

LEP Higgs

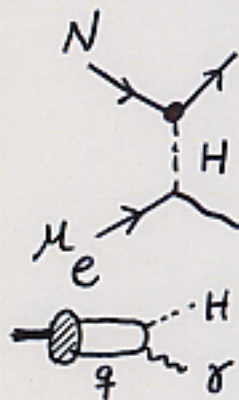
森 俊則

東京大学素粒子物理国際研究センター

Higgs Mass Limits Before LEP

- Muonic X rays
e-d/e-n scattering

M_H 0 ~ 3 MeV excluded
massless



- $\Upsilon, J/\psi \rightarrow H \gamma$
(CUSB, Crystal Ball) → invisible

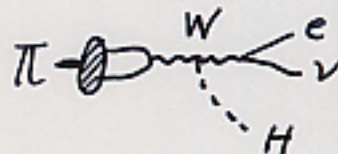
massless, 0 ~ 61 MeV

- n-N scattering
nuclear $O^+ \rightarrow O^+$

1 ~ a few MeV
2.8 ~ 11.5 MeV

- $\pi \rightarrow e^+ \nu H^0$
(SINDRUM)

10 ~ 110 MeV



- $K_L \rightarrow \pi^0 H^0$ (NA31)
 $L \rightarrow e^+ e^-$

110 ~ 2 M_μ
MeV

cancellation?

$$K \rightarrow \mu^+ \mu^-$$

2 M_μ ~ 2 M_π

- $B \rightarrow H^0 X \rightarrow \mu^+ \mu^- X$
(TASSO, JADE, CLEO)

2 M_μ ~ 3.5 GeV

Br(H⁰ → μ⁺ μ⁻) ?

$$B \rightarrow K H^0$$

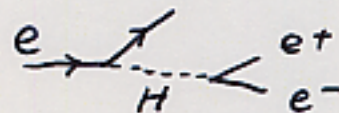
higher order
QCD ?

- $\Upsilon \rightarrow H \gamma$
(CUSB)

~ 5-6 GeV

- e⁻ beam dump

1.2 ~ 52 MeV



∴ $M_H = 0, 1.2 \sim 110 \text{ MeV} \approx \text{excluded}$
∴ $< 5 \sim 6 \text{ GeV} \approx \text{unlikely}$

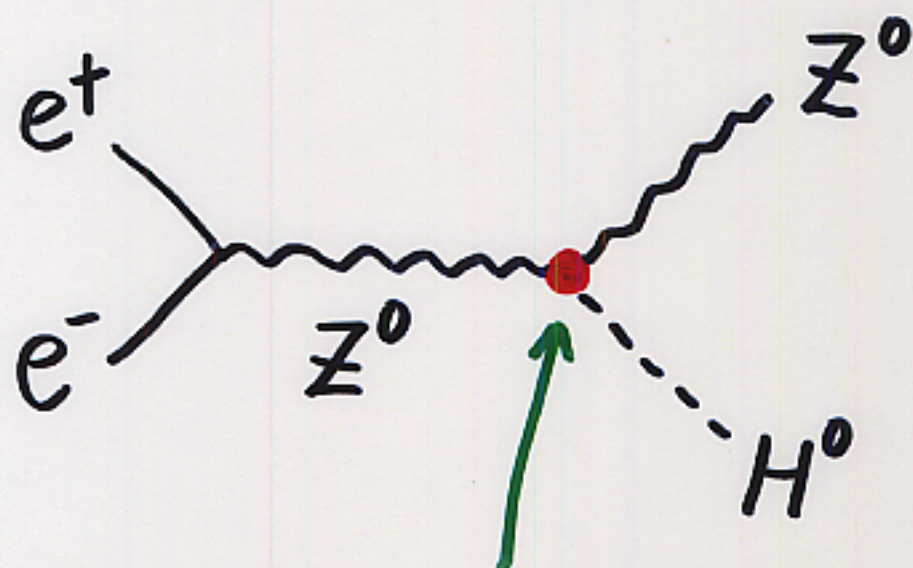
LEPでの Higgs 粒子探索

- 曖昧さのない探索が可能

- 重い Higgs ($> 2m_b$) 探索できる

唯一の場所

→ Tevatron, LHC, JLC



Z^0 に質量与える

ヒッグス粒子の質量

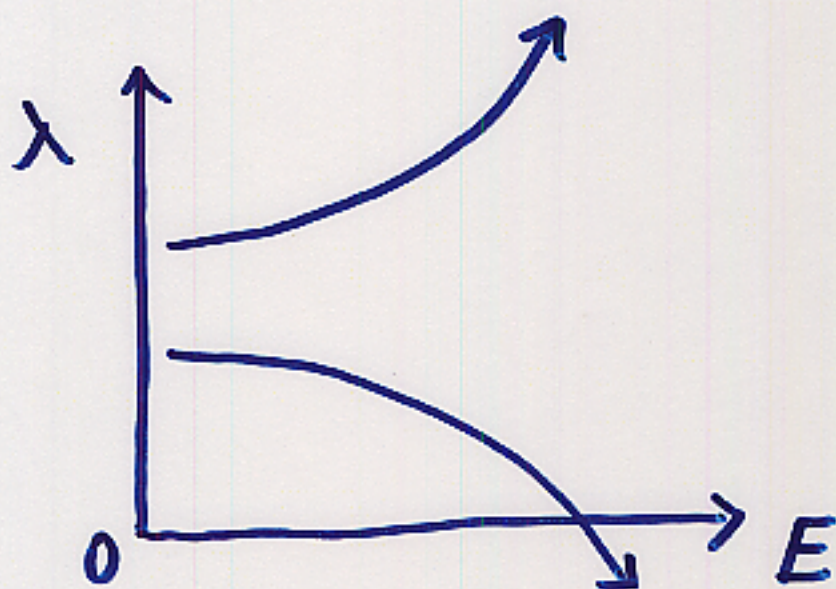
$$m_H = \sqrt{2\lambda} v$$



質量大 → 相互作用大

高エネルギーで破たん

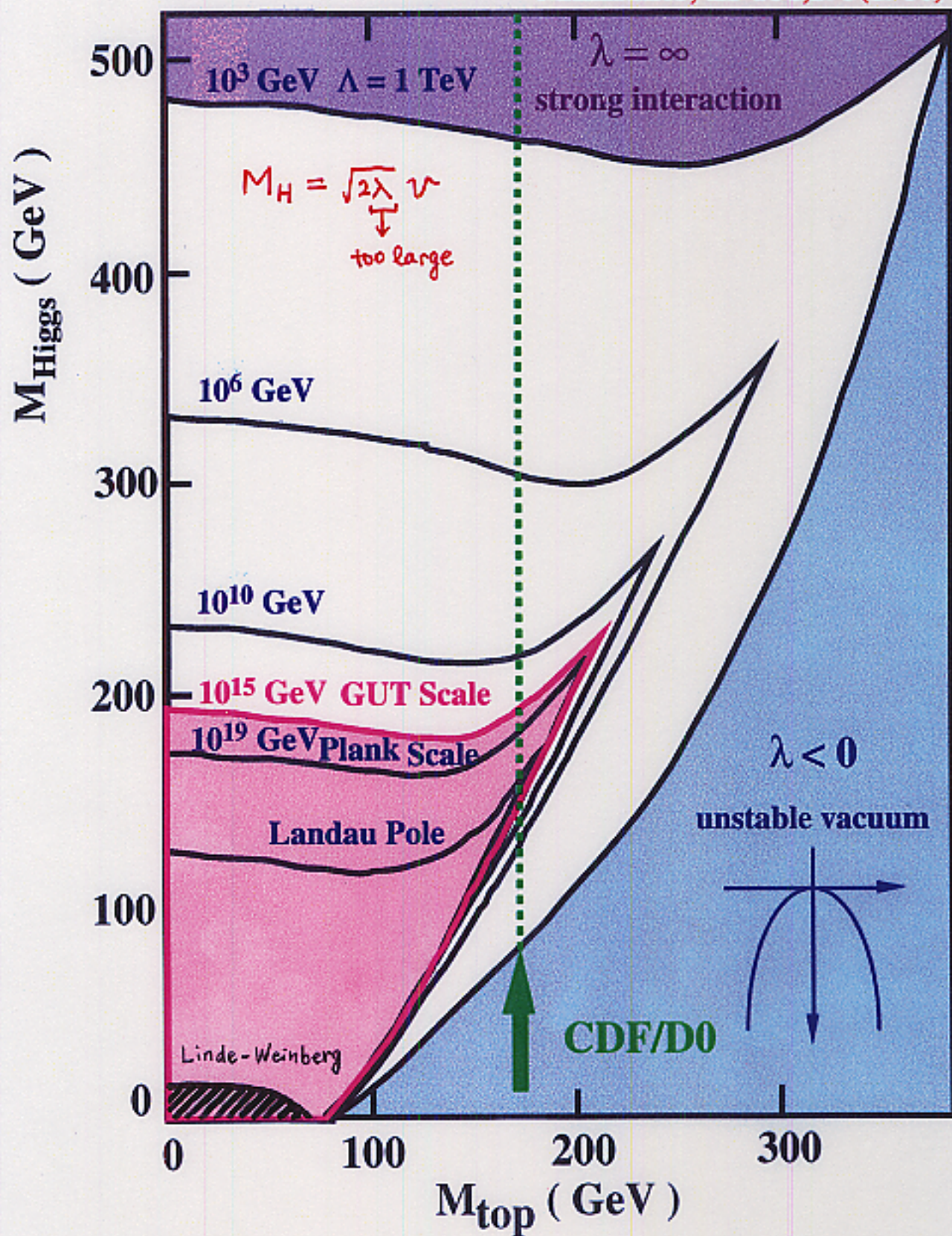
質量小 → 真空が不安定



“大統一理論”
~ 10^{16} GeV

130 ~ 200 GeV

M.Lindner, ZPC31,295(1986)



超对称性

tree level: $M_{h^0} < M_{Z^0}$

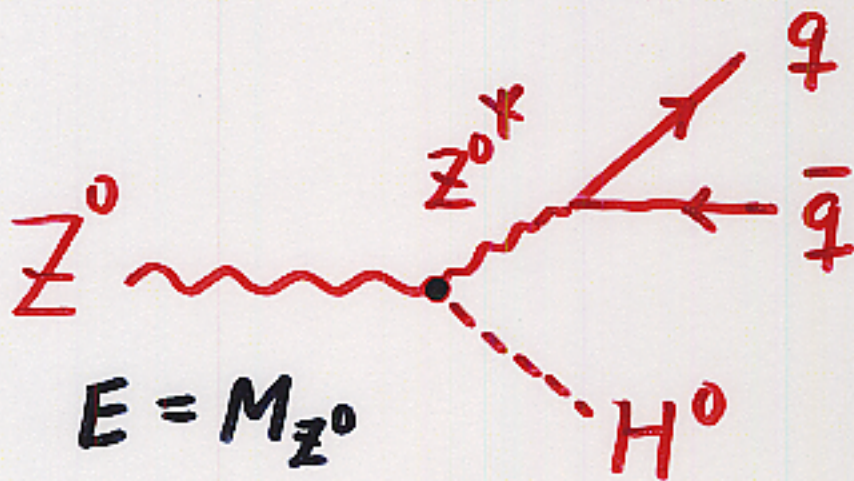
Radiative Corrections

$$M_{h^0} \lesssim 140 \text{ GeV}$$

ヒッグスの生成方法

• Z^0 粒子の崩壊

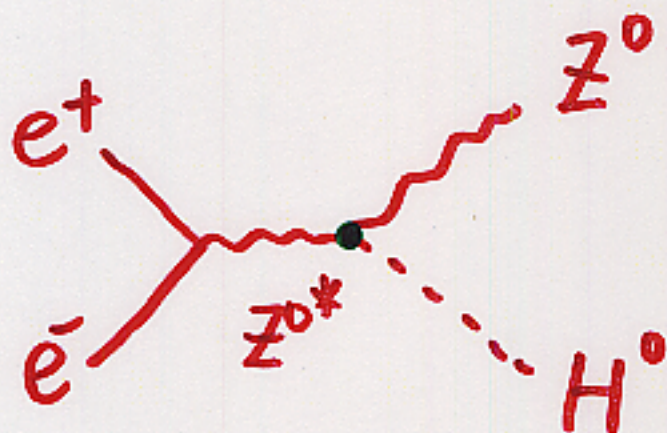
LEP-I



$$M_H < M_Z$$

• $Z^0 H^0$ 生成

LEP-II



$$E \geq M_{Z^0} + M_{H^0}$$

LEP-I vs. LEP-II

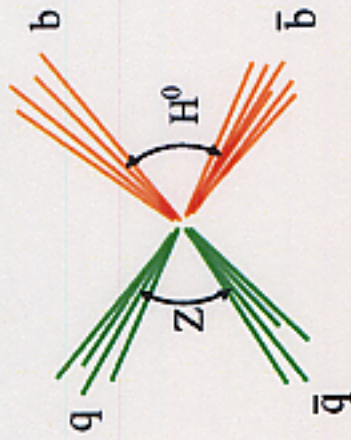
● LEP-I

- Z^0 の崩壊から探索: $0 \sim 60 \text{ GeV}$
- バックグラウンドがほとんどない
(4 ジェットを除く)

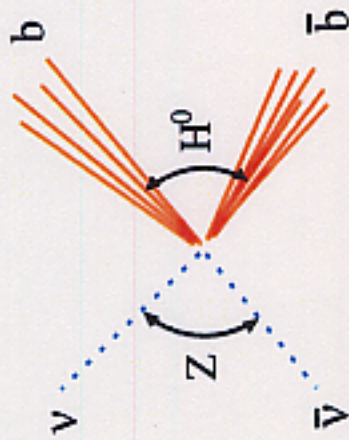
● LEP-II

- Z^0 と対生成: $E_{CM} \gtrsim M_Z + M_H$
- 4 ジェットも探索
 - kinem. constraints (質量の再構成)
 - b-tag
- バックグラウンド多い (4-fermion)
 ZZ, WW

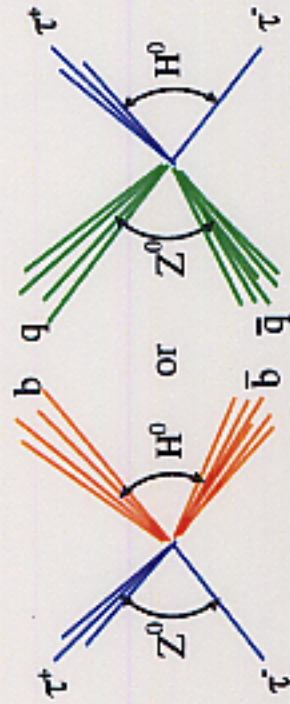
Event Topology



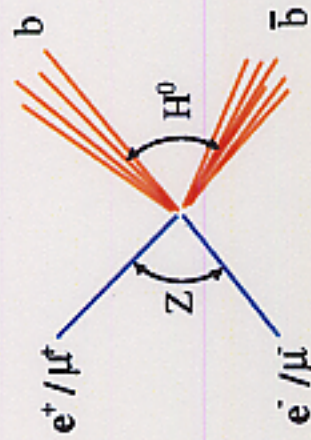
Four Jets Channel (~55%)
 $e^+e^- \rightarrow Z^0 H^0 \rightarrow q\bar{q}b\bar{b}$



Neutrino Channel (~15%)
 $e^+e^- \rightarrow Z^0 H^0 \rightarrow \nu\bar{\nu}b\bar{b}$

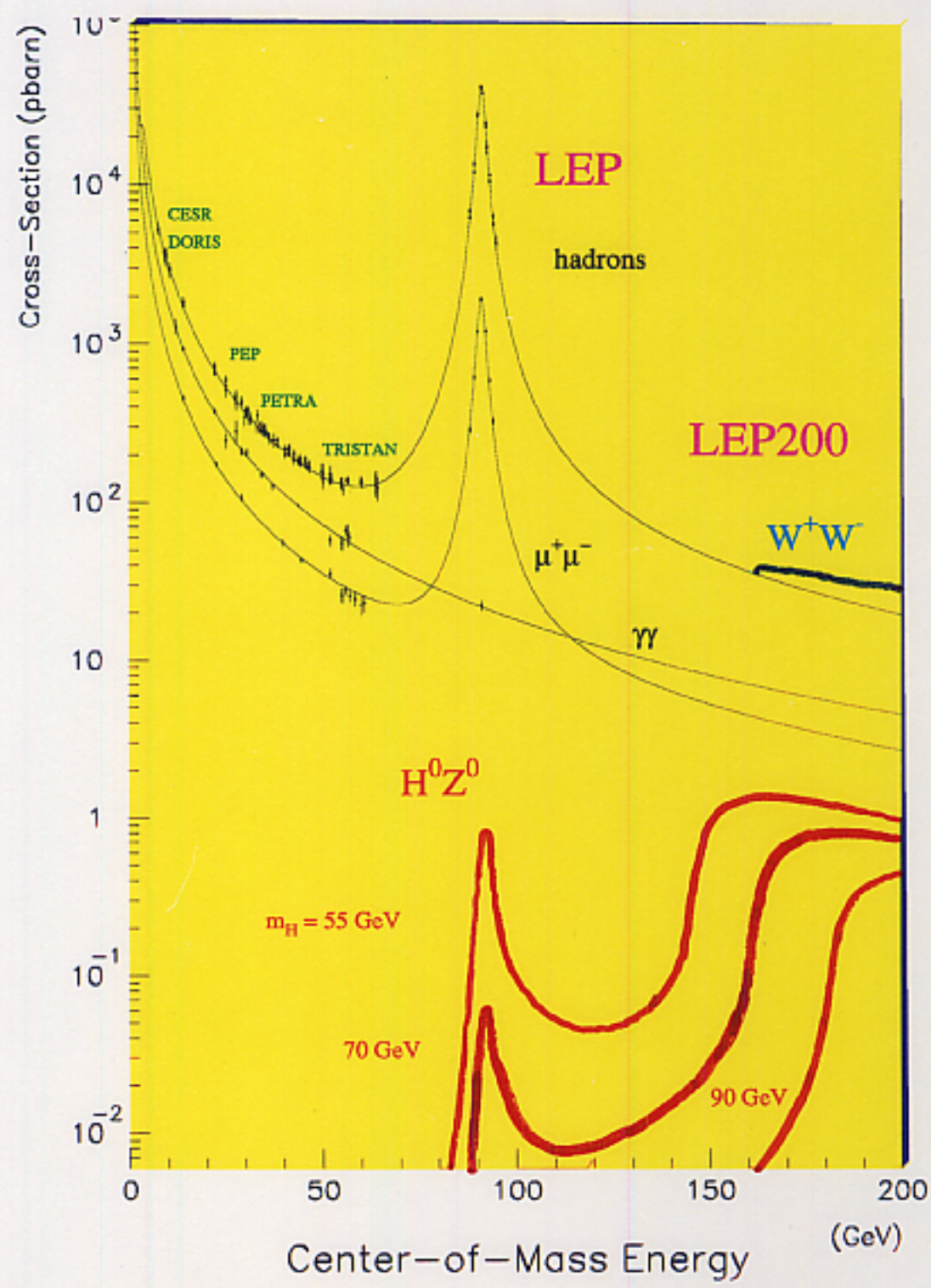


Tau Channels (~3%+~5%)
 $e^+e^- \rightarrow Z^0 H^0 \rightarrow \tau^+\tau^-b\bar{b}, q\bar{q}\tau^+\tau^-$

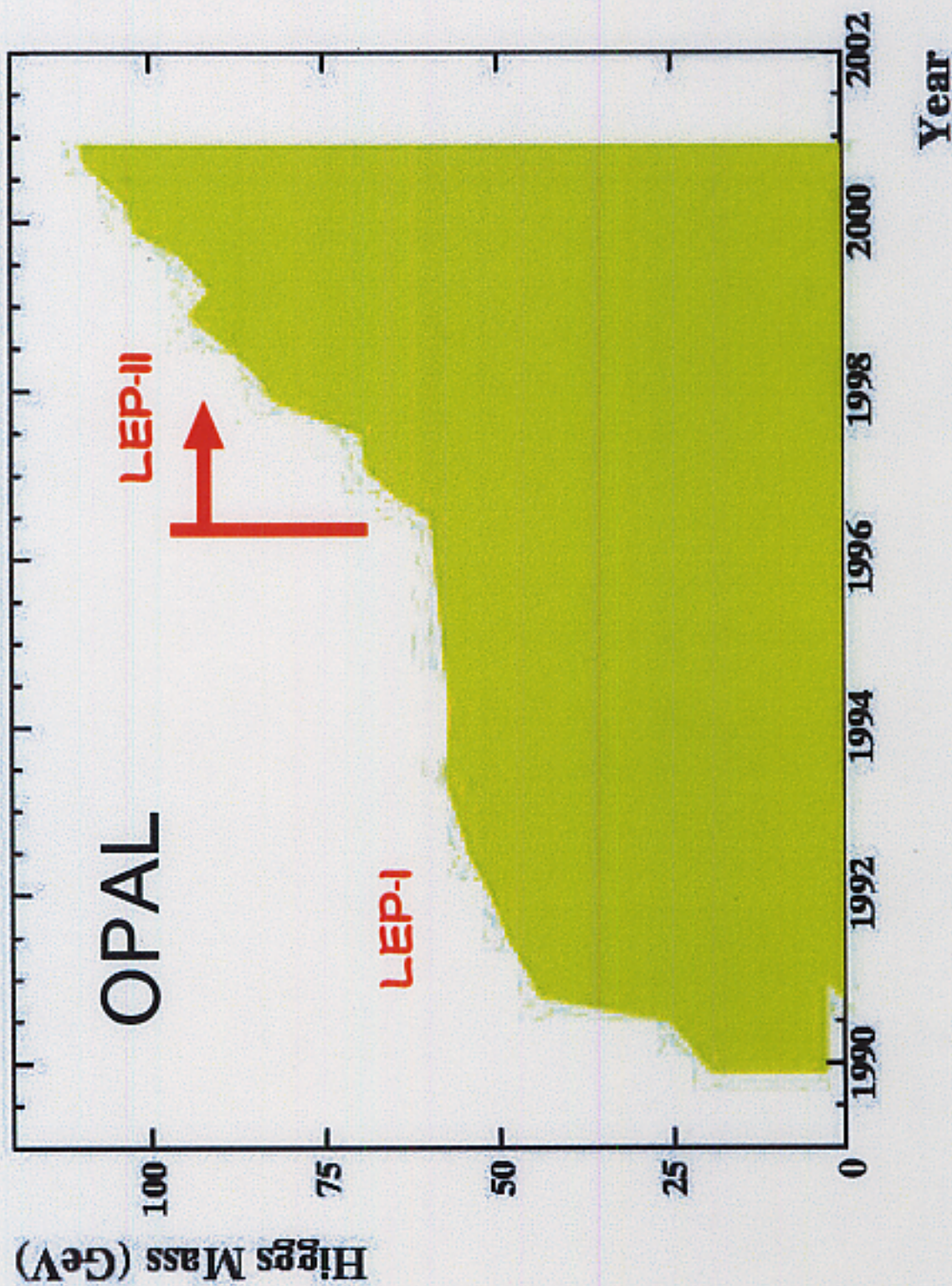


Electron and Muon Channels
 (~3%+~3%)
 $e^+e^- \rightarrow Z^0 H^0 \rightarrow \ell^+\ell^-b\bar{b}$

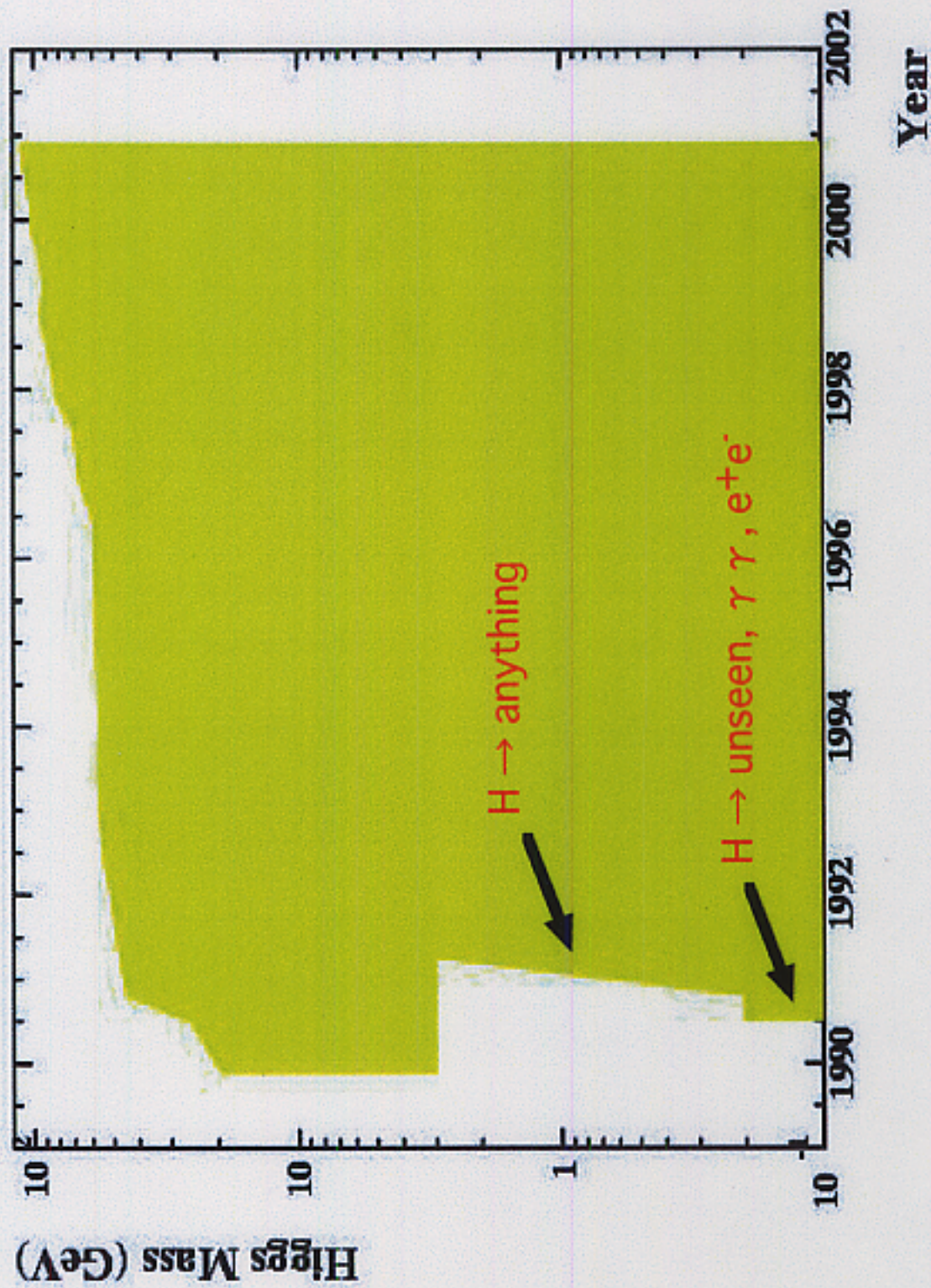
LEP-I vs. LEP-II



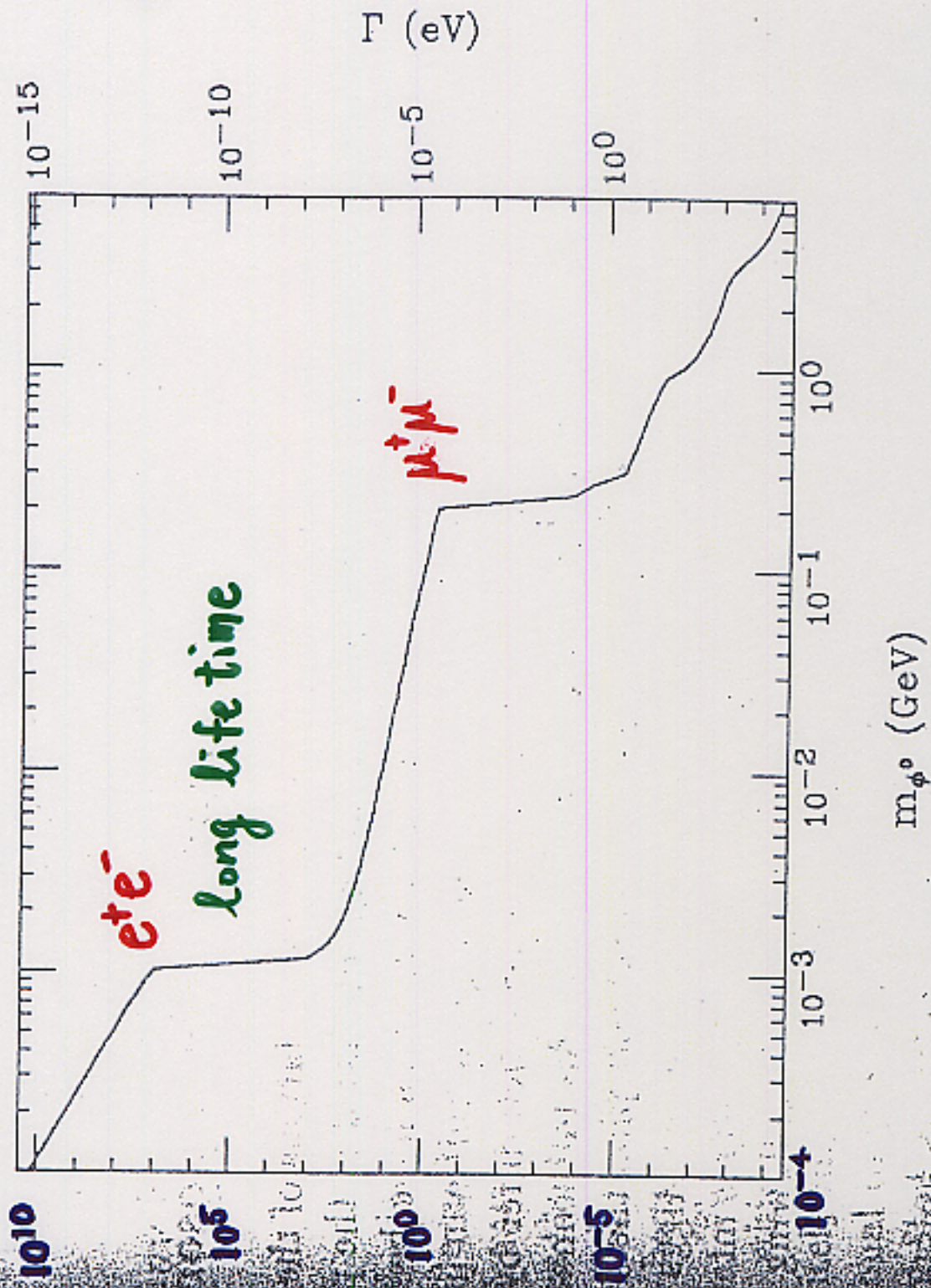
History of Higgs Mass Limits



History of Higgs Mass Limits



Light Higgs Boson Lifetime and Width



22
(cm)

Very Light Higgs $< 2 \cdot m_\mu$

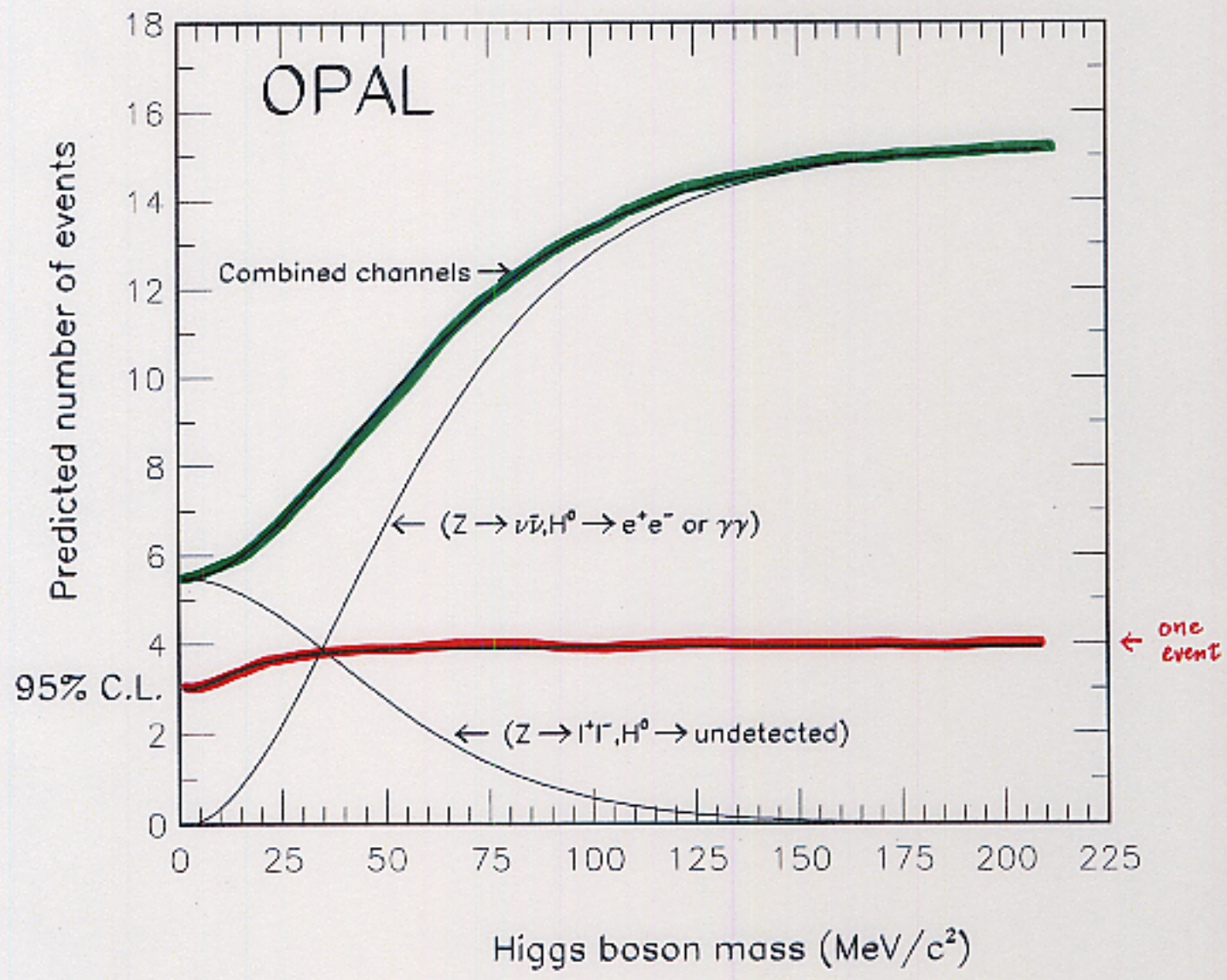
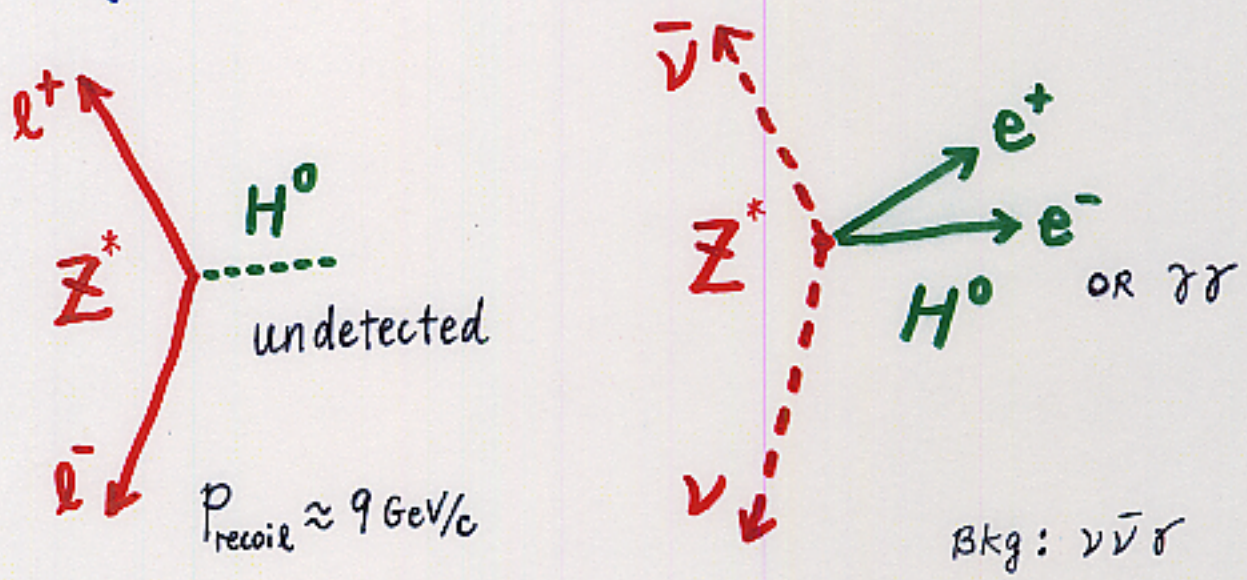


FIGURE 4

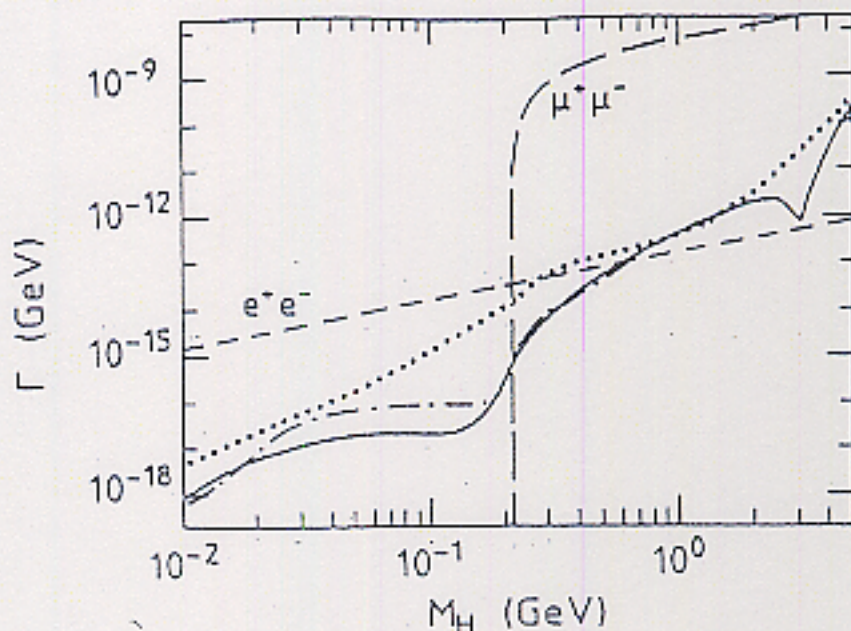


Figure 3. The partial decay widths of H to $\gamma\gamma$, and for comparison, to e^+e^- and $\mu^+\mu^-$ (both dashed). The solid line is for a three generation model, with $m_u = 5$ MeV, $m_d = 10$ MeV and $m_s = 150$ MeV; the dotted-dashed line is also for a three generation model, with $m_u = 10$ MeV, $m_d = 10$ MeV and $m_s = 200$ MeV; and the dotted line is for a four generation model, with $m_u = 5$ MeV, $m_d = 10$ MeV and $m_s = 150$ MeV.

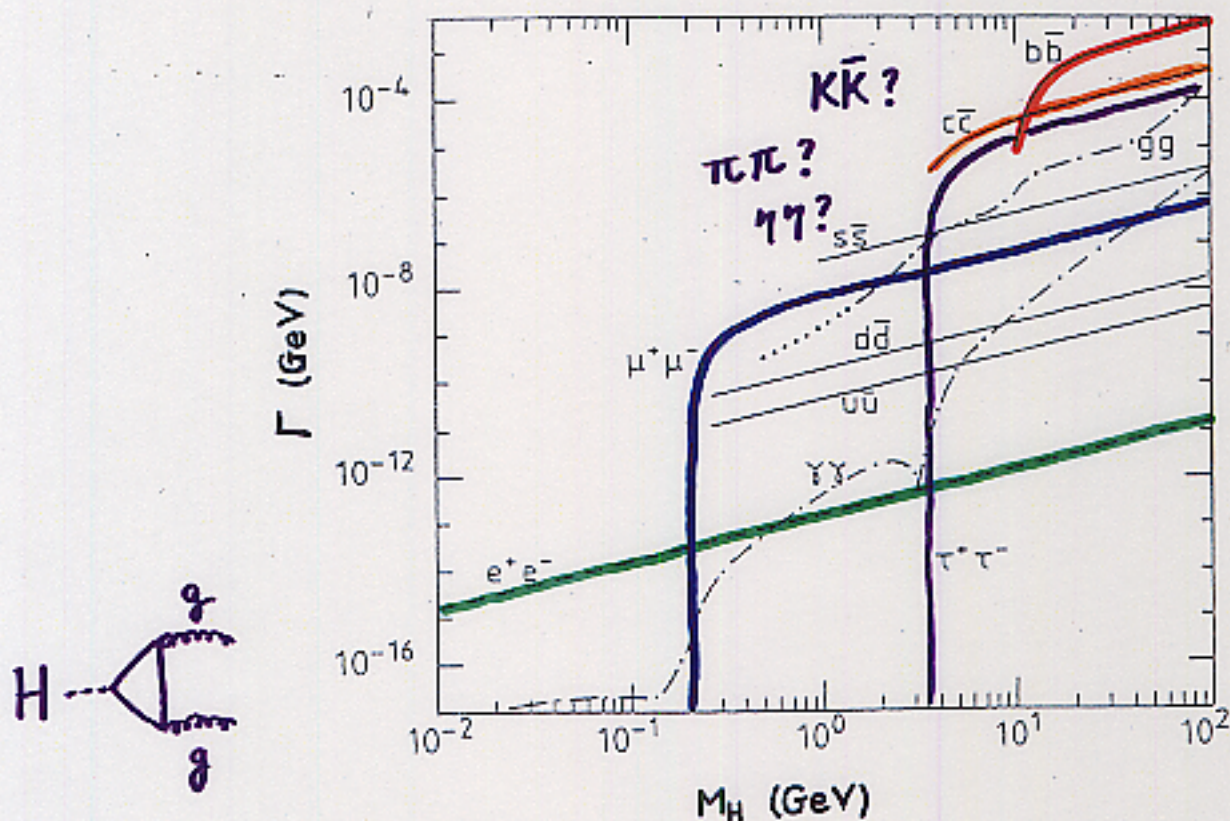
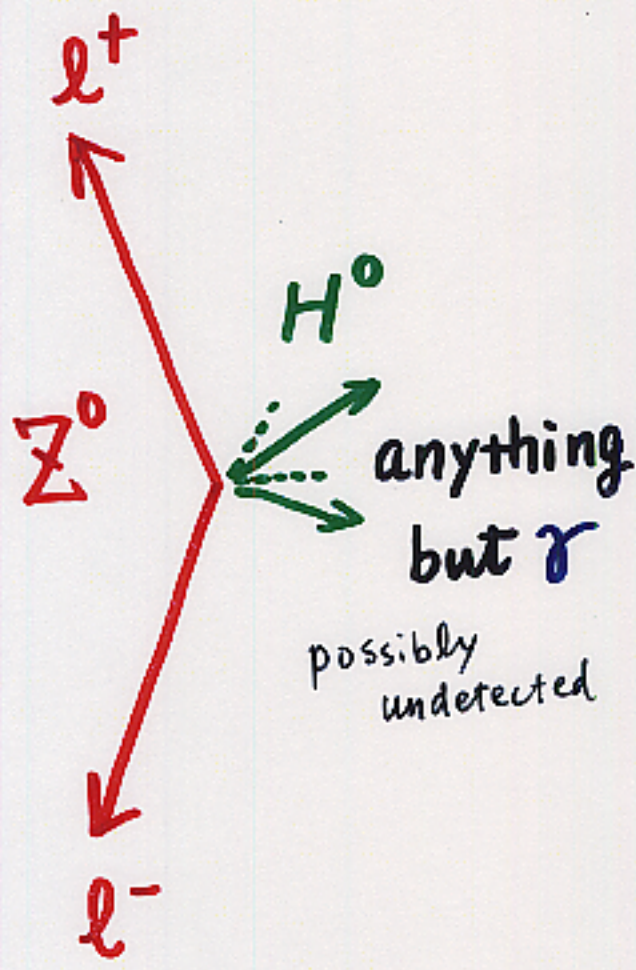


Figure 4. The approximate partial decay widths of H to all 2-body partonic decay modes. We use $m_u = 5$ MeV, $m_d = 10$ MeV, $m_s = 150$ MeV, $m_c = 1.5$ GeV, $m_b = 5$ GeV, and $m_t = 60$ GeV. The dashed curves show decays to charged leptons, the solid curves the decay into hadrons as computed from the contributions to each quark separately. The dotted-dashed curves illustrate the two gluon and two photon decays; for gluons we use the constant value $\alpha_s = 0.15$, with the understanding that the partial width given should be scaled by $\left(\frac{\alpha_s}{0.15}\right)^2$.

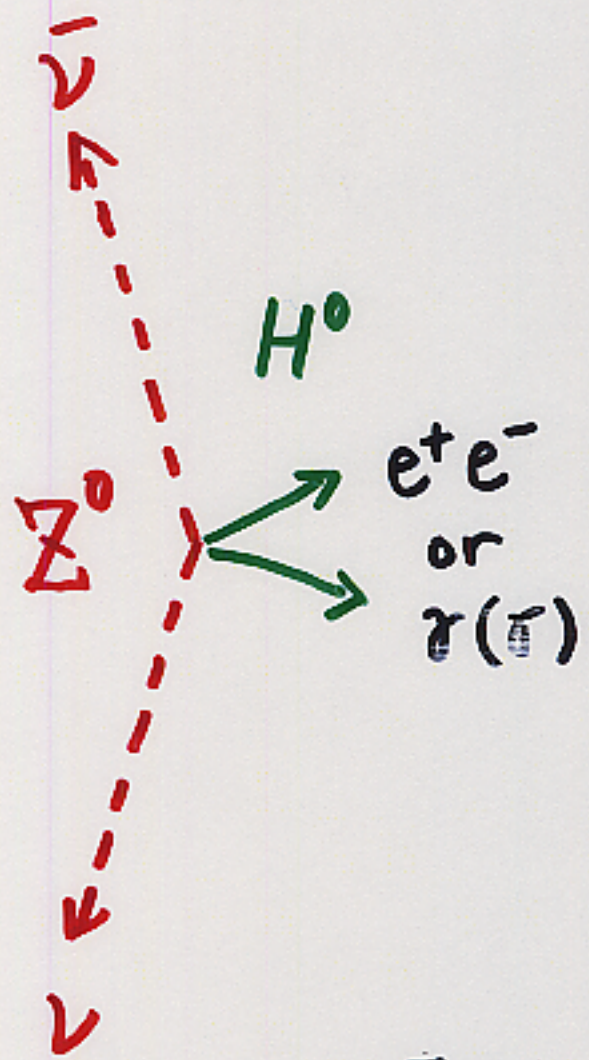
Light Higgs

$$\leq 2 m_b$$

$$\approx 11 \text{ GeV}$$



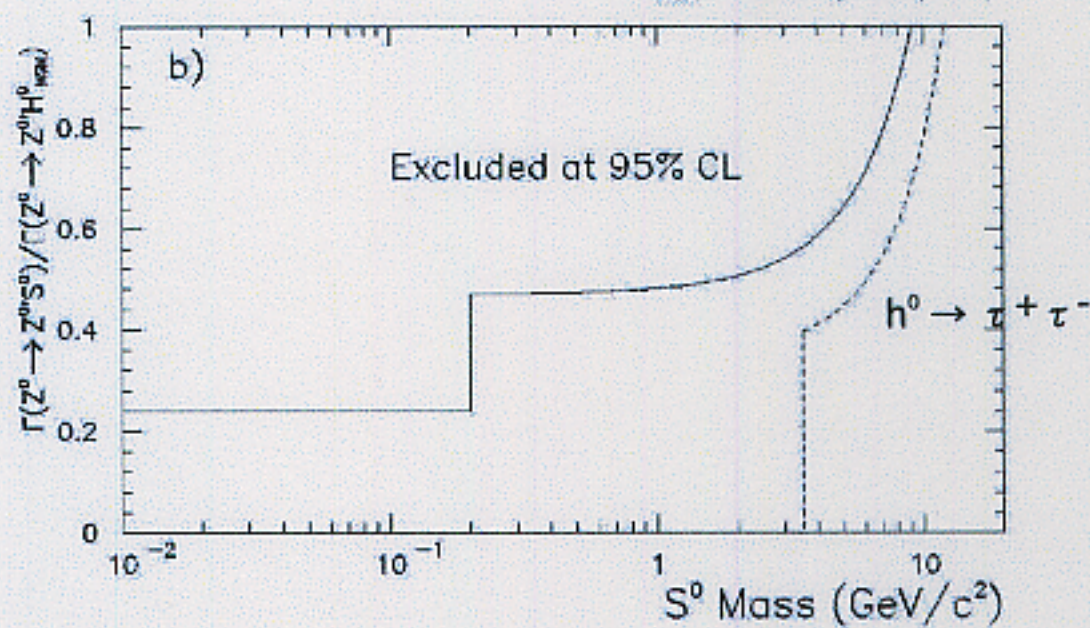
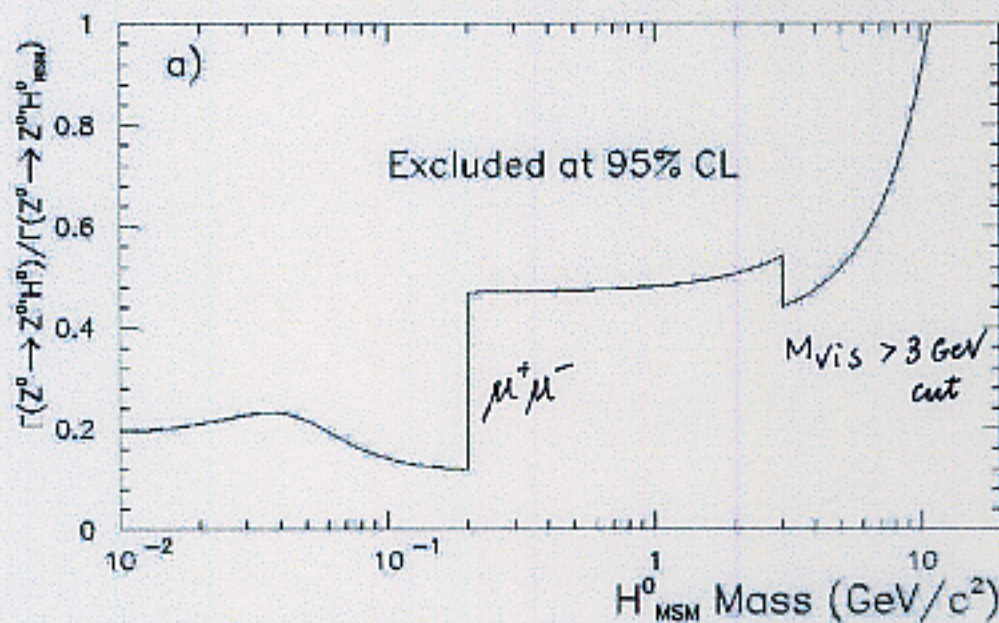
$$\text{Bkg: } l^+ l^- \underline{\gamma}$$



$$\text{Bkg: } \nu \bar{\nu} \gamma$$

Decay Mode Indep. Search

Decay Mode Indep. Search



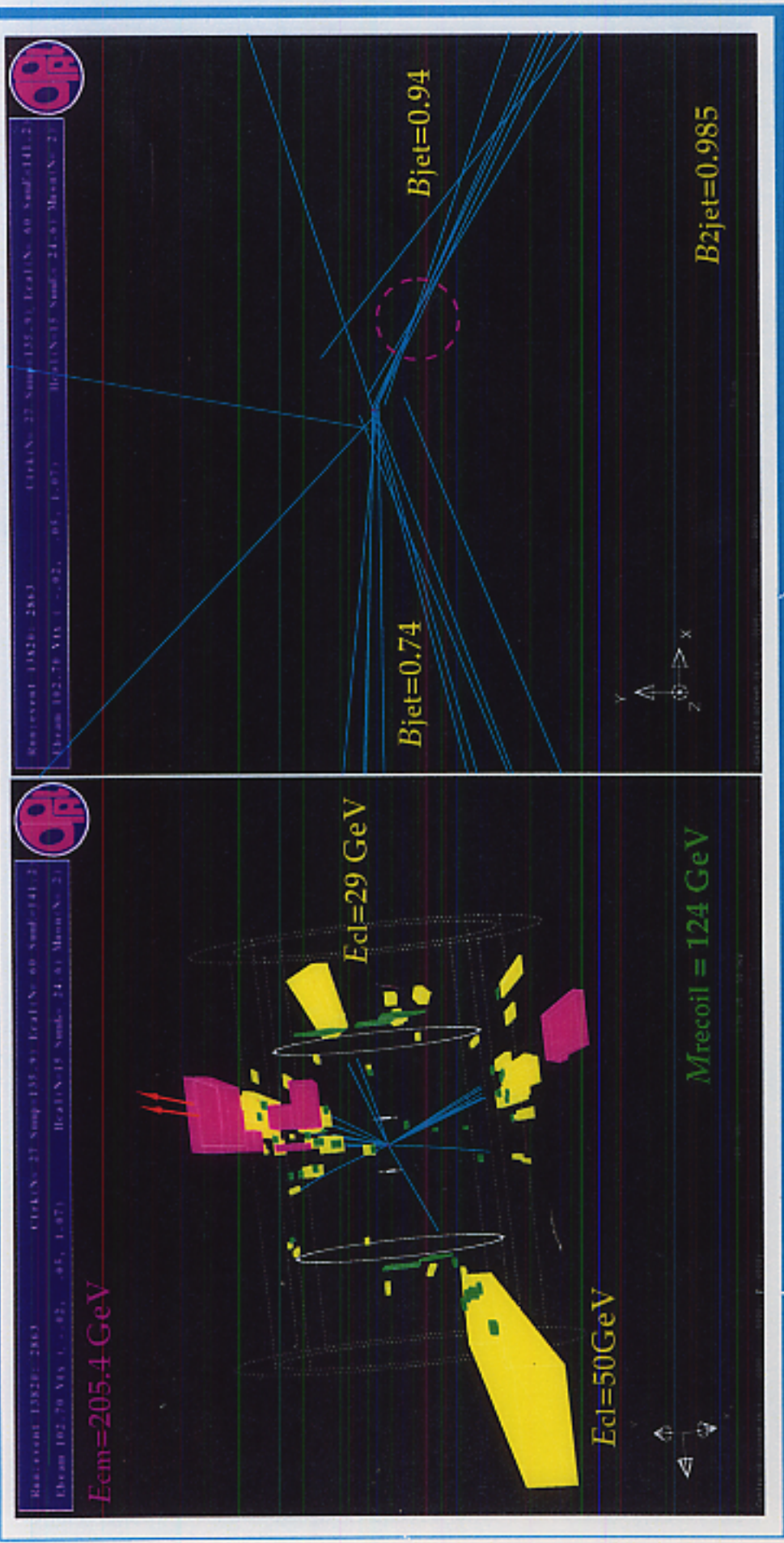
LEP-II の Higgs 探索

Essential:

- b-tag
- M_H reconstruction
- Beam Energy

Tagging b-quark jets

Candidate in the Electron Channel



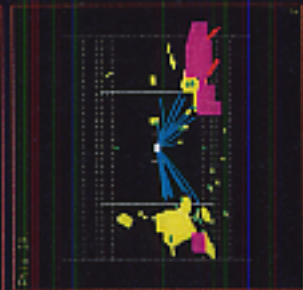
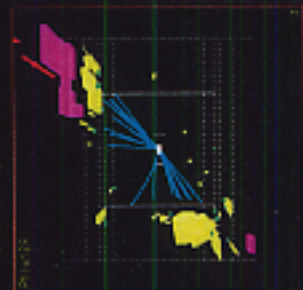
B hadrons travel $\sim \mathcal{O}(\text{mm})$ before decaying

Candidate in the Missing Energy Channel

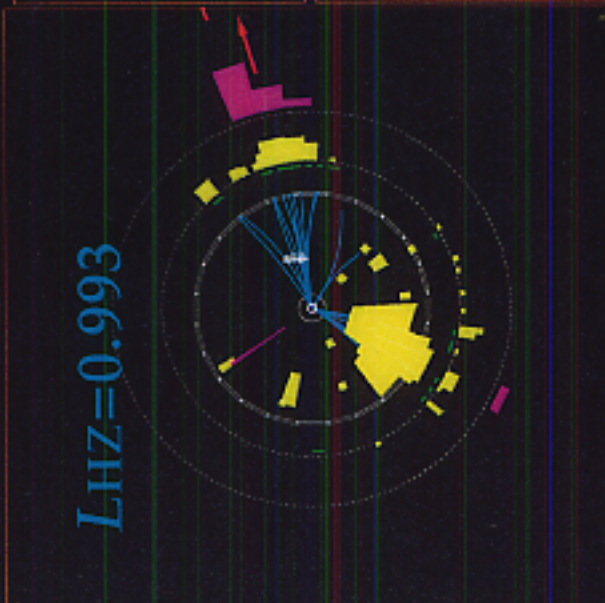
Run: event 14419, 3312 CPU: 42 Samps, 47.73 CPU: 49 Samps, 64.8
Beam: 105.36 Vtx z: .06, .87, 1.82 Beam: 9 Samps, 16.41 Beam: 9 Samps, 16.41 Beam: 9 Samps, 16.41 Beam: 9 Samps, 16.41 Beam: 9 Samps, 16.41

Run: event 14419, 3312 CPU: 42 Samps, 47.73 CPU: 49 Samps, 64.8
Beam: 105.36 Vtx z: .06, .87, 1.82 Beam: 9 Samps, 16.41 Beam: 9 Samps, 16.41 Beam: 9 Samps, 16.41 Beam: 9 Samps, 16.41

3-D view - plane of Transverse



3-D view - plot of z vs. t

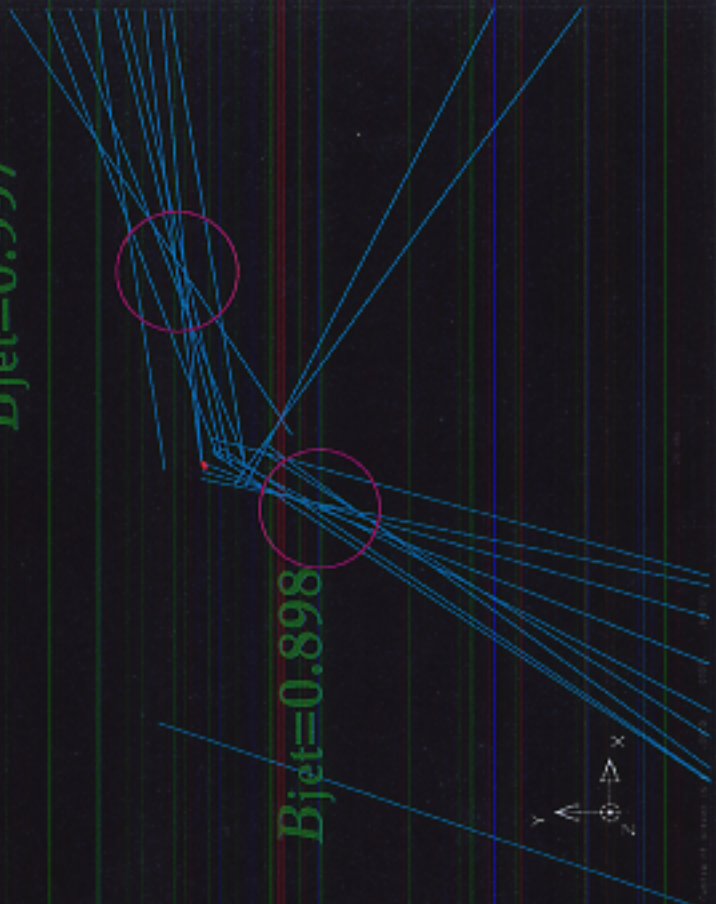


$LHZ=0.993$

$B_{jet}=0.997$

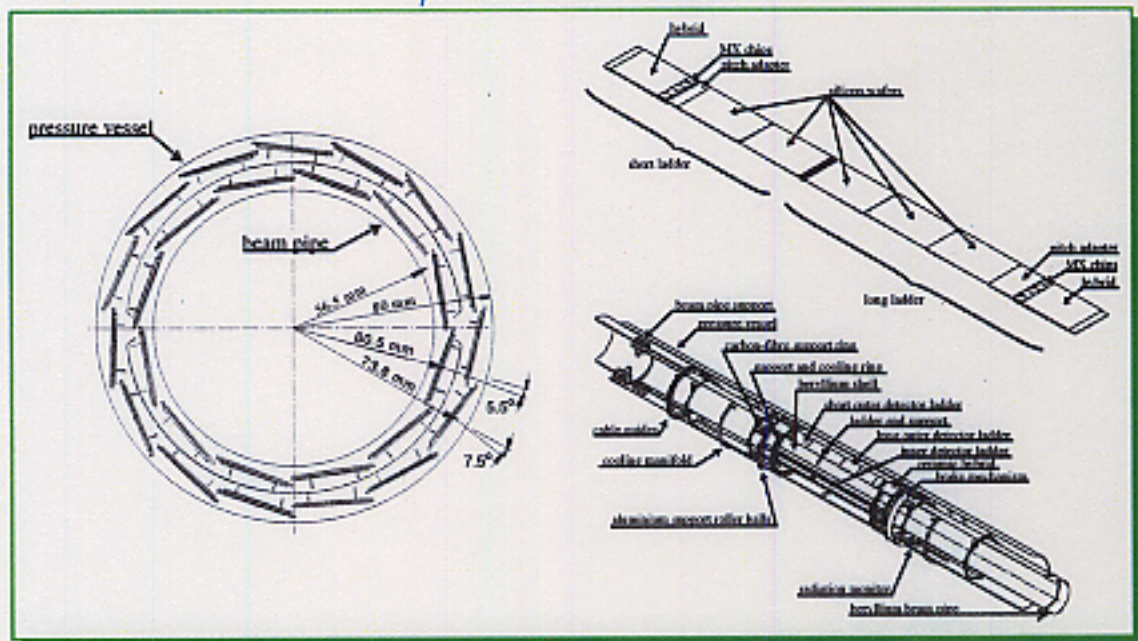
$B_{jet}=0.898$

$m_{rec}=97.1$

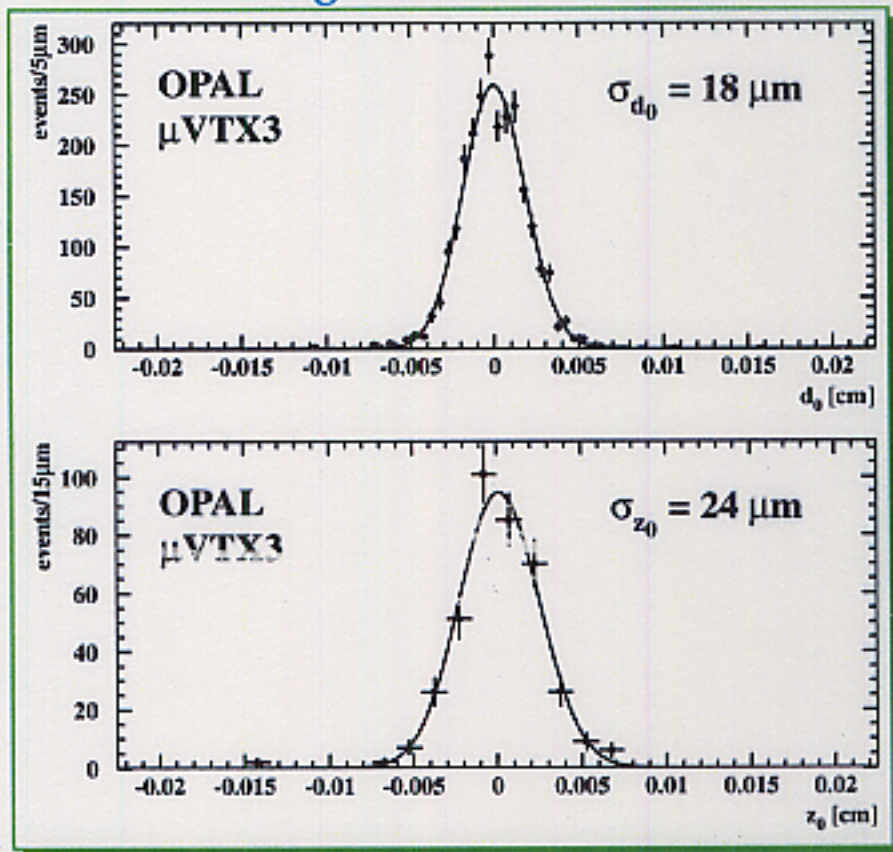


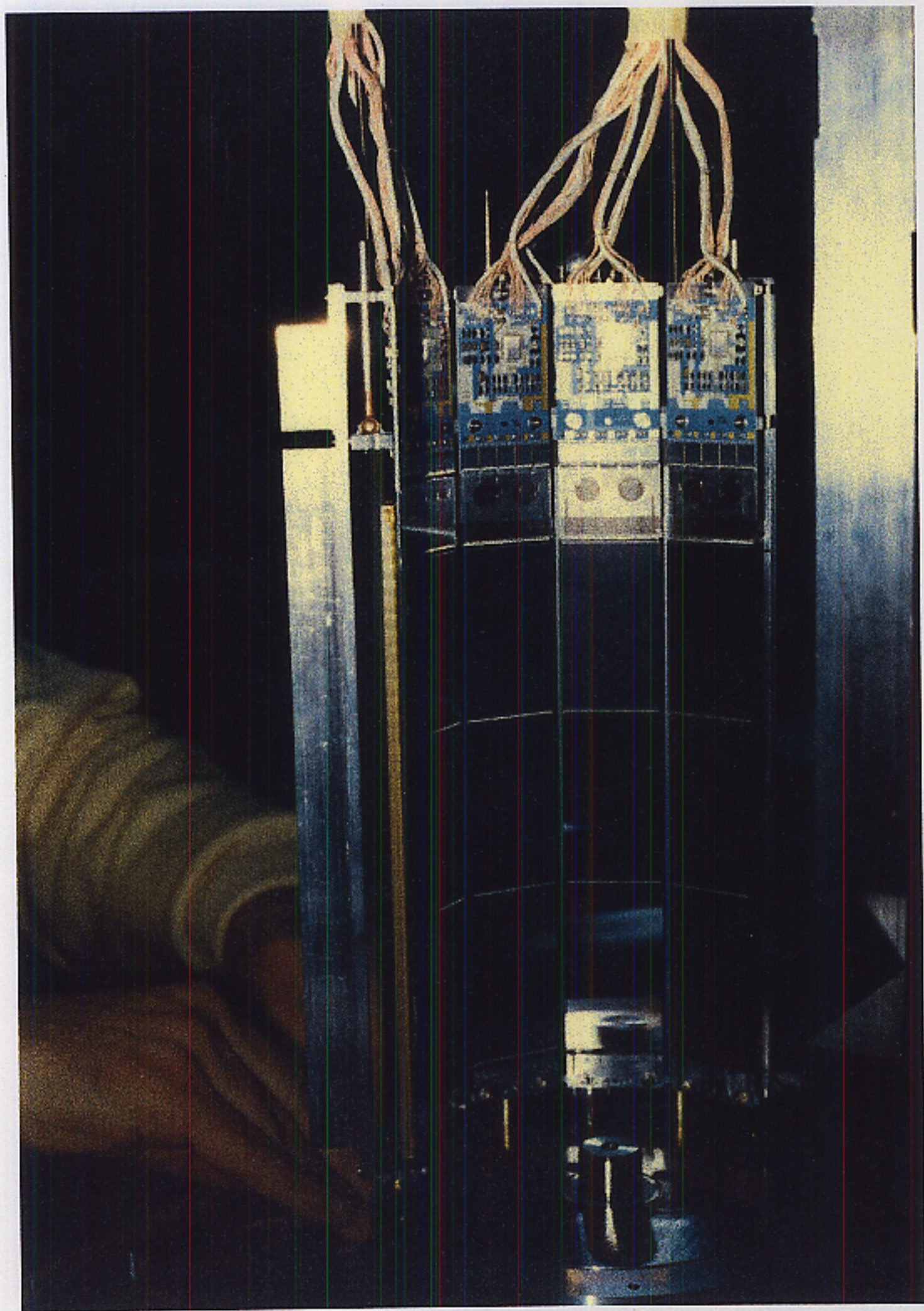
Silicon Micro Strip Detector

μ VTX Detector



Tracking Resolution with SI





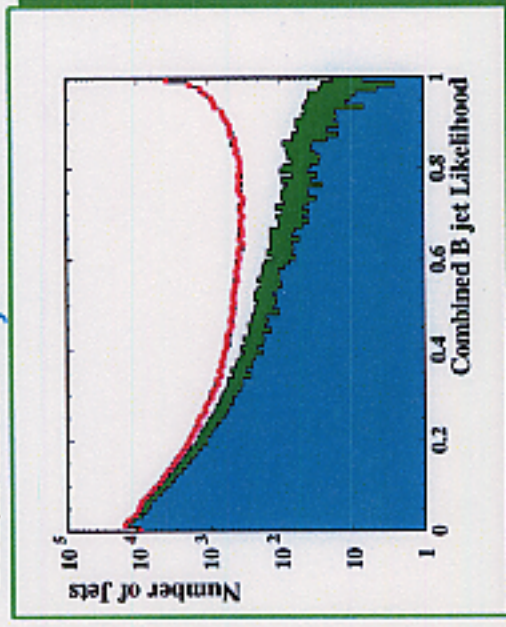
Tagging b-Quark Jets @ OPAL

- Lifetime Artificial Neural Network
 - Impact Parameter Likelihood $\times 2$
 - Secondary Vertex Likelihood $\times 2$
- Lepton p_t
- Kinematic Artificial Neural Network
 - Jet C-parameter
 - Jet Sphericity Vector Direction
 - Number of Particle in Jet

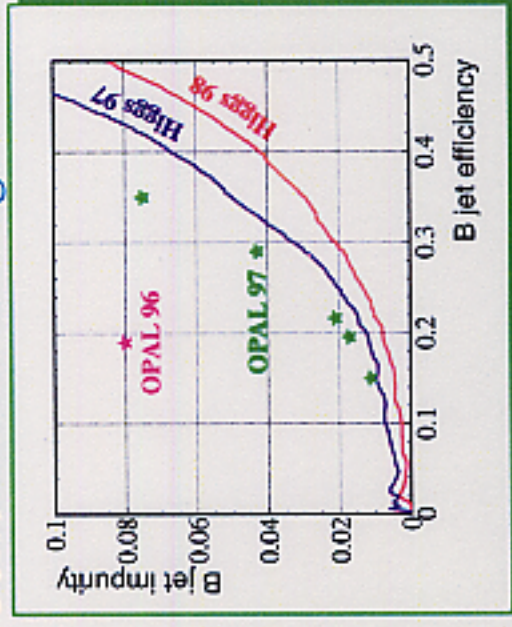


Un-binned Likelihood

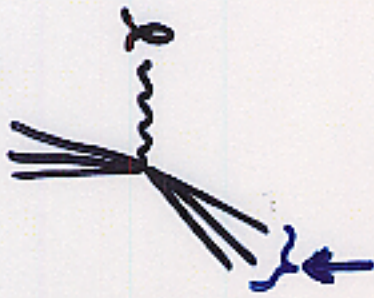
Combined B-jet Likelihood



Performance of B-tag @ OPAL



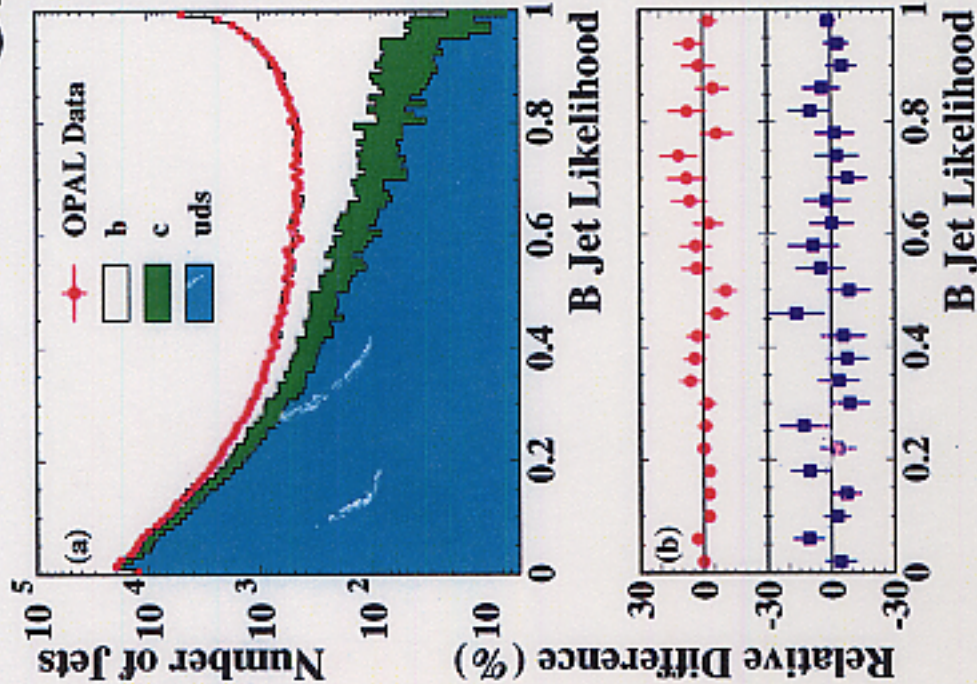
b-tagged



Look

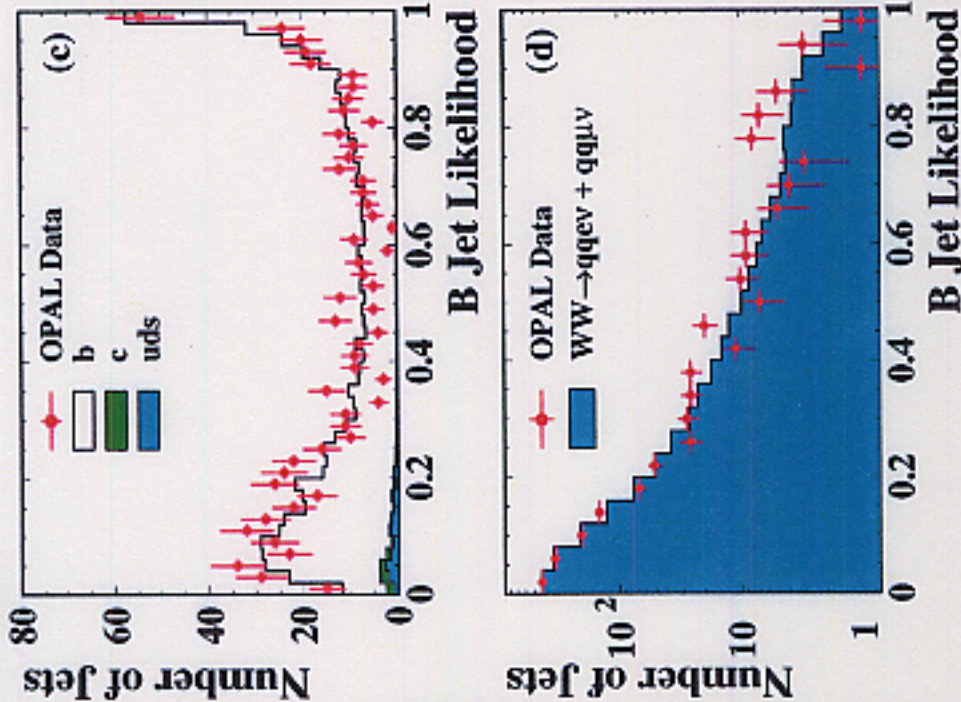
$W^+W^- \rightarrow q\bar{q}l\nu$

OPAL



@ Z⁰

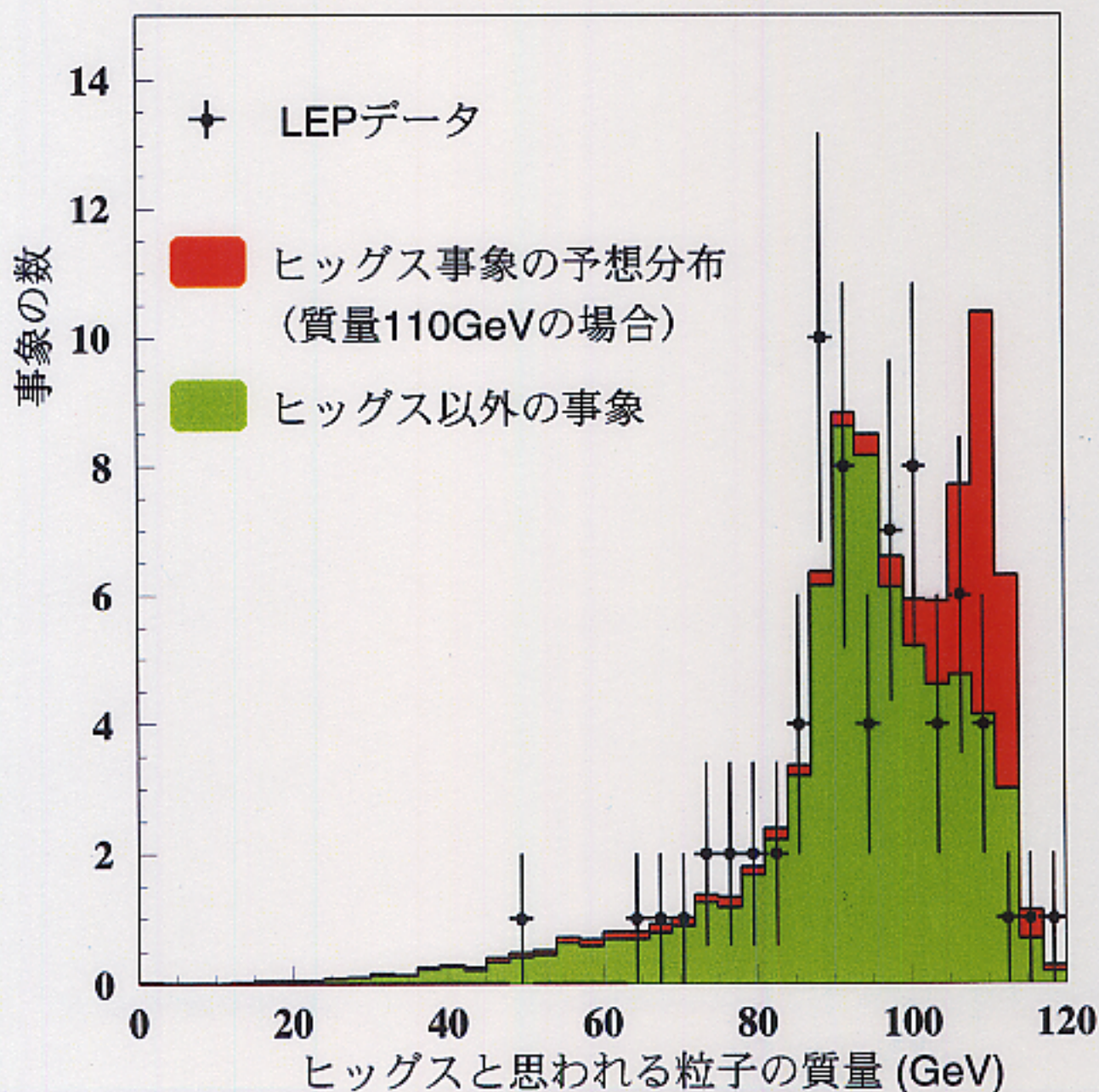
$\frac{\text{data}}{\text{MC}}$



b-tag performance / modelling

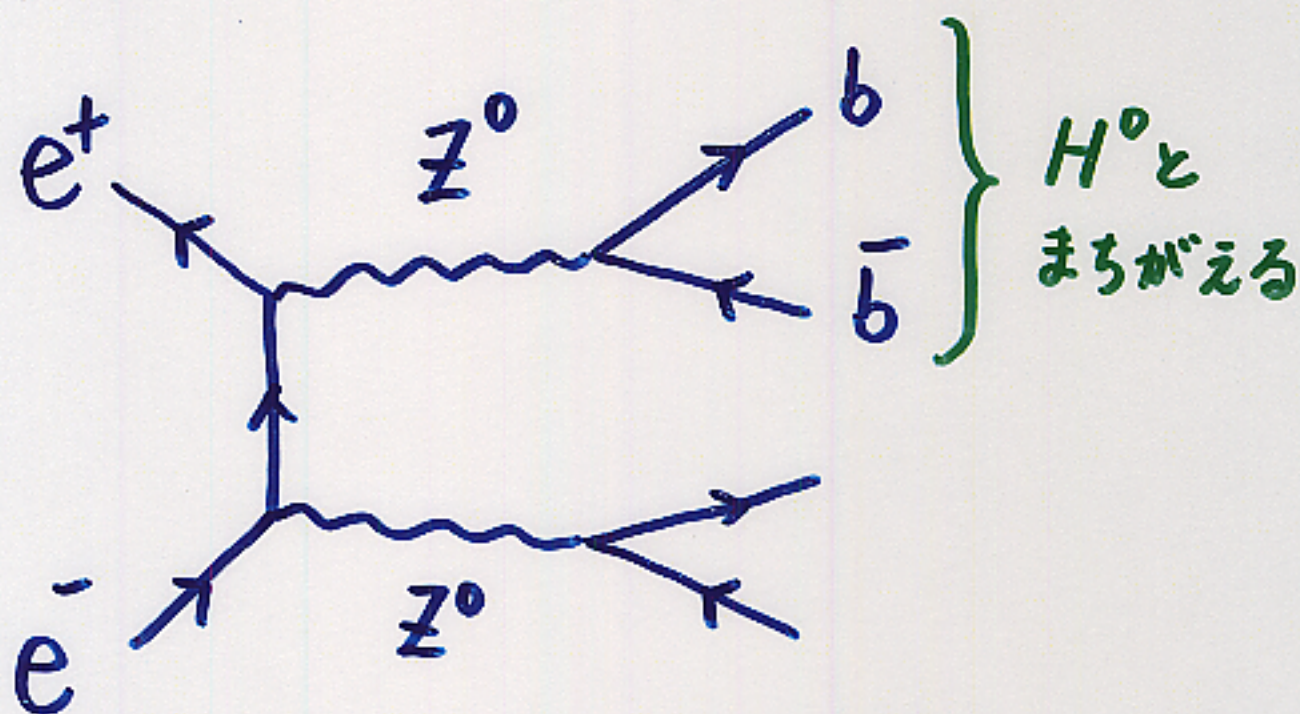
M_H Reconstruction

2000年夏



区別できない

「バックグラウンド」事象



$M \approx M_{Z^0}$ となる

質量測定重要

Mass Reconstruction

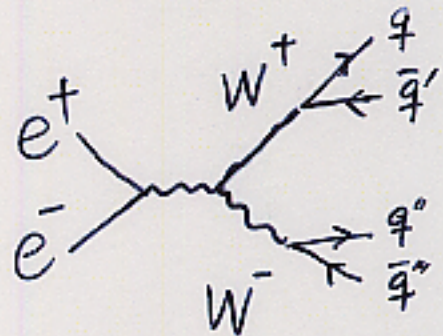
• ジェット・エネルギー

- Kinematical Fit

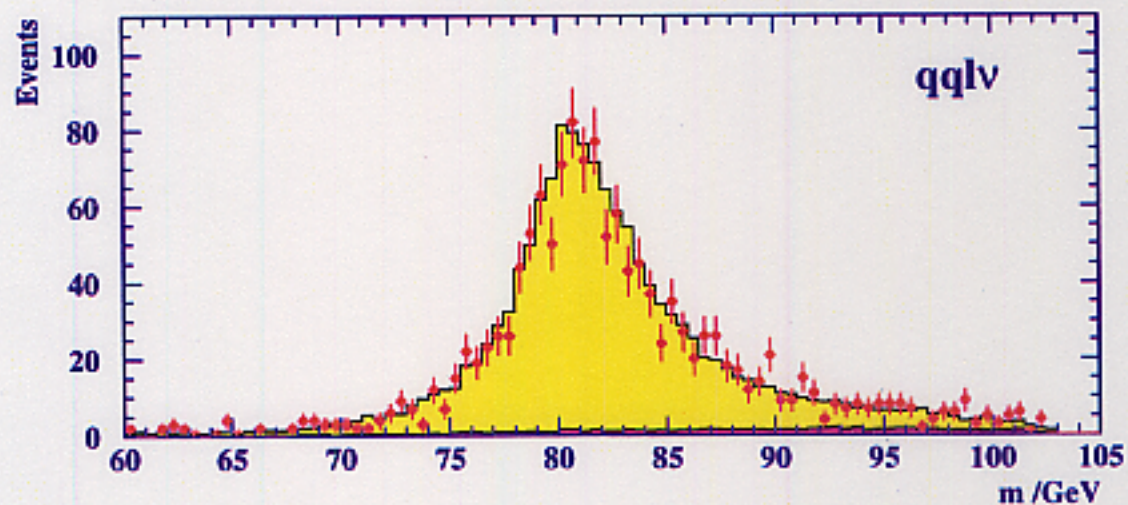
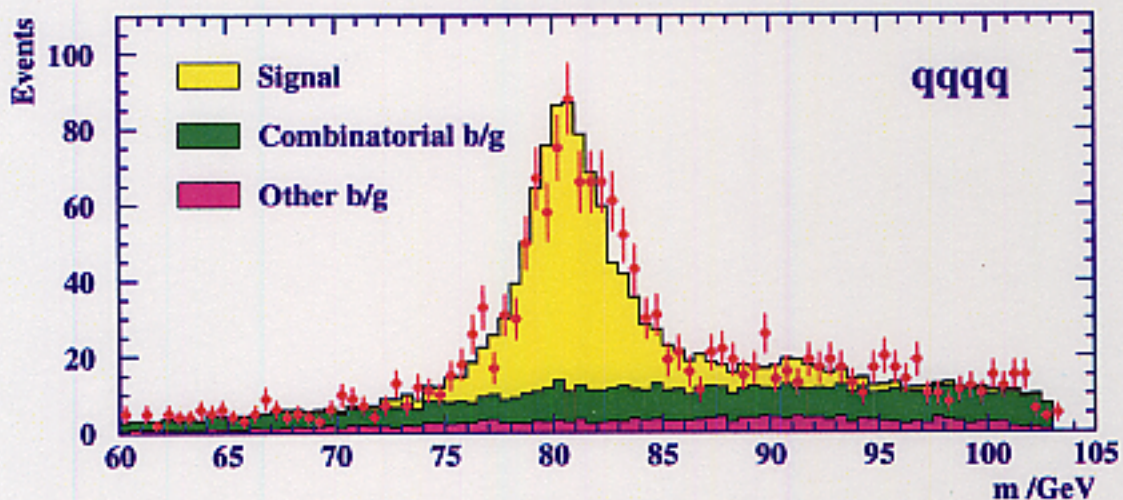
Mass Resolution: 10 GeV \rightarrow 2–5 GeV

- W Mass Reconstruction

Negligible Bias:

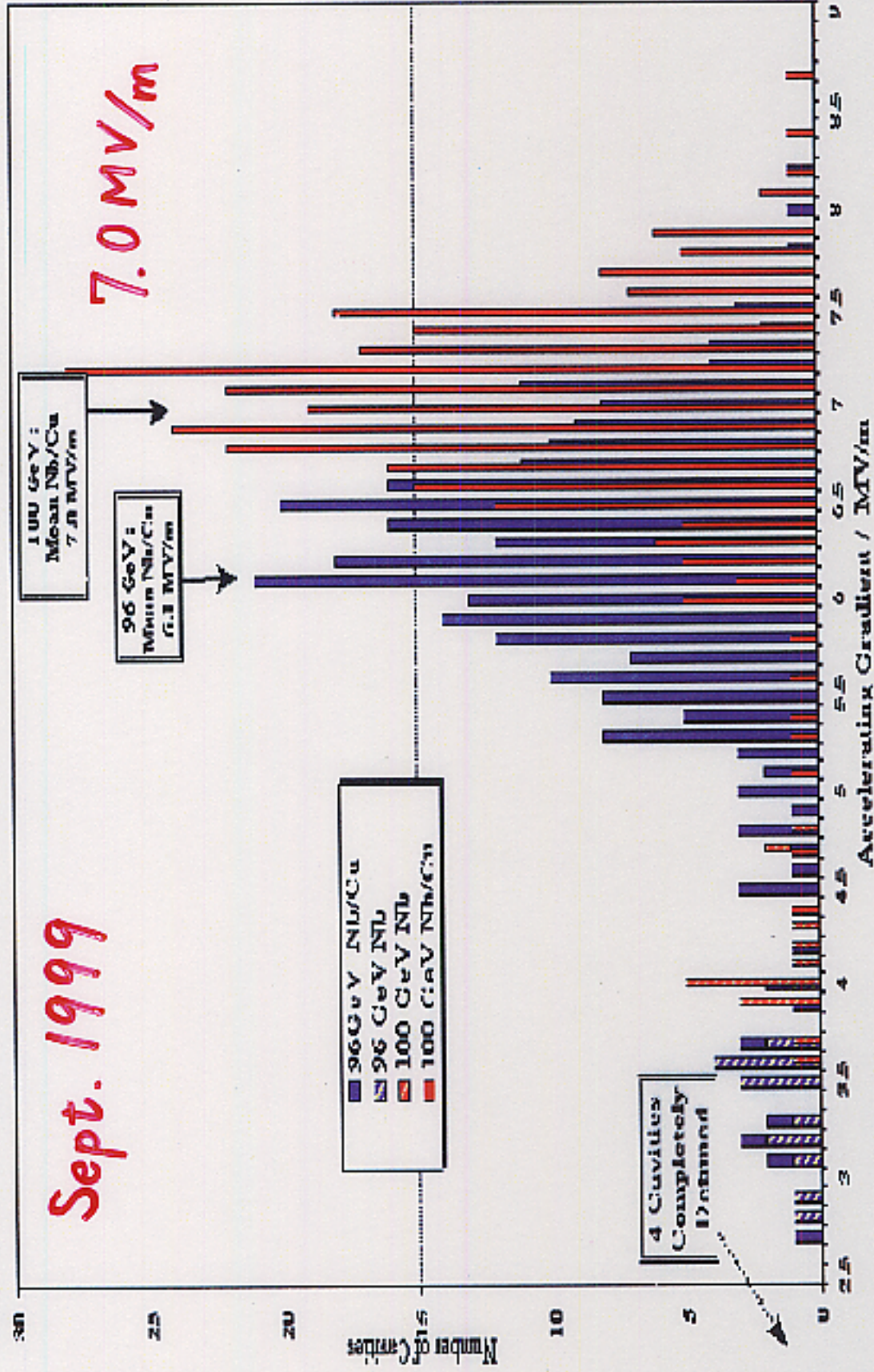


OPAL Preliminary 206 GeV



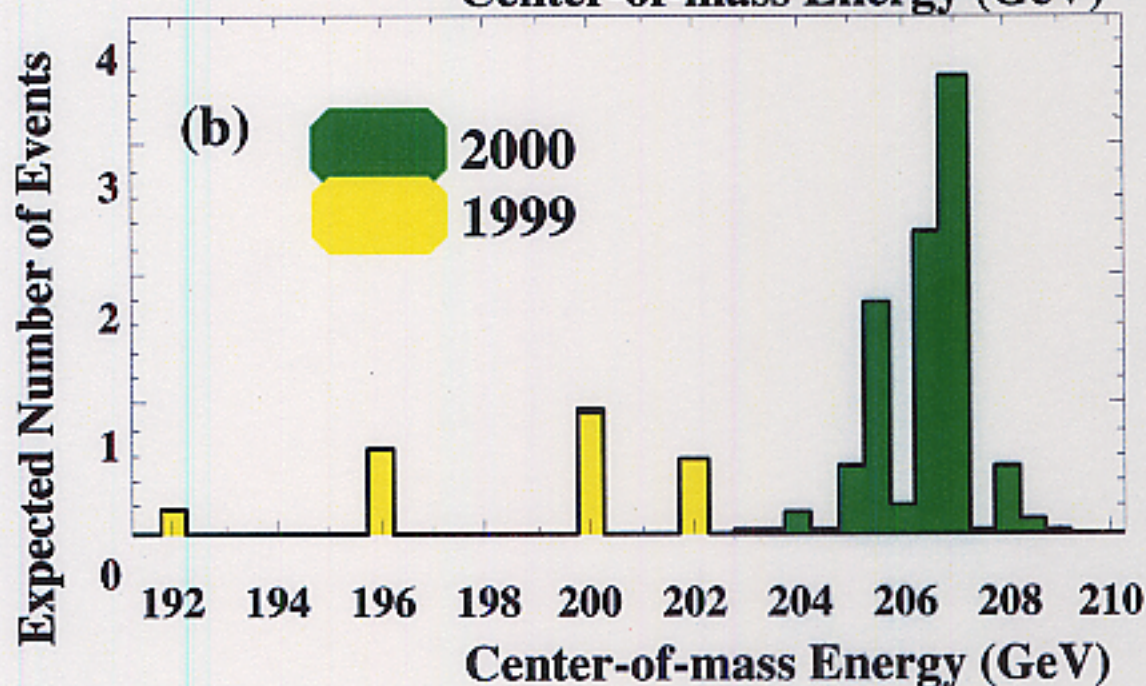
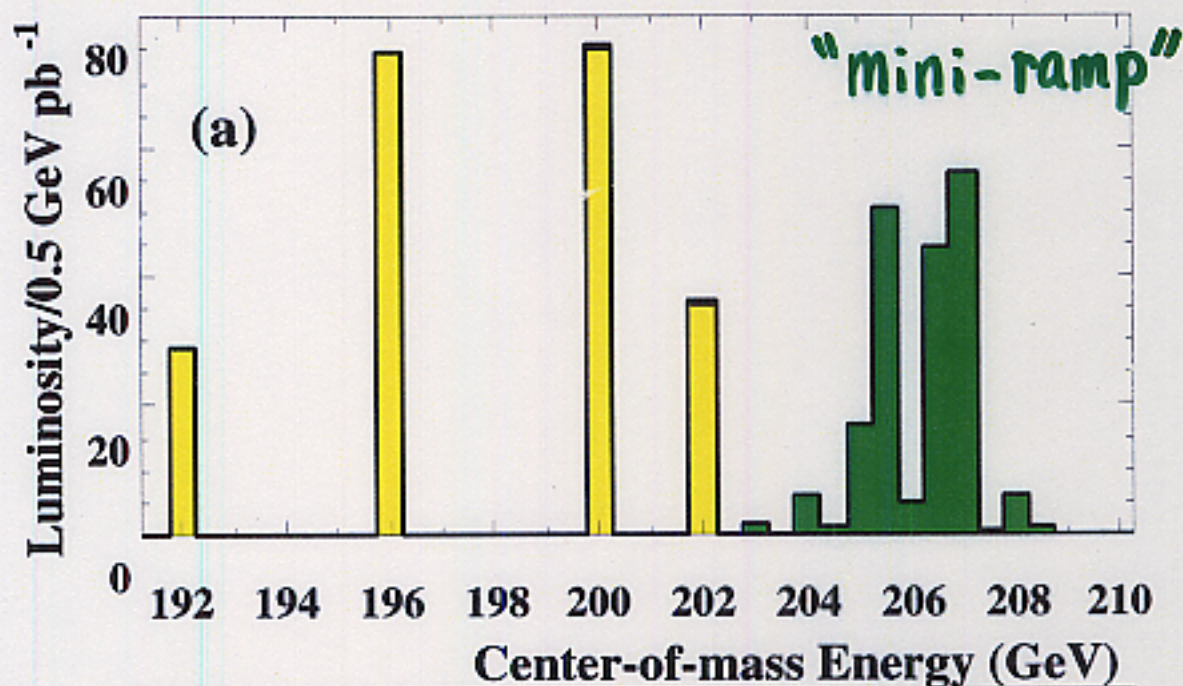
Beam Energy

Distribution of Cavity Gradients for 96 GeV (Beginning of Year) and for 100 GeV



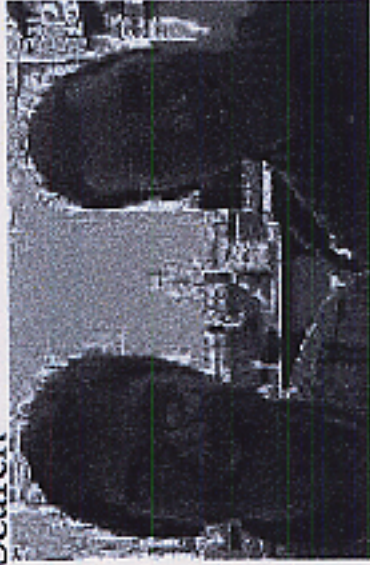
1999–2000 Luminosity and Expected # of 115 GeV Higgs

OPAL



Prologue – August 2000

- A Possible Mass Peak Seen by ALEPH's "online" Search

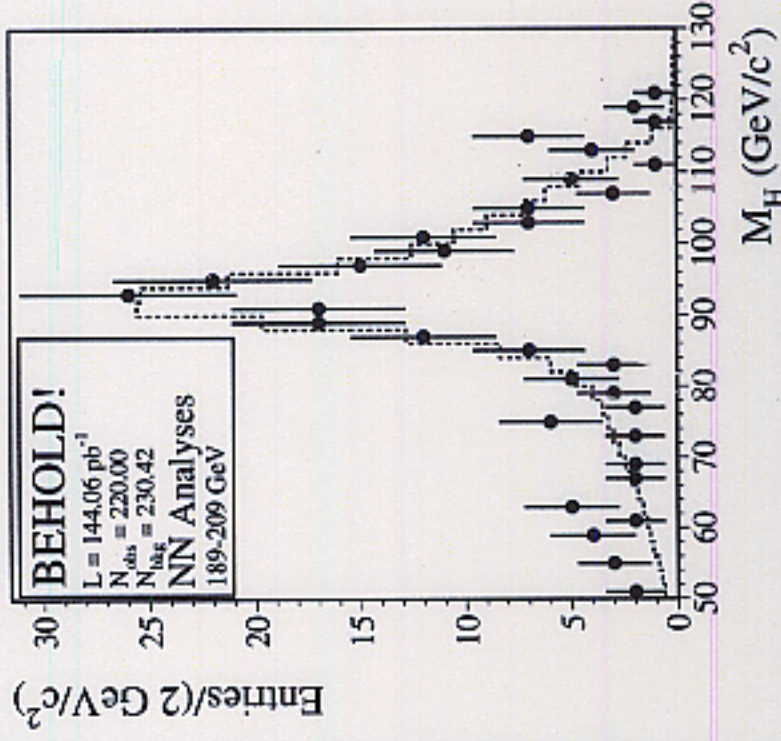


- Seen in both the NN and the cut streams

Luminosity	144 pb ⁻¹
CL _b	0.99952 at 115.5 GeV
Likelihood Ratio	~ 30
Significance	3.3 sigma

Mass Distribution

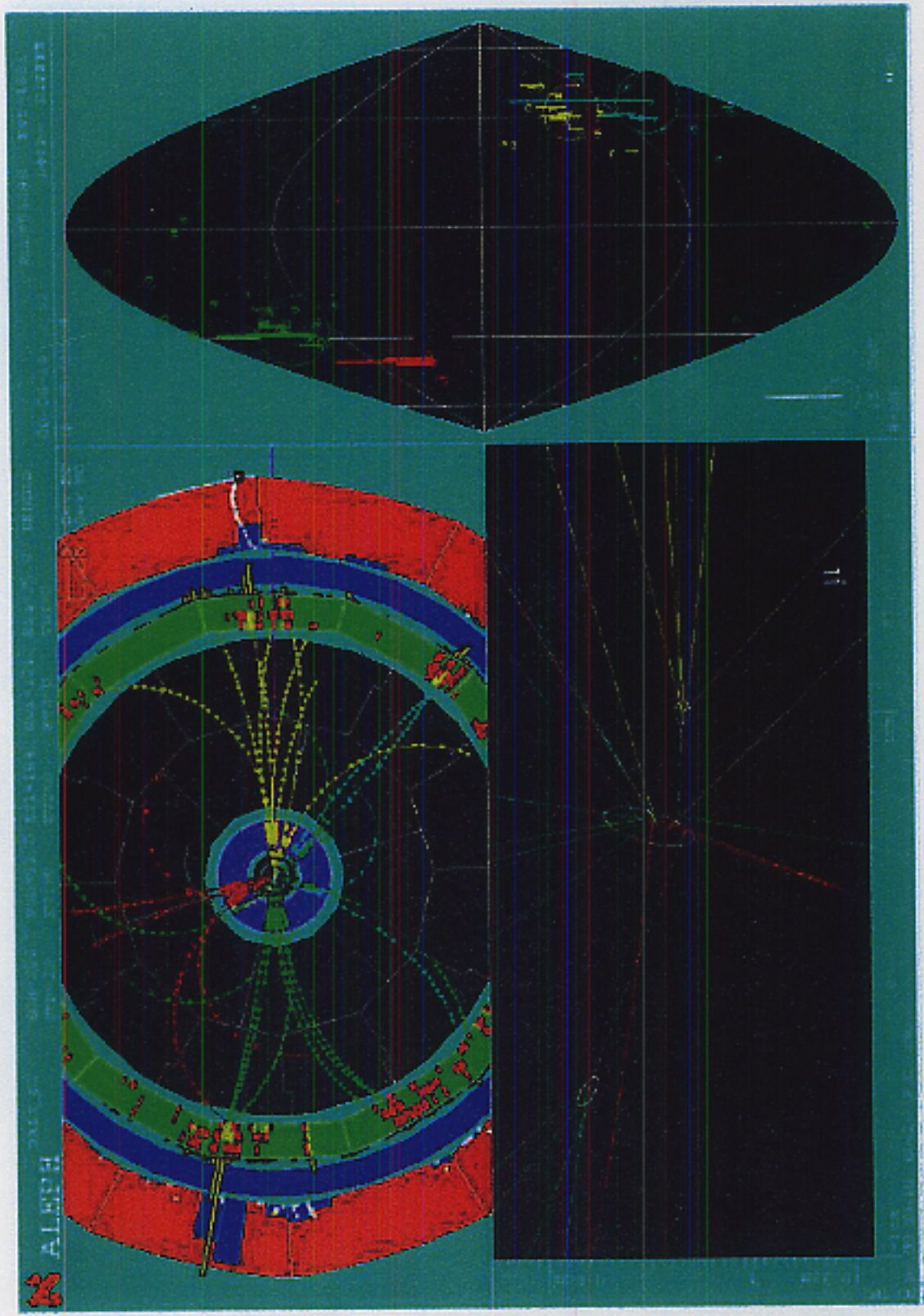
2000/08/20 19.32



It's Higgs or Not?

LEP: 9月終了予定 -> 11月初めまで

ALEPH Higgs Candidate Event



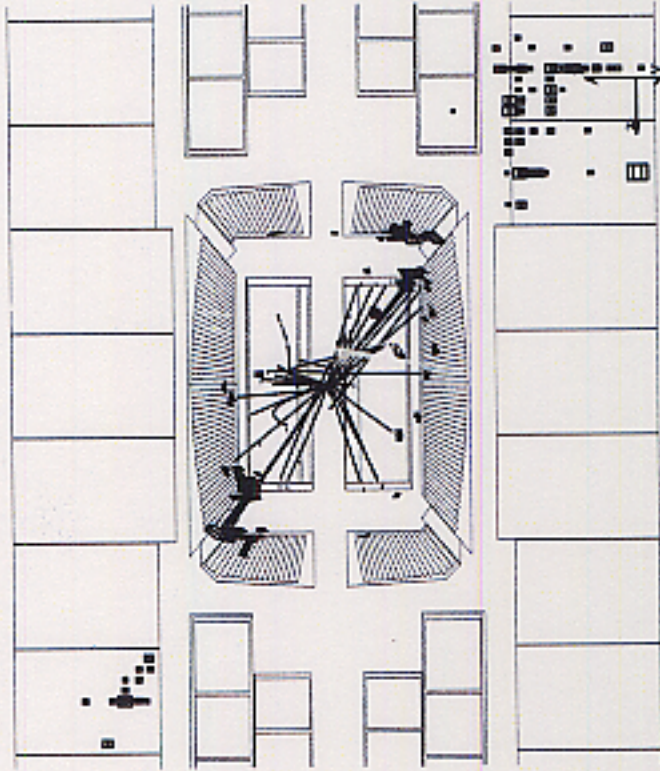
$$206 = 97 + 115$$

L3's Highest Weight Candidate

Side View

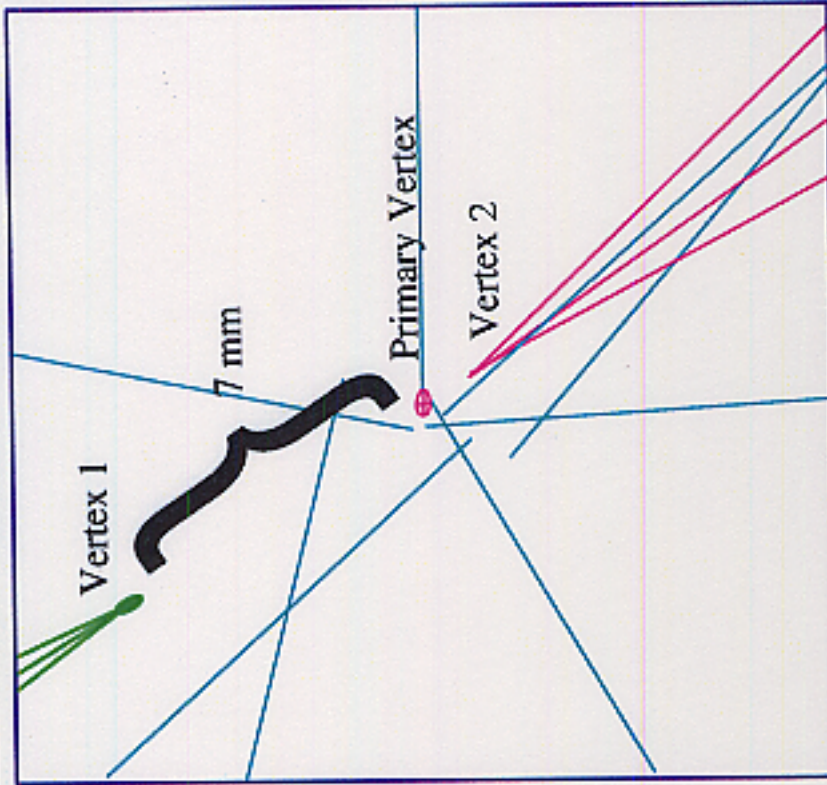
a.)

Run # 933204 Event # 4704 Total Energy : 112 GeV



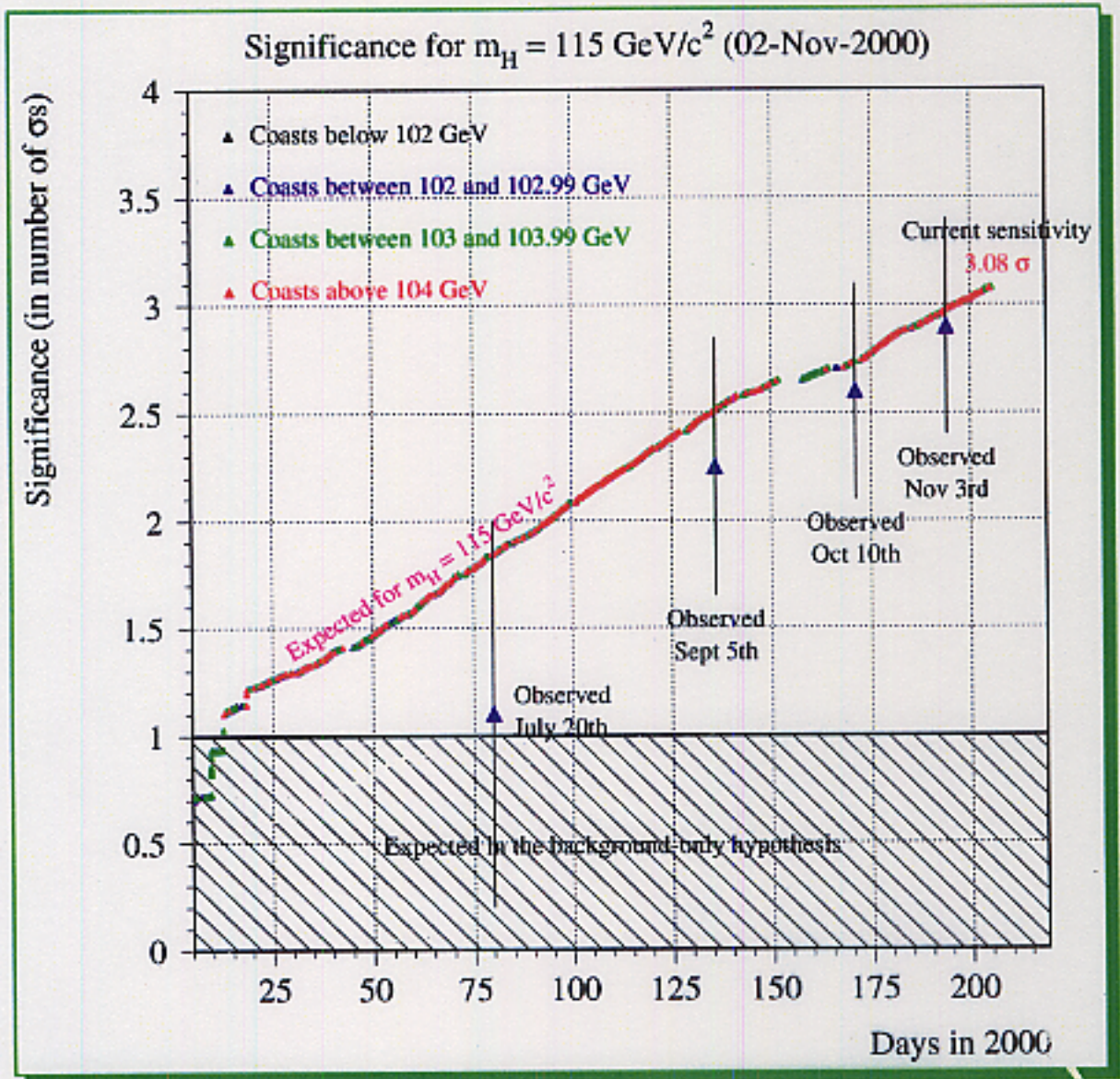
Vertex View

b.)



LEP combination

Significance vs Time



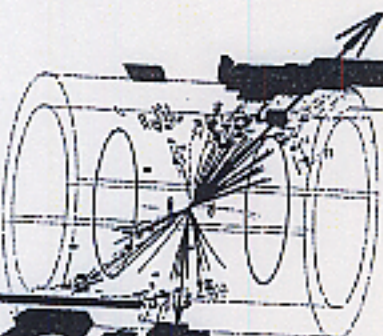
by Patrik Janot

世界中の物理学者が追い求めてきた未発見の素粒子で、物質に質量を与える鍵になる「ヒッグス粒子」が観測された可能性が高まってきた。ジュネーブの欧州合同原子核研究機関(CERN)が、電子・陽電子衝突型加速器(LEP)を使い、あと一步で「ヒッグス発見」と宣言できる位の実験データを集めたからだ。しかし、LEPは年内に閉鎖されることが内定しており、現場の研究者を中心に、実験継続を求める声が高まっている。(芝田 将一)

質量のもと ヒッグス粒子

観測の可能性高まる

ヒッグス粒子の発見は、素粒子物理学の最大の謎の一つを解くことになる。ヒッグス粒子は、物質に質量を与える鍵になる。ジュネーブの欧州合同原子核研究機関(CERN)が、電子・陽電子衝突型加速器(LEP)を使い、あと一步で「ヒッグス発見」と宣言できる位の実験データを集めたからだ。しかし、LEPは年内に閉鎖されることが内定しており、現場の研究者を中心に、実験継続を求める声が高まっている。(芝田 将一)



ディテール測定器が検出したヒッグス粒子の有力候補。4種類の線はヒッグスとZが崩壊してできた荷電粒子の痕とみられる



欧州合同原子核研究機関の地下トンネル内にあり、大型加速器(同機)のトンネル

「それ以外」 確率 0.3%

欧州研究機関「決着」目前に閉鎖か

「超対称性理論」後押し

ヒッグス粒子の発見は、素粒子物理学の最大の謎の一つを解くことになる。ヒッグス粒子は、物質に質量を与える鍵になる。ジュネーブの欧州合同原子核研究機関(CERN)が、電子・陽電子衝突型加速器(LEP)を使い、あと一步で「ヒッグス発見」と宣言できる位の実験データを集めたからだ。しかし、LEPは年内に閉鎖されることが内定しており、現場の研究者を中心に、実験継続を求める声が高まっている。(芝田 将一)

「超対称性理論」後押し。ヒッグス粒子の発見は、素粒子物理学の最大の謎の一つを解くことになる。ヒッグス粒子は、物質に質量を与える鍵になる。ジュネーブの欧州合同原子核研究機関(CERN)が、電子・陽電子衝突型加速器(LEP)を使い、あと一步で「ヒッグス発見」と宣言できる位の実験データを集めたからだ。しかし、LEPは年内に閉鎖されることが内定しており、現場の研究者を中心に、実験継続を求める声が高まっている。(芝田 将一)

H.12.12.17 毎日

素粒子「ヒッグス」探し断念

欧州合同原子核研究所(CERN)、シエーナには15日午後7時、超伝導加速器の冷却が完了され、11月15日開始の素粒子「ヒッグス」探しに使用された大型加速器「LHC」の運転がスタートした。CERNは、11月15日までに約10兆回の衝突で、ヒッグスの兆候を示すデータを確保し、次の大型加速器の建設が遅れることを推定で約1億ユーロにのぼる追加経費が必要と推定して、断念を決めた。

LHCは、素粒子加速器の中心にあり、長さ27キロメートルのトンネルに埋め込まれた超伝導磁石で、1996年にスイスとフランスが共同で建設された。

欧州合同原子核研

大型加速器解体へ

断念された。当初は、今年9月に加速器の冷却が完了したと見られていたが、ヒッグスの兆候を示すデータが不足したため、断念を決めた。

加速器の中心に埋め込まれた超伝導磁石は、冷却が完了したにもかかわらず、ヒッグスの兆候を示すデータが不足したため、断念を決めた。LHCは、素粒子加速器の中心にあり、長さ27キロメートルのトンネルに埋め込まれた超伝導磁石で、1996年にスイスとフランスが共同で建設された。

断念された。当初は、今年9月に加速器の冷却が完了したと見られていたが、ヒッグスの兆候を示すデータが不足したため、断念を決めた。

Update

Publications to include All 2000 Data
calibration/refinement of analysis

ALEPH Phys. Lett. B495 (2000) 1

DELPHI Phys. Lett. B499 (2001) 23

OPAL Phys. Lett. B499 (2001) 38

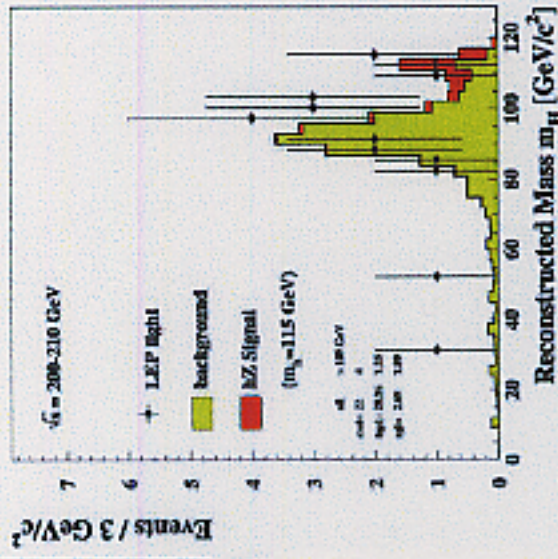
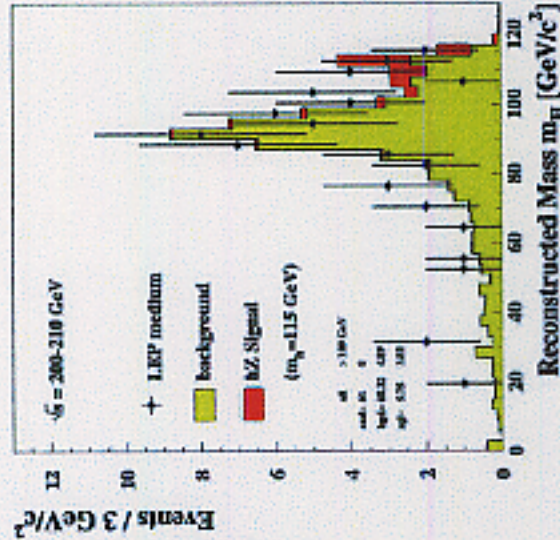
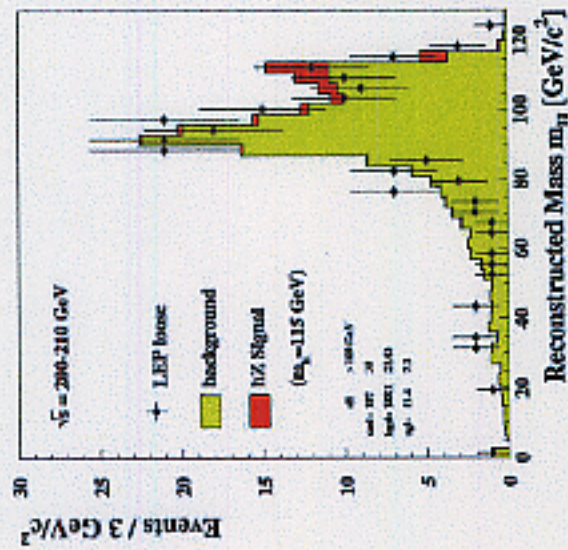
↗ L3
Final Phys. Lett. B517 (2001) 319

LEP combination:

LHWG Note/2001-03

July 2001

Reconstructed Mass Distributions



S/B = 0.5, 1.0, 2.0 above 109 GeV

ヒッグスがあるかないか？

① イベントの数をかぞえる

候補事象数 $>$ バックグラウンド
期待される数

\parallel

ヒッグス + バックグラウンドの数

S B

② 各イベントに重みを付けて数える

"ヒッグスらしさ" = $\ln \left(\frac{S+B}{B} \right)$

likelihood

- M_H
- Higgs selection
- b-tag

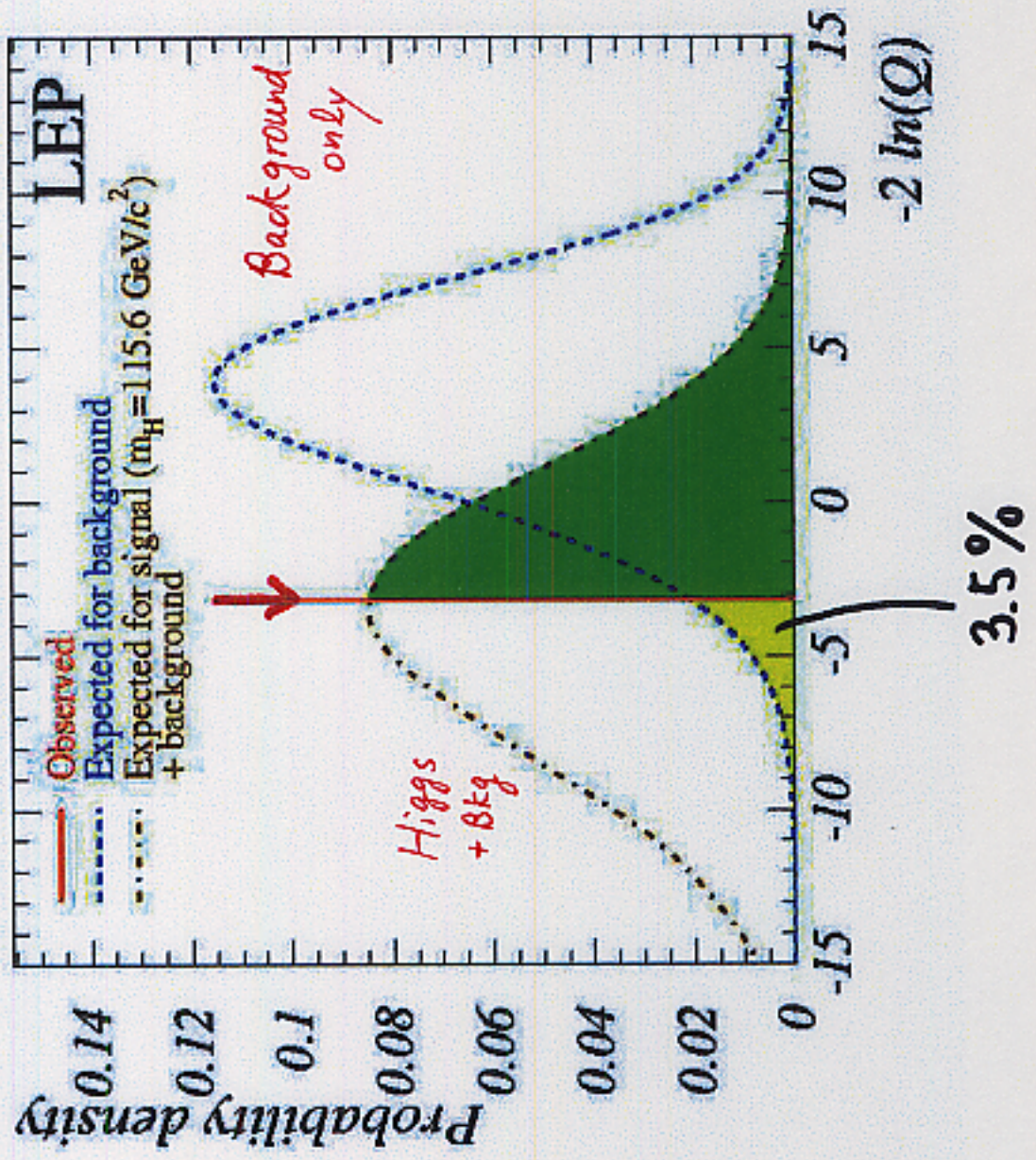
$$\ln Q \equiv \sum_{\text{イベント}} \ln \left(\frac{S+B}{B} \right) + \text{const.}$$

$$\cong \ln \mathcal{L}(S+B) / \mathcal{L}(B)$$

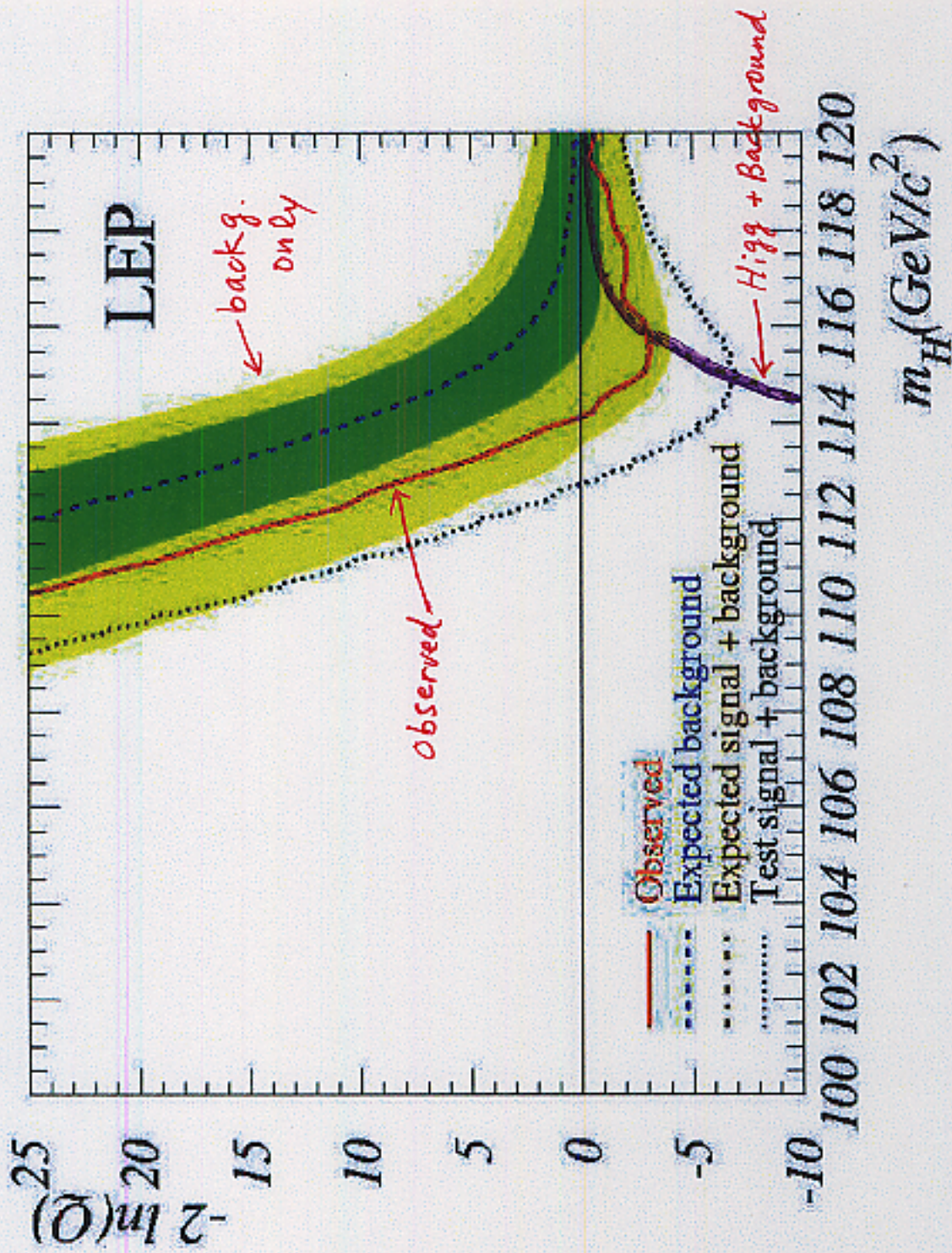
$$-2 \ln Q \xrightarrow{\text{高統計}} \chi^2(S+B) - \chi^2(B)$$

ヒッグスあれば負になる

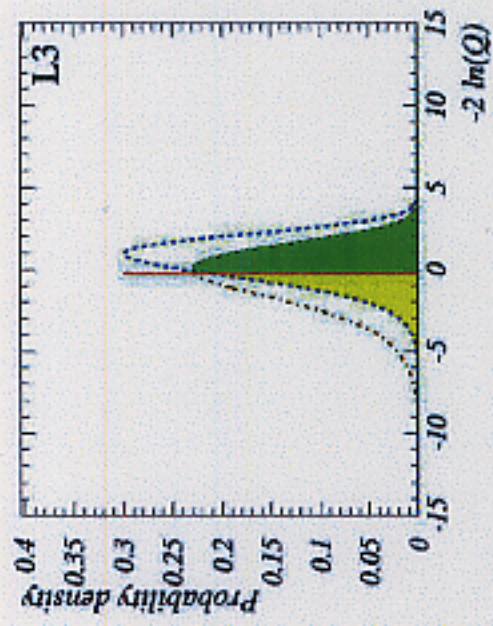
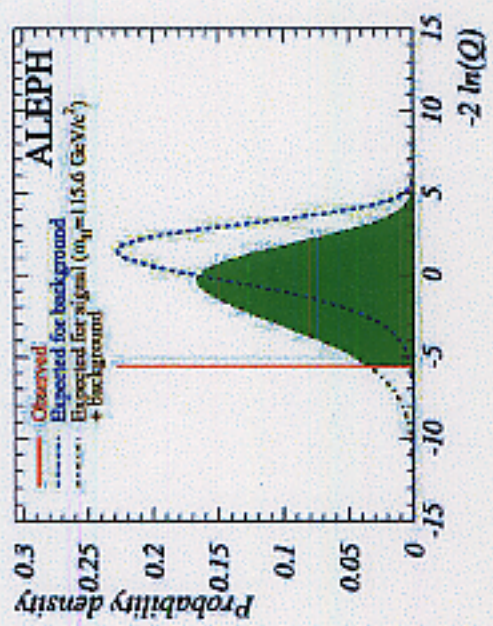
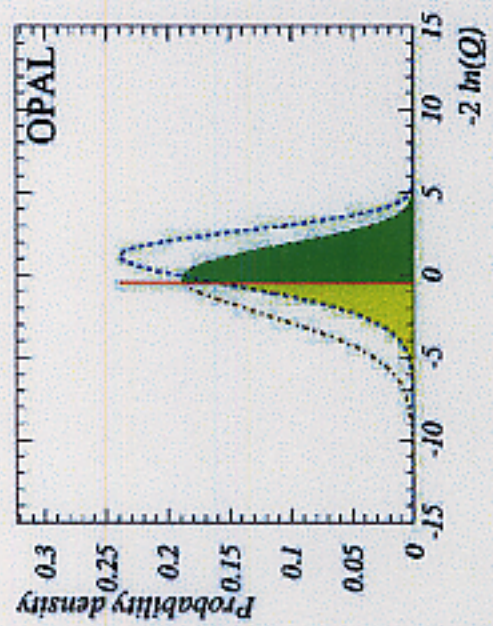
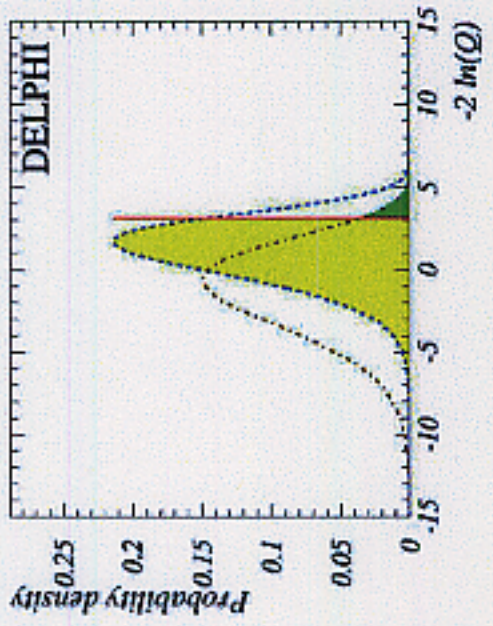
Probability Density Distributions



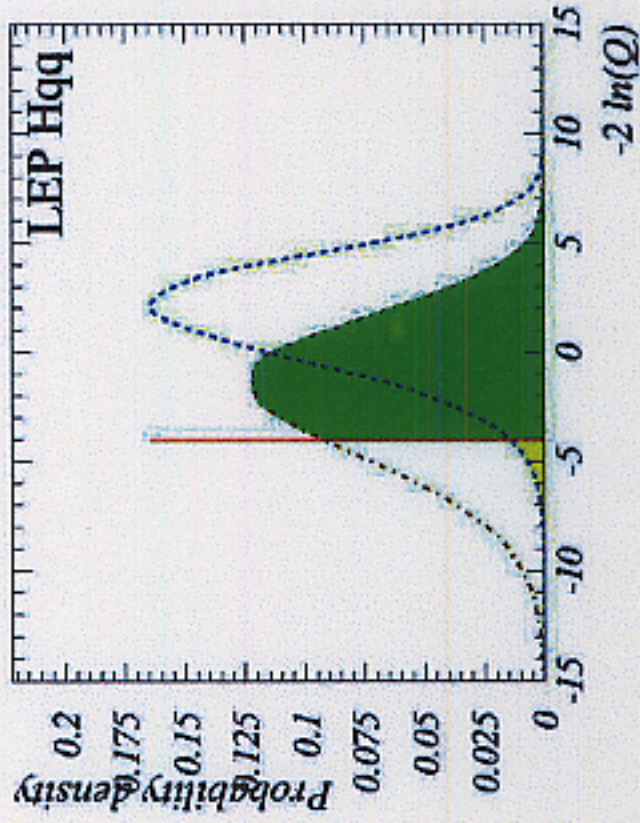
"-2 ln Q" as a Function of m_H



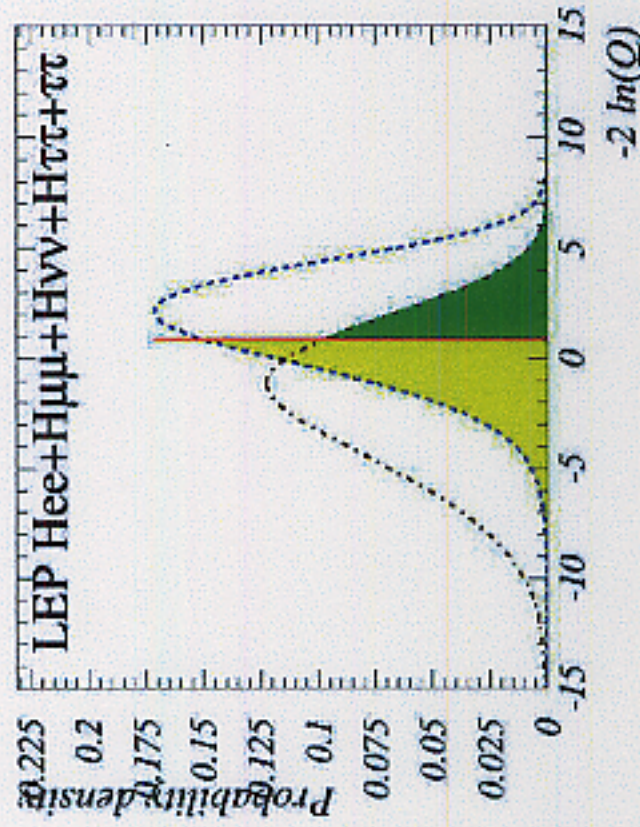
Each Experiment : $m_H = 115.6 \text{ GeV}$



Decay Channels : $m_H = 115.6 \text{ GeV}$



4 jet

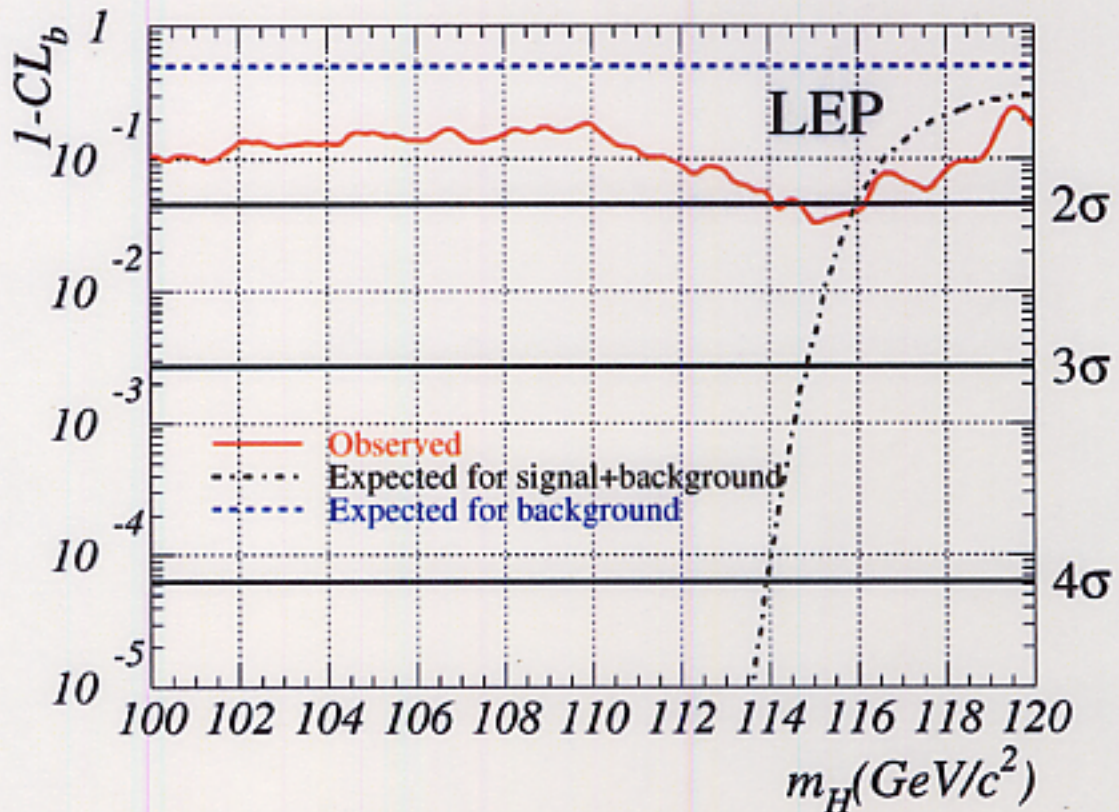


non 4 jet

Candidate weights @ $m_h = 115$ GeV

	Expt	E_{cm}	Channel	M_H^{rec} (GeV)	$\ln(1 + s/b)$ @115 GeV
1	A	206.7	4-jet	114.3	1.73
2	A	206.7	4-jet	112.9	1.21
3	A	206.5	4-jet	110.0	0.64
4	L	206.4	E-miss	115.0	0.53
5	O	206.6	4-jet	110.7	0.53
6	D	206.7	4-jet	114.3	0.49
7	A	205.0	Lept	118.1	0.47
8	A	208.1	Tau	115.4	0.41
9	A	206.5	4-jet	114.5	0.40
10	O	205.4	4-jet	112.6	0.40
11	D	206.7	4-jet	97.2	0.36
12	L	206.4	4-jet	108.3	0.31
13	A	206.5	4-jet	114.4	0.27
14	A	207.6	4-jet	103.0	0.26
15	O	205.4	E-miss	104.0	0.25
16	A	206.5	4-jet	110.2	0.22
17	L	206.4	E-miss	110.1	0.21
18	O	206.4	E-miss	112.1	0.20
19	D	206.7	4-jet	110.1	0.20
20	L	206.4	E-miss	110.1	0.18

Background fluctuation probability: $1-CL_b$



- background fluctuation probability at $m_h = 115.6$ GeV: $1 - CL_b = 3.5\%$

- at the 95% C.L.:

$$m_h > 114.1 \text{ (115.4 exp.) GeV}$$

ALEPH 除くと > 114.8 (114.9) exp.

何が変ったのか

	ALEPH	DELPHI	L3	OPAL	LEP
Nov 2000	6.5×10^{-4}	0.68	0.068	0.19	4.2×10^{-3}
Published	2.6×10^{-3}	0.77	0.32	0.20	0.035

Table 2: The background probabilities presented in November 2000 and published later in Ref. [7, 8, 9, 10]. The combined results are also shown [11].

- $10 \sim 16 \text{ pb}^{-1} / \text{実験}$ データ増えた
- sensitivity improved } thorough revision of
- better understanding } analysis procedures
- preferred mass 115.0 \rightarrow 115.6 GeV

SuperSymmetric Higgs

h^0, H^0, A^0, H^+, H^-

Searches for :

$e^+e^- \rightarrow h Z$ just like SM

$h \rightarrow CC, \bar{e}e, WW, AA$ also considered
and: flavor independent search

$e^+e^- \rightarrow h A$ phase space β^3

mass limits worse by $\sim 70\text{GeV}$

$hA \rightarrow b\bar{b}b\bar{b}, b\bar{b}\tau\tau$

Limits in MSSM Parameter Space:

"Constrained MSSM"

LHW G

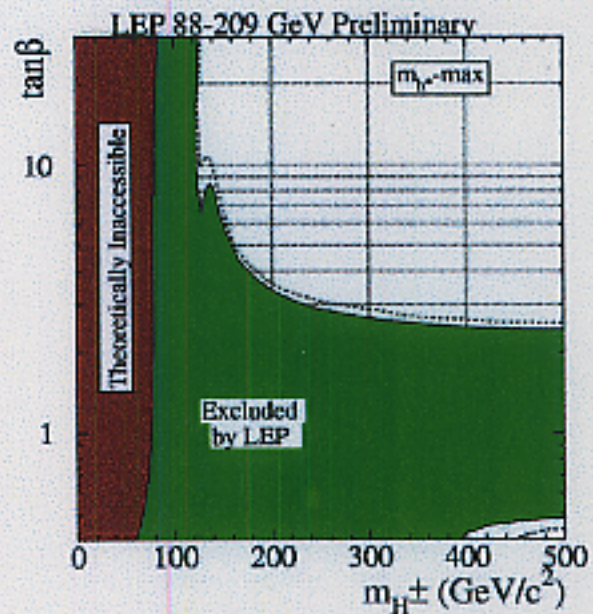
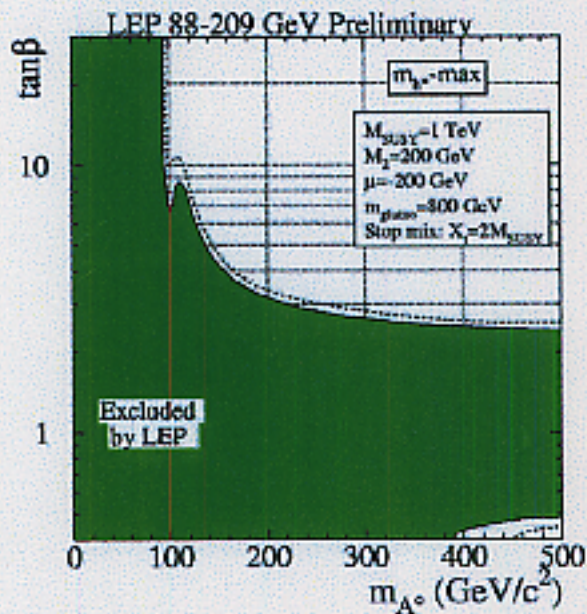
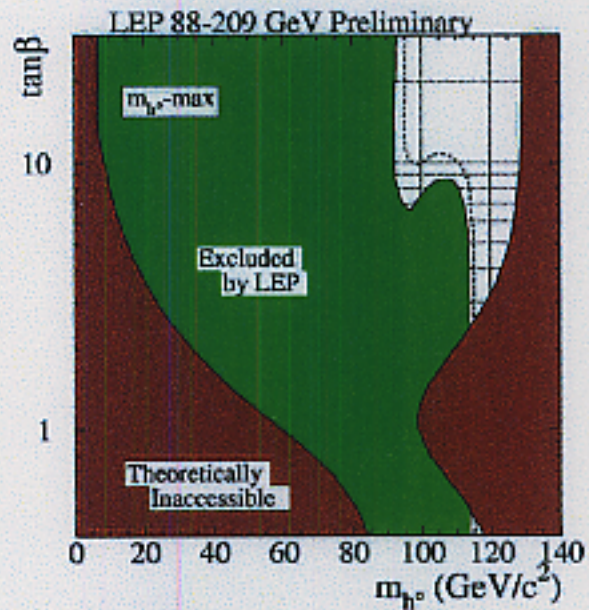
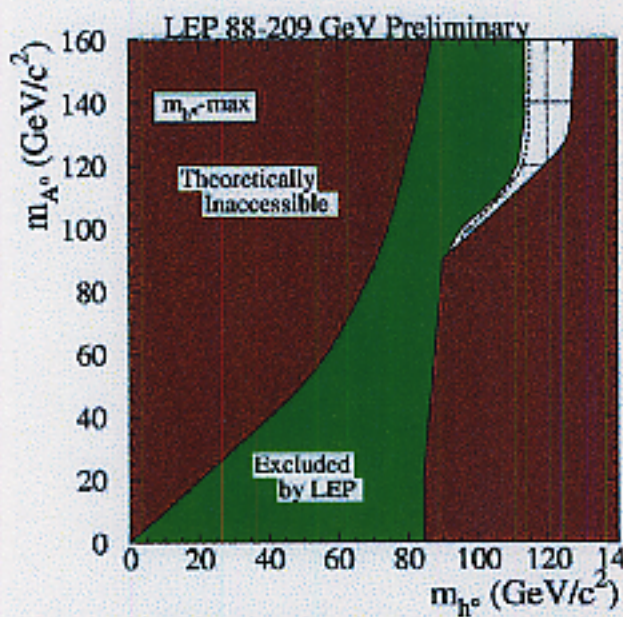
Note 2001-04

July 2001

Constrained MSSM

m_h -max benchmark

$0.5 < \tan \beta < 2.4$ excluded



Constrained MSSM

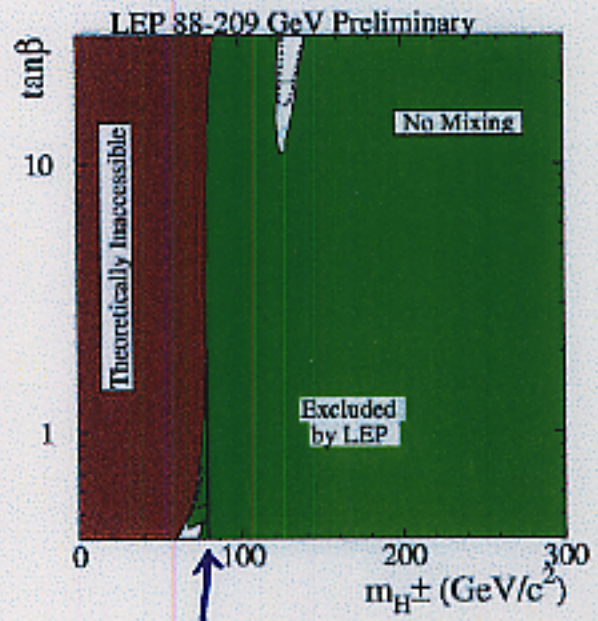
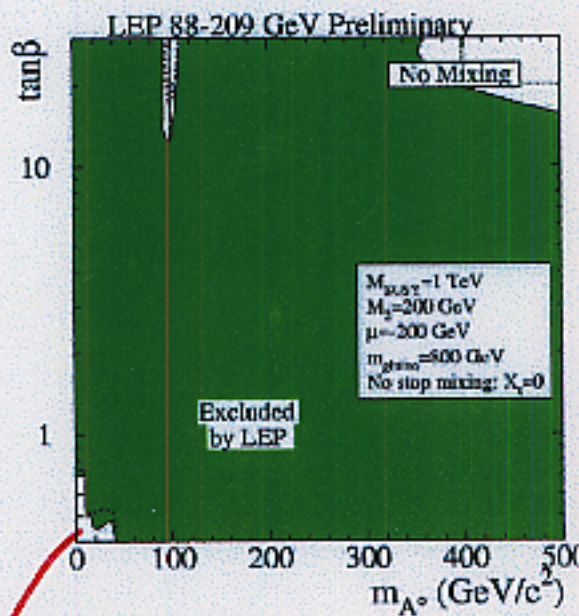
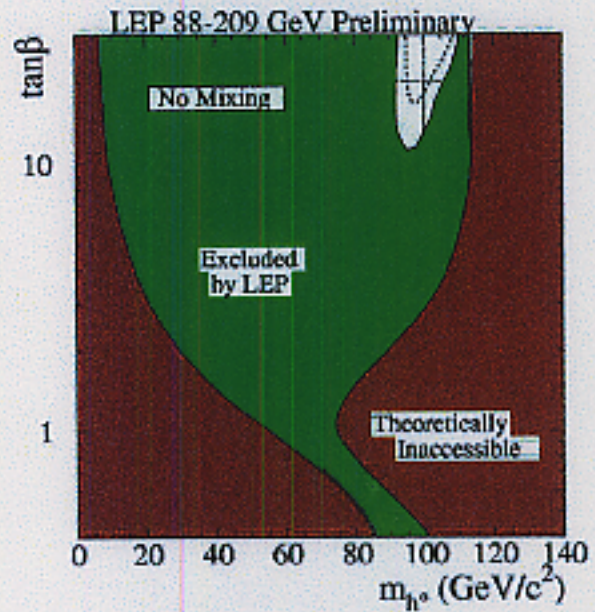
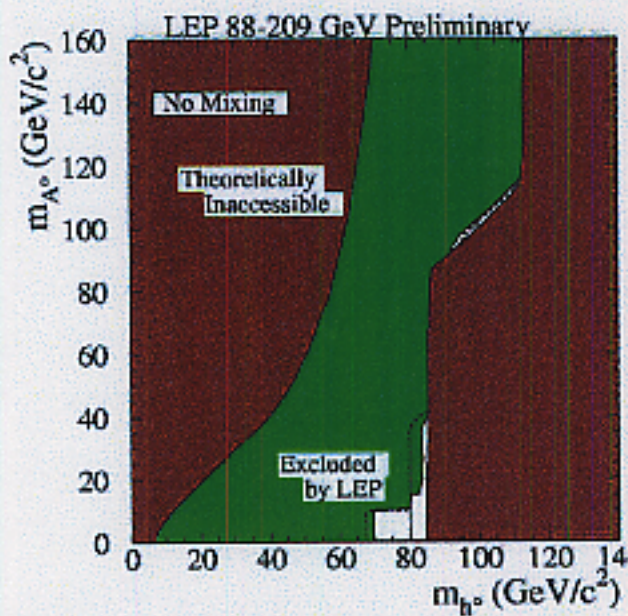
m_h -max benchmark

- not excluded at large $\tan\beta$, $m_A = m_h$:
 - h Z suppressed
 - h A slow threshold rise $\sim \beta^3$

Constrained MSSM

no-mixing benchmark

$0.7 < \tan \beta < 10.5$ excluded



$h \rightarrow AA$
 $L \rightarrow b\bar{b}$

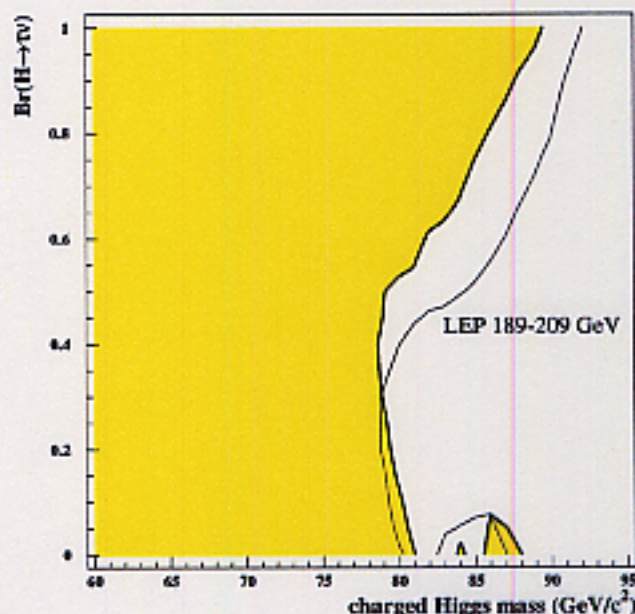
m_{H^\pm} limit

Charged Higgs, H^\pm

Assume $B(H^+ \rightarrow c\bar{s}) + B(H^+ \rightarrow \tau^+\nu) \doteq 1$

→ $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{s}s\bar{c}, c\bar{s}\tau^-\bar{\nu}, \tau^+\nu\tau^-\bar{\nu}$

- L3 observe a large excess in the 4-jets channel
- compatibility with ALEPH, DELPHI, OPAL is being investigated.



LEP combined search excludes (95%CL)

$$m_{H^\pm} < 78.6 \text{ (78.8 exp.) GeV}$$

for any $B(H^+ \rightarrow \tau^+\nu)$

Constrained MSSM

no-mixing benchmark

Not Excluded Yet:

- light A , small $\tan\beta$:

$h Z \rightarrow AA Z$

$A \rightarrow bb$ not allowed

Possibly excluded by H^+ search

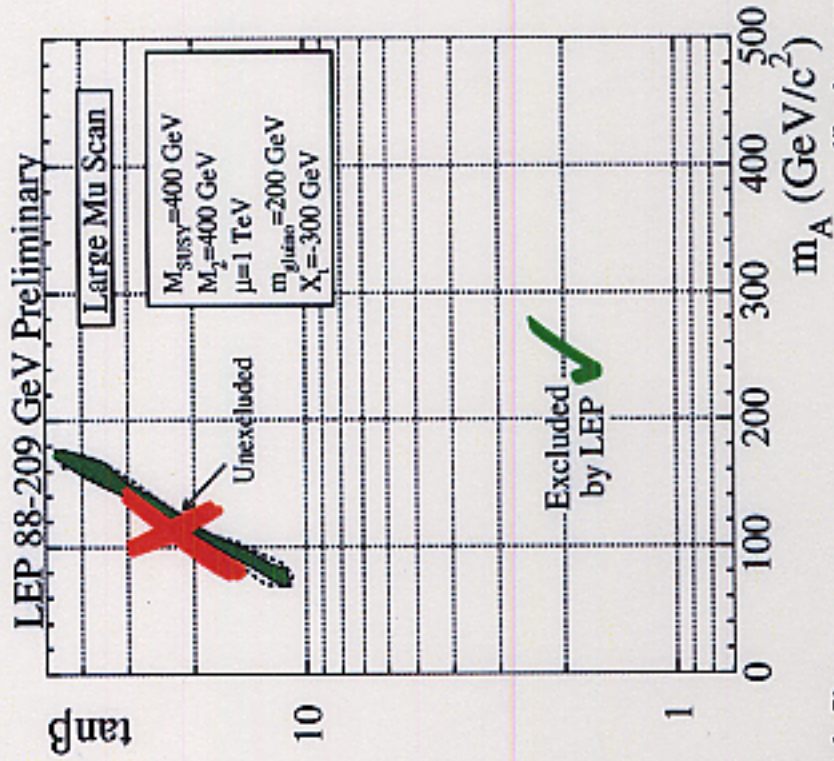
...But $H^+ \rightarrow W^+A$ possible

- heavy A , large $\tan\beta$:

$m_h > 114.7 \text{ GeV}$ not accessible

MSSM: large- μ benchmark

$(m_h, \tan \beta)$ plane:



→ scenario designed to

suppress $h \rightarrow b\bar{b}$

→ **previous exclusion (at right)**

based only on $h \rightarrow b\bar{b}, \tau^+\tau^-$

→ **new flavour-independent search**

⇨ **cover** $h \rightarrow c\bar{c} \text{ \& } h \rightarrow gg$

→ **All points excluded @ 95% CL**

Flavour-blind Higgs searches

→ $h \rightarrow q\bar{q}, gg$

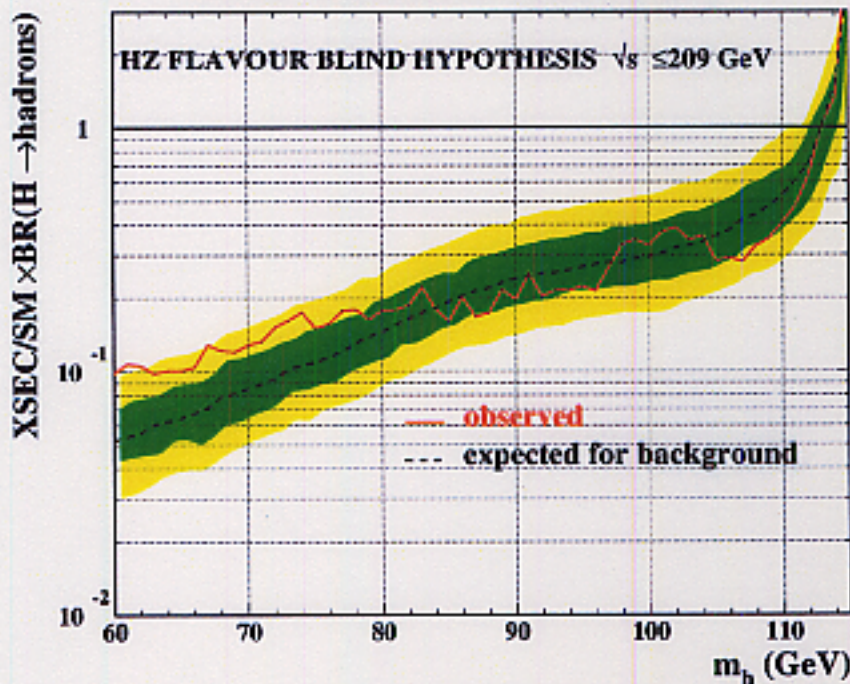
dedicated searches, not relying on b-tagging:

- improved sensitivity if suppressed $h \rightarrow b\bar{b}$
- less model-dependent search results

For SM Higgs σ and $B(h \rightarrow \text{hadrons})=100\%$:

- $m_h > 112.9$ (113.0 exp.) GeV

LEP PRELIMINARY



Constrained MSSM

large- μ benchmark

$$M_{\text{SUSY}} = 400 \text{ GeV}, \mu = 1 \text{ TeV}$$

$$M_2 = 400 \text{ GeV}, m_g = 200 \text{ GeV}$$

$$4 < m_A < 400 \text{ GeV}, X_t = 300 \text{ GeV}$$

$h \rightarrow b\bar{b}$ suppressed for $\tan\beta > 20$

Flavor-Independent hZ Search

helps to exclude the entire region up to $\tan\beta < 50$ at 95% CL!

Invisible Higgs

e.g., $h \rightarrow \chi\chi$ ($\chi = \text{LSP}$)

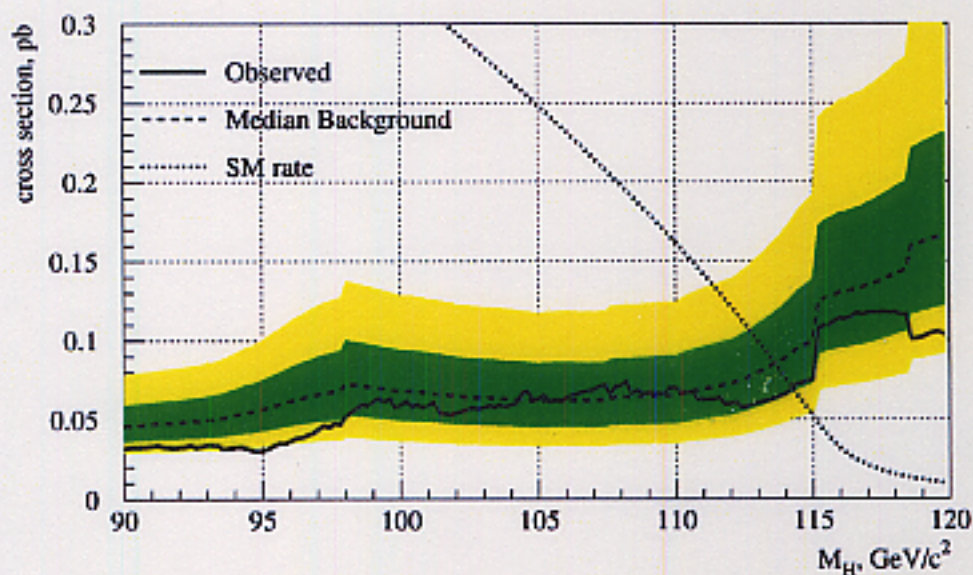
Search for $h \rightarrow \text{inv.} + Z \rightarrow q\bar{q}, \ell^+\ell^-$:

- acoplanar jets / leptons

- $m_h > 114.4$ (113.5 exp.) GeV

Upper bound on production cross-section:

(for SM Higgs σ , and $B(h \rightarrow \text{inv.})=100\%$)



... predicted cross-section for $\sqrt{s} = 206$ GeV

結論

- 標準理論ヒッグス粒子は 114.1 GeV より重なり (95% C.L.)
- ・ 115 GeV 付近の「超過事象」は、バックグラウンドで説明が可能 (3.5%の確率)。
- ・ 超対称性ならば、 $\tan\beta$ は小さくなり。

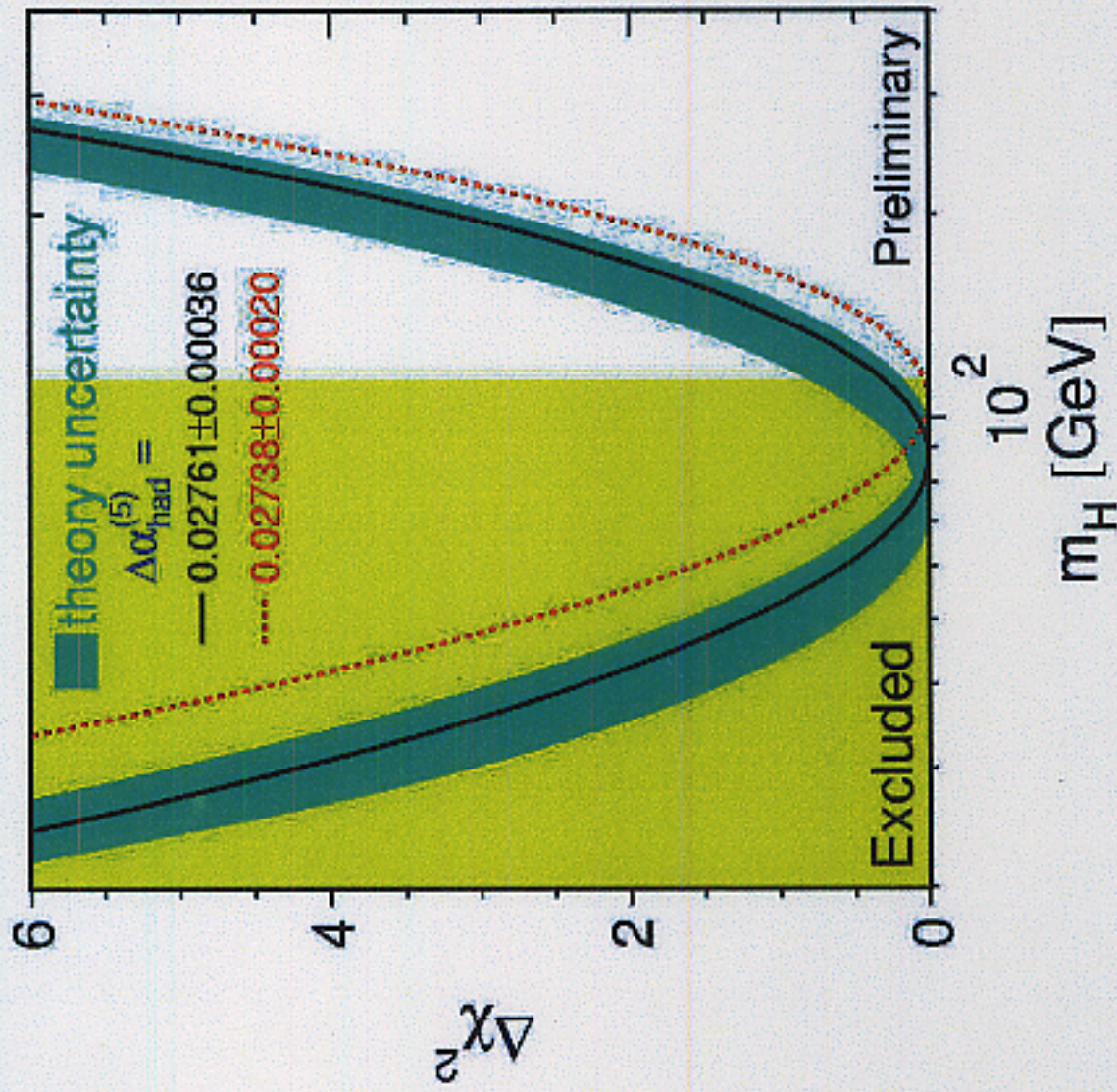
ヒッグス粒子は $114\sim 200\text{ GeV}$ にある
超対称性ならばあと 20 GeV 以内



JLC + LHC



EW Measurements @summer 2007



LEPに

追い詰められた Higgs 粒子

