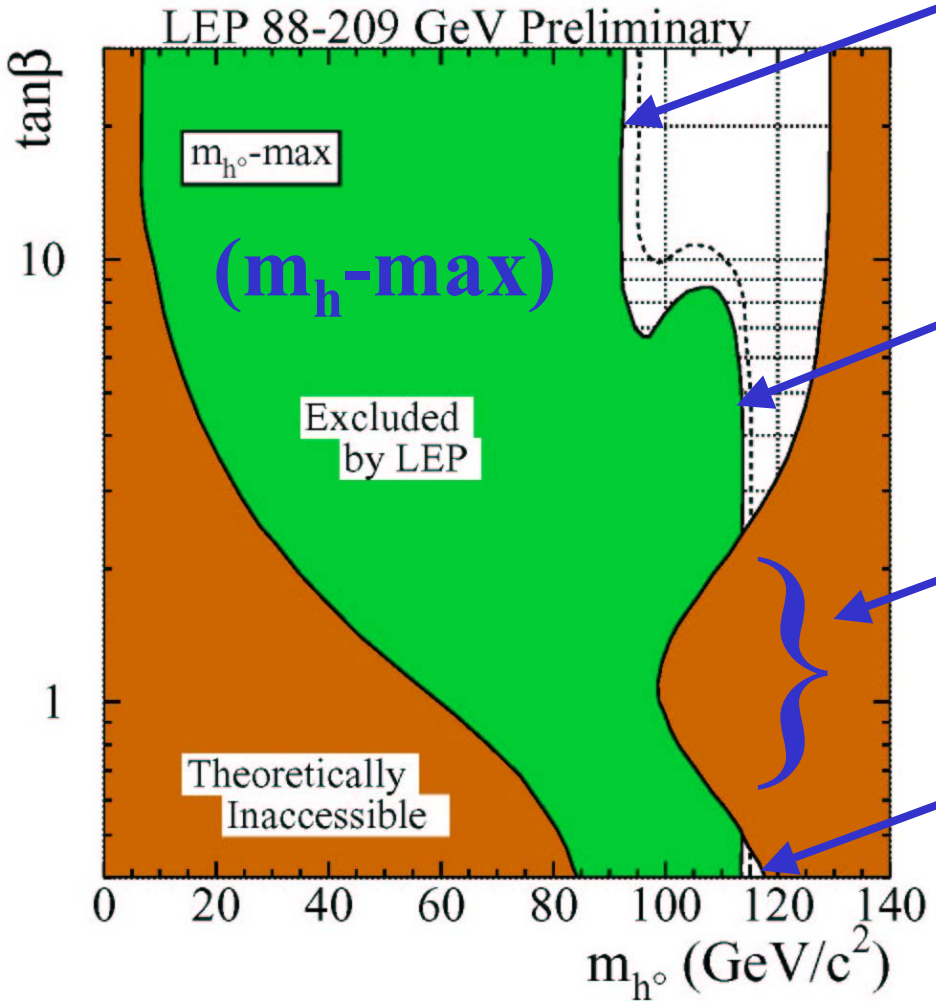
$\sigma = \overline{\lambda}\cos^2(\beta-\alpha) \cdot \sigma_{hZ}^{SM}$





Scanning for the MSSM

$(m_h, \tan\beta)$–Exclusion plane



Excluded past ZZ for equal mass hA production

Lightest h excess at 115.6 GeV

Excluded region of tan β

Small region of allowed low tan β values

Higgs' Quest

Fermilab (Chicago, USA)

Tevatron Run II
In progress

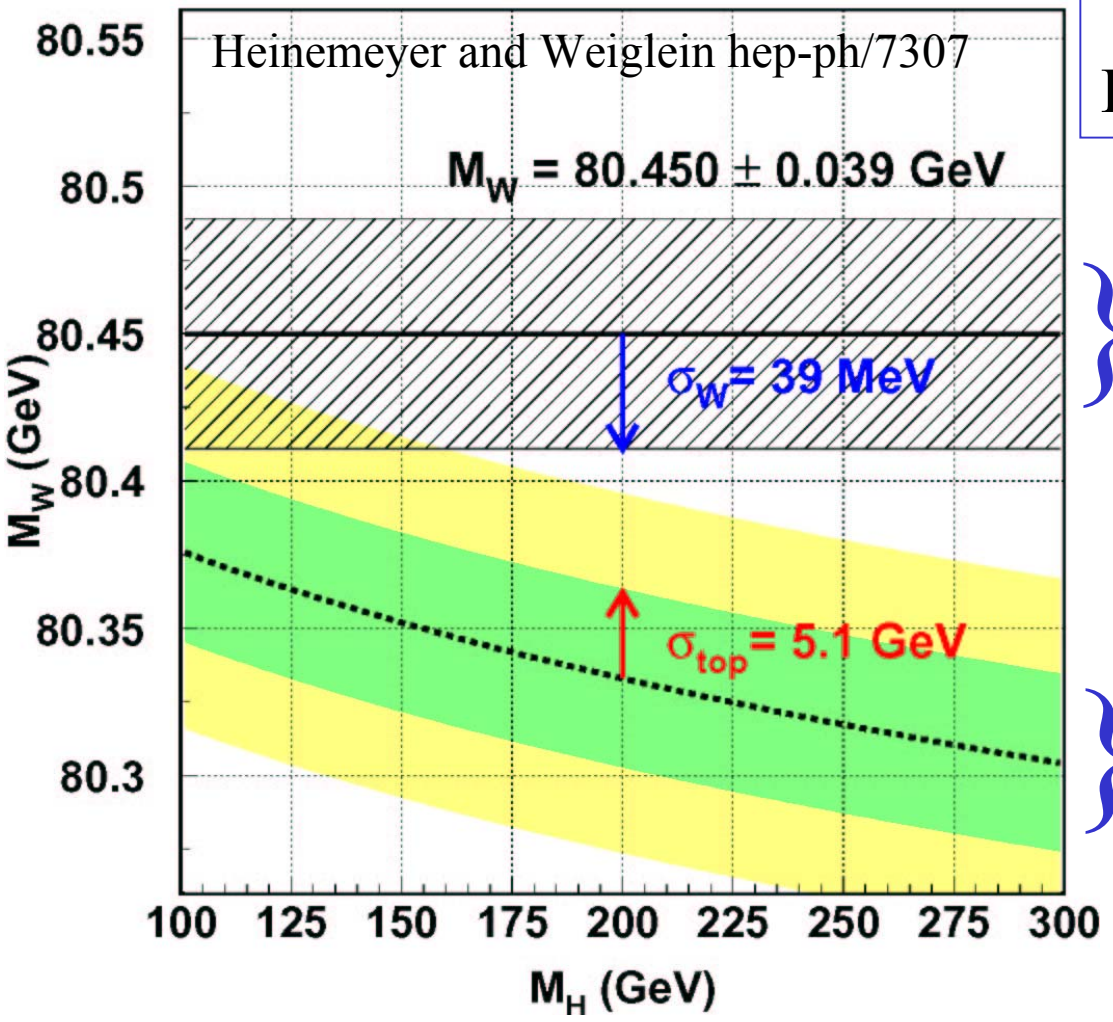
LEP Dismantling
November 2000

LEP (Geneva, Switzerland)

6 years

Startup of LHC
2006 or later

Indirect Higgs Search



Standard Model
Precision Electroweak Data

Shrink the uncertainties on M_W and M_{top}

Low mass preference for the Higgs boson