LEP2

THE LARGE ELECTRON - POSITRON PROJECT PART 2

OR

THE LAST ENERGY-FRONTIER CIRCULAR e^+e^- COLLIDER PROJECT PART 2

APPC 2000 + ACFA LCWS

10. AUG. 2000

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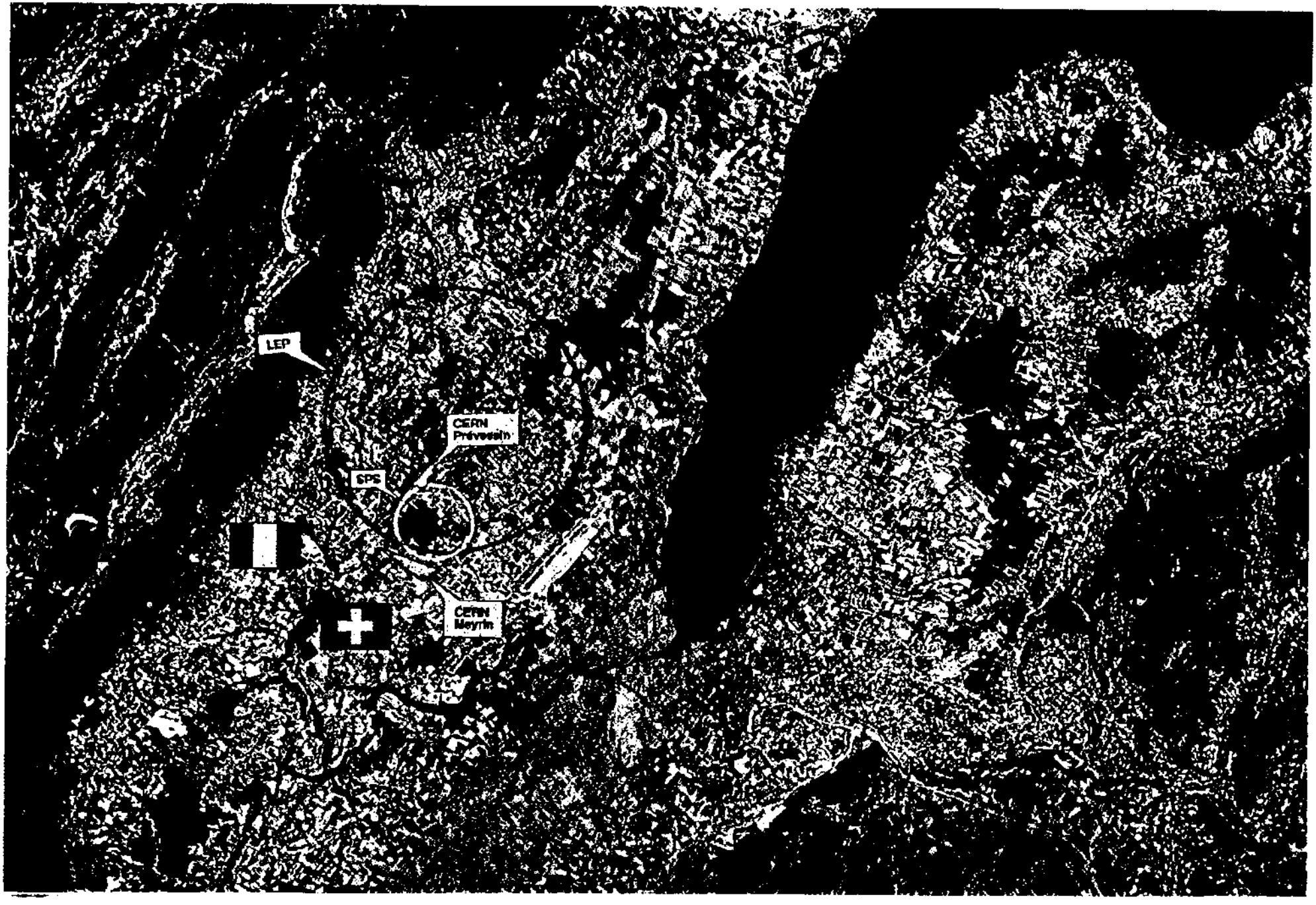
LEP
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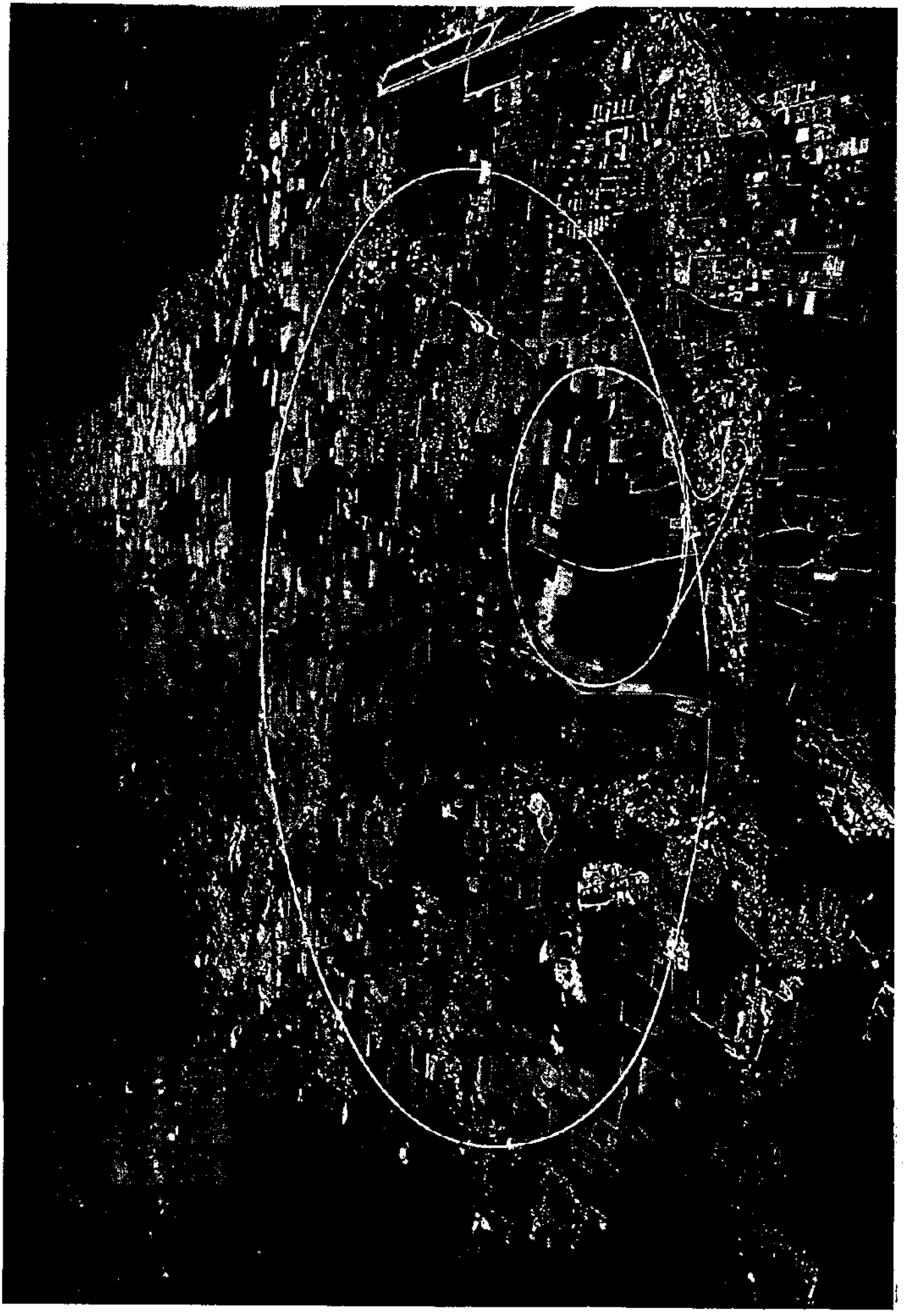
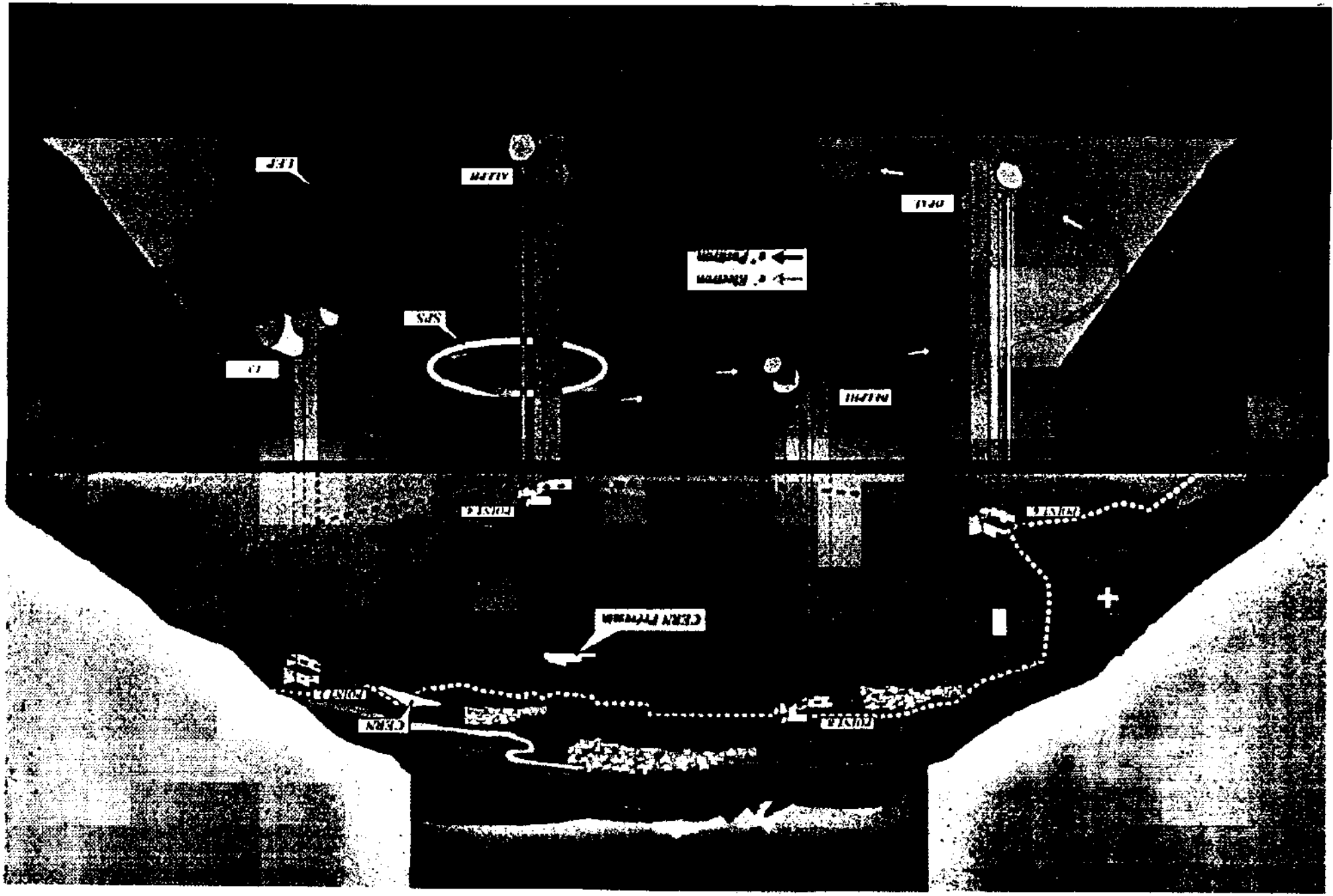
SPS
CERN
Meyrin

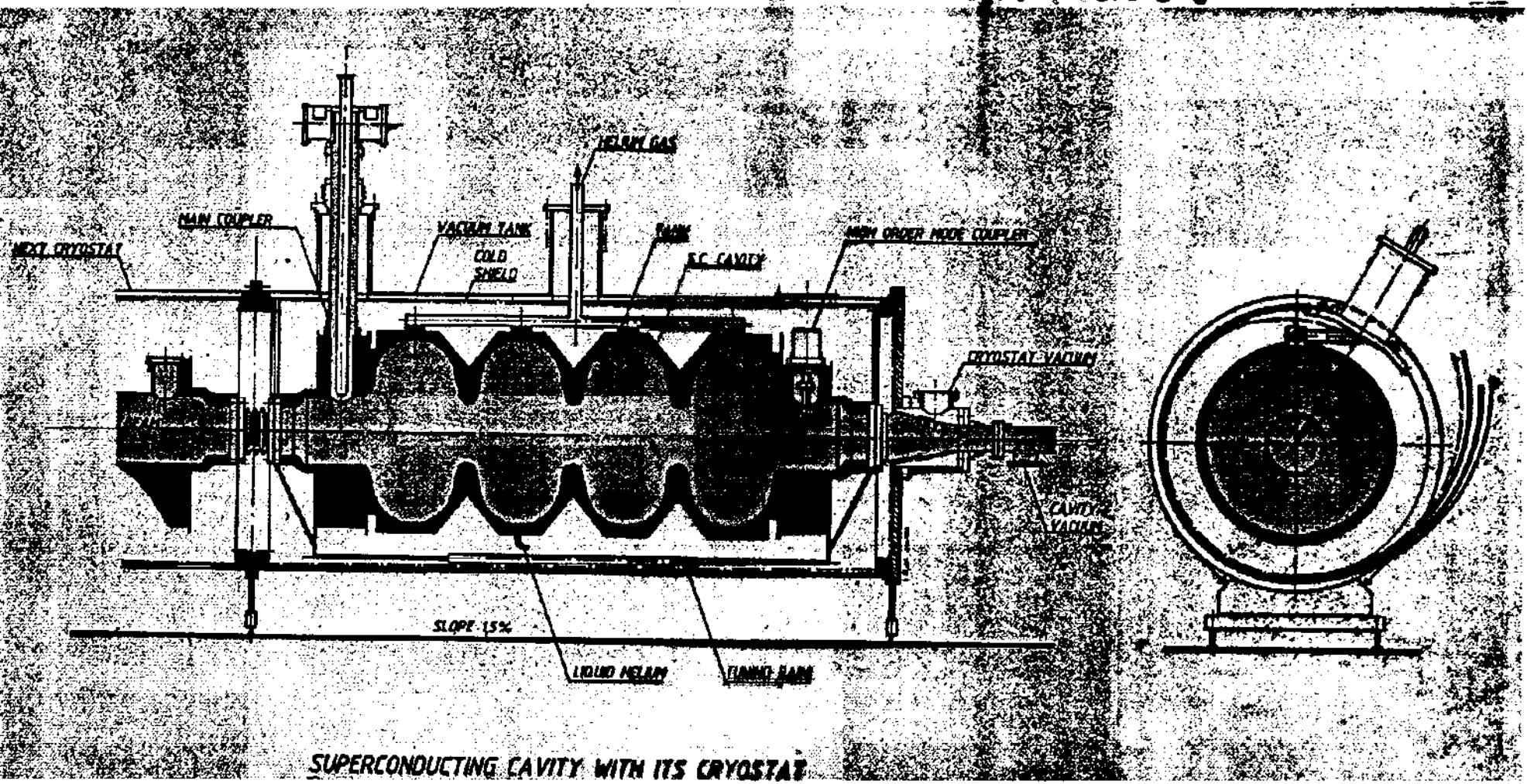




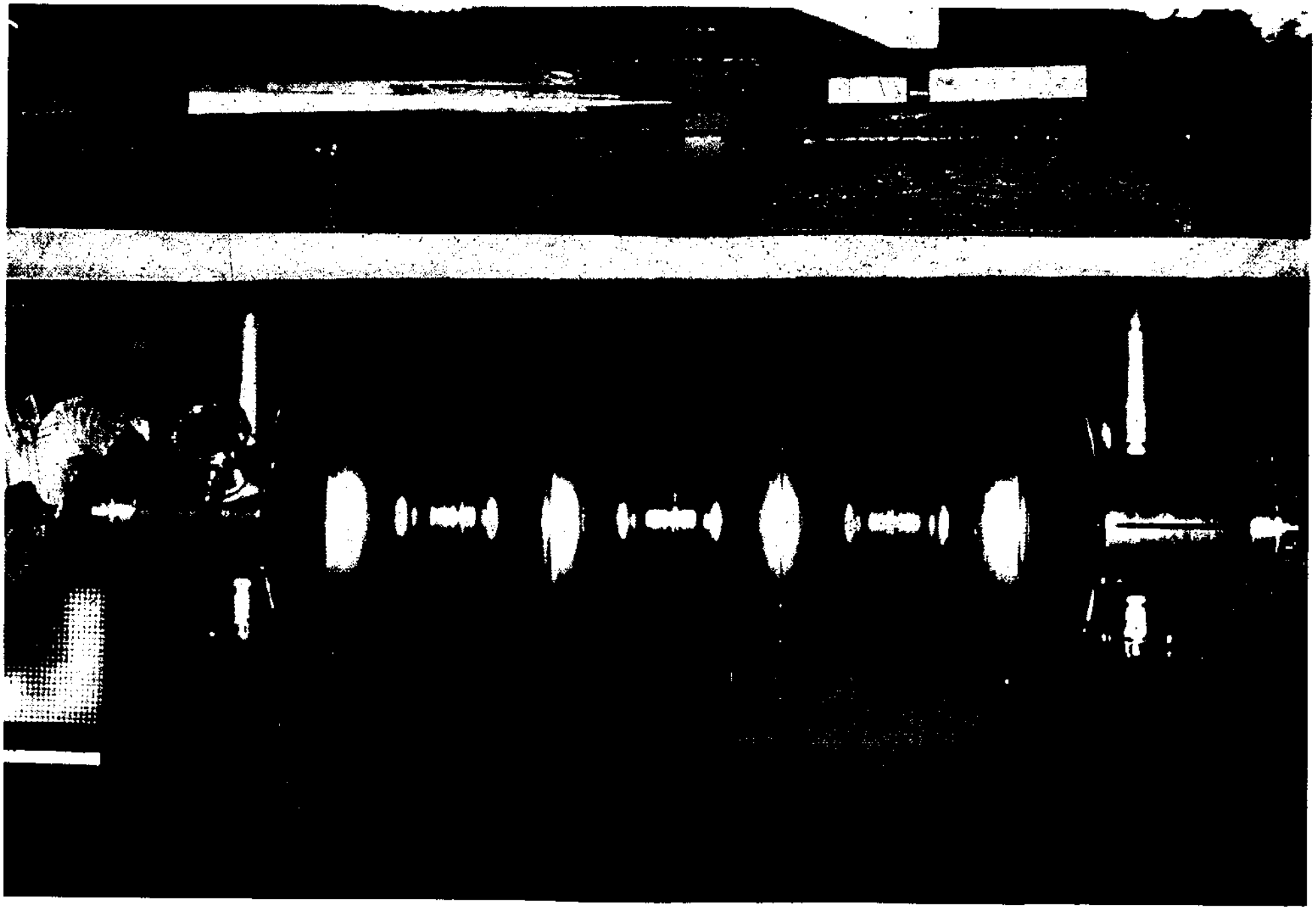
$\Delta E_{\text{synch radiation}} \propto \frac{E_{\text{beam}}^4}{\rho_{\text{bending}}}$

$E_{\text{beam}} \simeq 100$ GeV

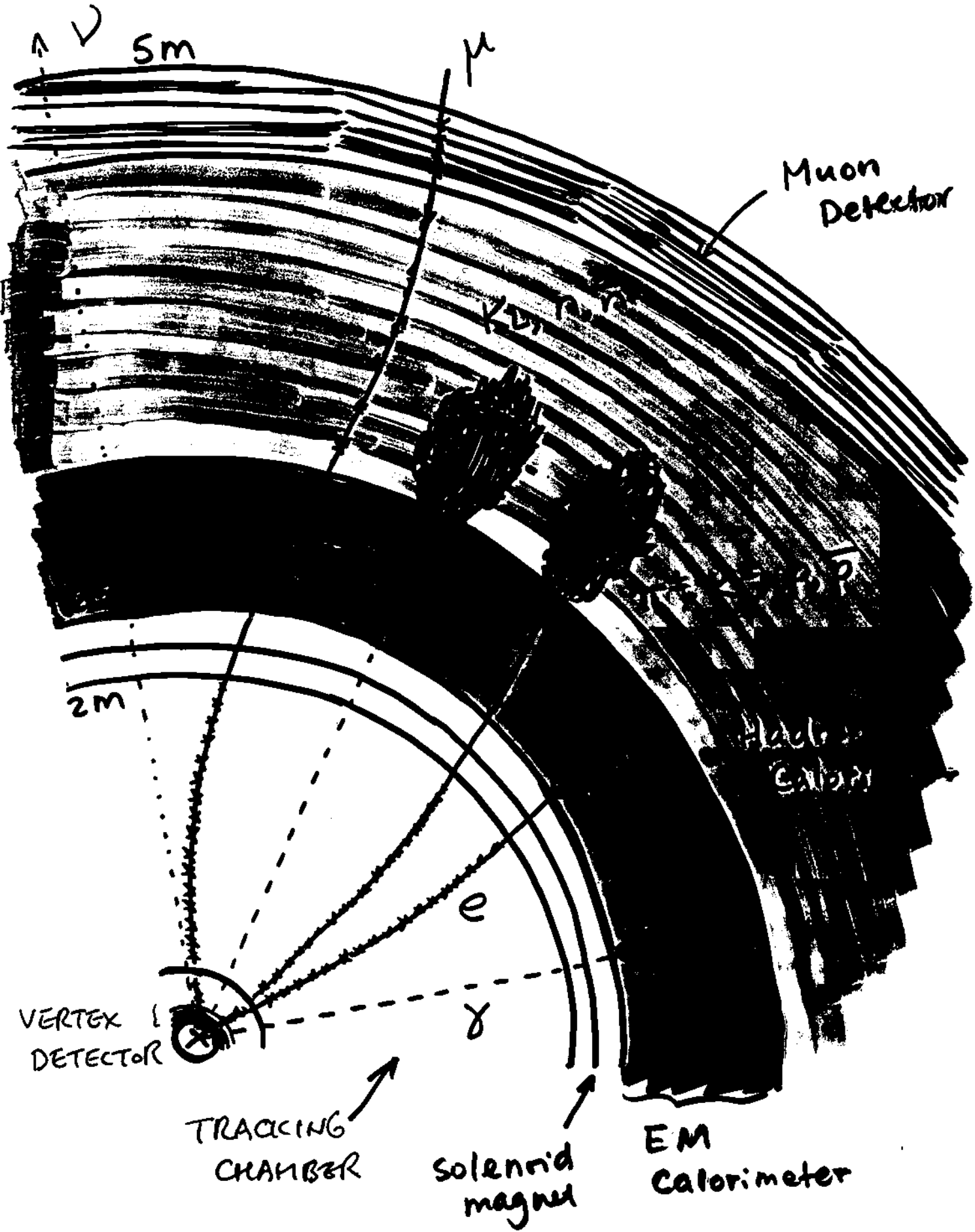
$\Delta E_{\text{syn.}} \simeq 3.5$ GeV

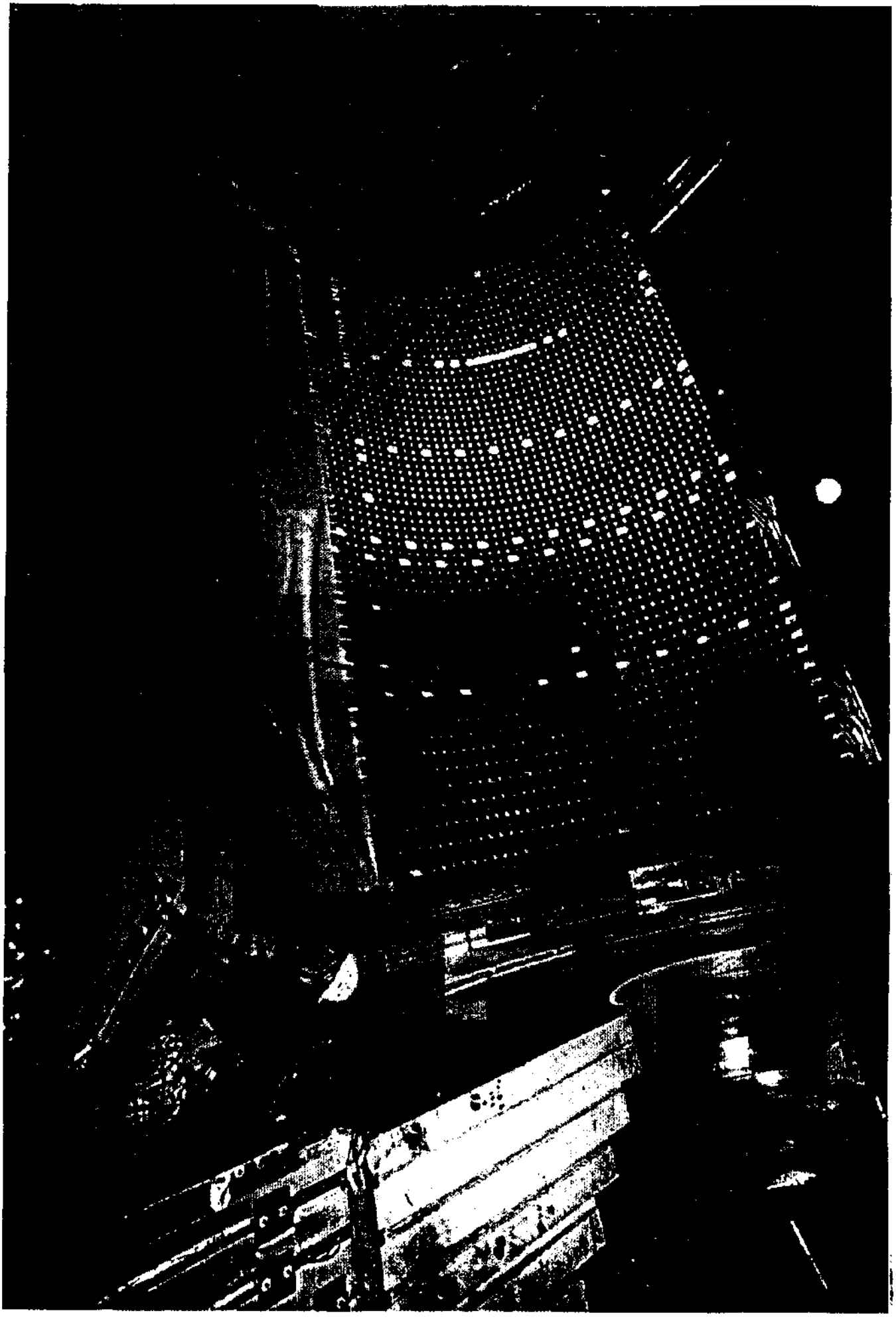


SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT

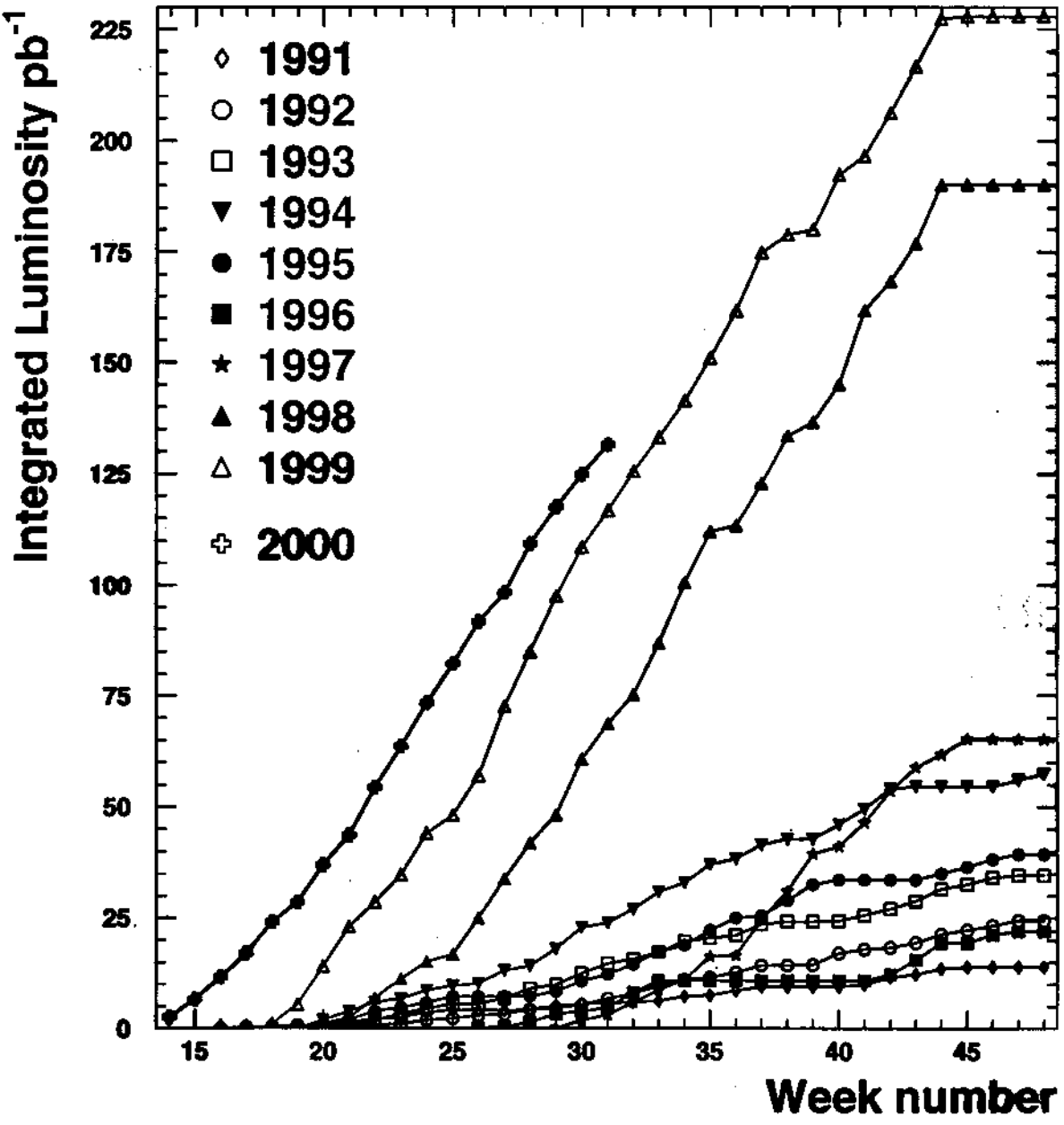


A LEP DETECTOR





OPAL Online Data-Taking Statistics



Yr. 2000

$\sqrt{s} \simeq 205\text{-}207$ GeV

$\sqrt{s}_{max} \simeq 209$ GeV

LEP1 (1989-1995)

$\sqrt{s} \simeq m_Z = 91.187\,GeV$

~5M Z DECAYS / EXPERIMENT

⇒ PRECISE TESTS OF
ELECTRO-WEAK UNIFIED GAUGE
THEORY + QCD
HEAVY FLAVOUR PHYSICS (b, τ)
⇒ B-FACTORIES

LEP1 RESULTS

① # of ν SPECIES = 3
⇒ # of q, l GENERATIONS = 3

② • INDIRECT DETERMINATION OF m_t
BEFORE THE TOP DISCOVERY.
• AFTER THE TOP DISCOVERY
INDIRECT DETERMINATION OF m_H

③ $\sin^2\theta_W$, α_s, (G_F)
⇒ HINT OF SUSY-GUT
UNIFICATION OF
$SU(3)_c$ $SU(2)_L$ $U(1)$
COUPLINGS @ $\sim 10^{16}$ GeV

LEP2 PHYSICS

• W BOSON PHYSICS

m_W

SEARCH FOR ANOMALOUS GAUGE COUPLING (γWW, ZWW γZZ, ZZZ)

• SEARCH FOR HIGGS

SM HIGGS

HIGGS IN SUSY MODELS

$\Rightarrow$ • ORIGIN OF $SU(2)_L \times U(1) \rightarrow U(1)_{EM}$ BREAKING
• ORIGIN OF MASS

• SEARCH FOR SUSY

GAUGINOS + HIGGSINOS
SFERMIONS

$\Rightarrow$ ORIGIN OF SUSY BREAKING

• NEW PHYSICS

SEARCH FOR ANY NEW PARTICLES AND PHENOMENA @ ENERGY-FRONTIER

1 ELECTRO-WEAK

(1) TWO FERMION PROCESSES

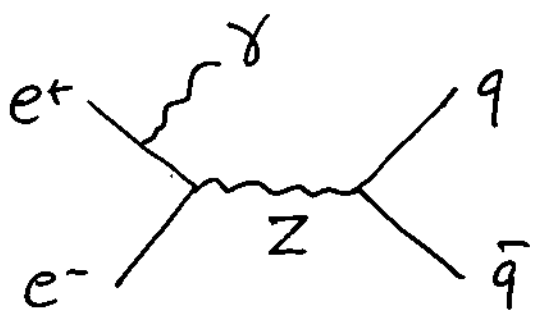
$e^+e^- \longrightarrow e^+e^-\ (\gamma)$

$\mu^+\mu^-\ (\gamma)$

$\tau^+\tau^-\ (\gamma)$

$q\bar{q}\ (\gamma)$

$(\ b\bar{b}\ (\gamma)\ )$



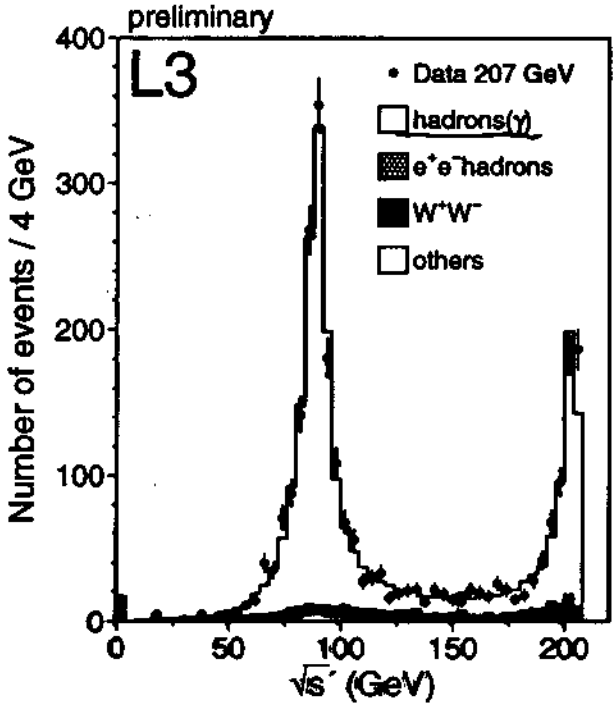
$$\sqrt{s'} = M_{q\bar{q}}$$

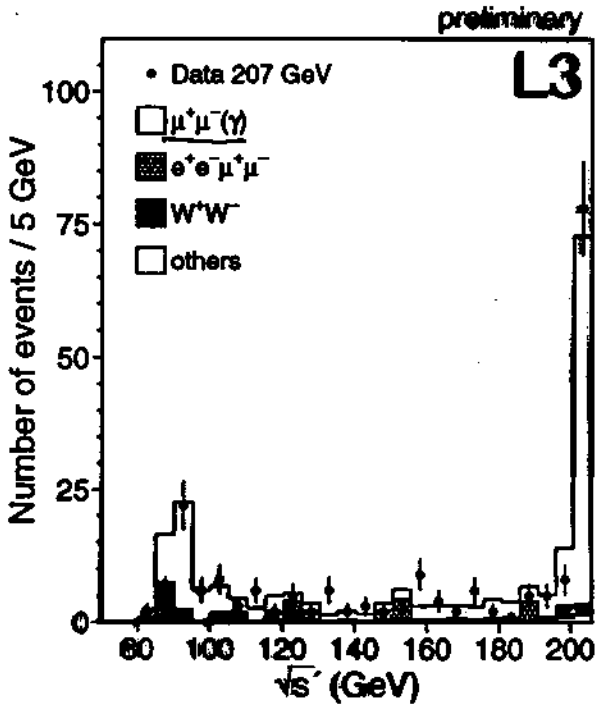
$$= \sqrt{s\,(1 - 2E_\gamma/\sqrt{s})}$$

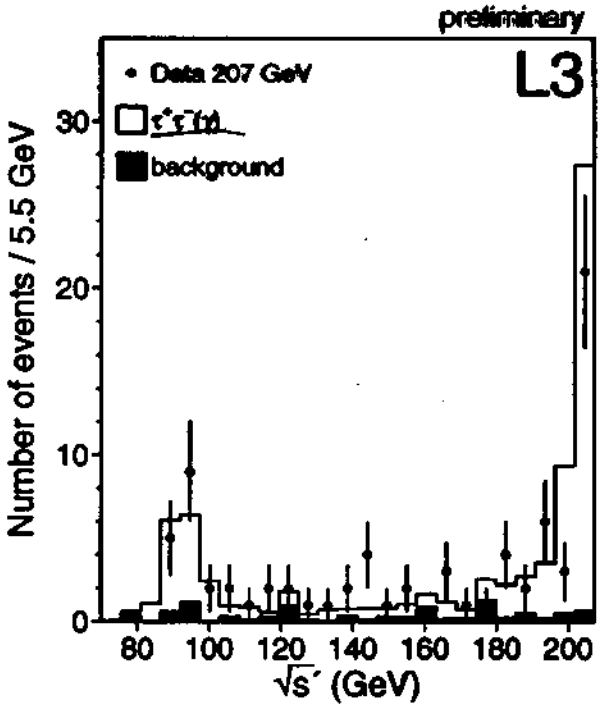
$\sigma_{q\bar{q}(\gamma)}$ IS LARGE

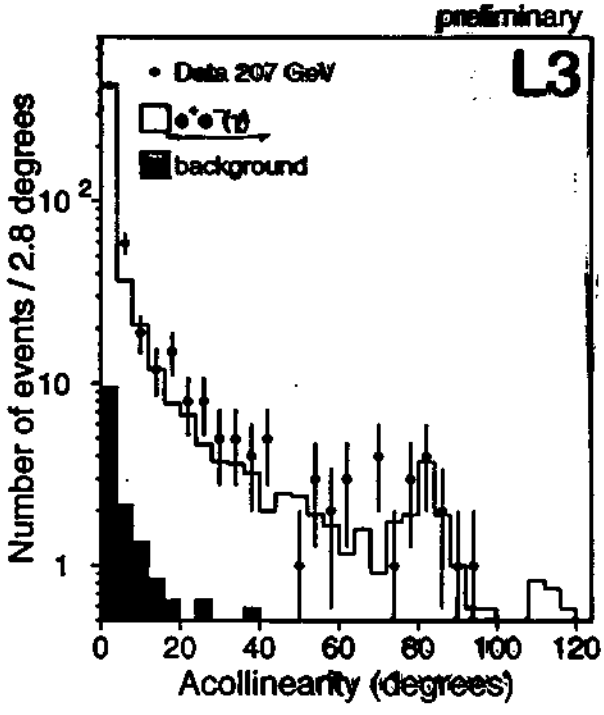
FOR $\sqrt{s'} \approx M_Z$

Fermion-Pair Production - $\sqrt{s'}$



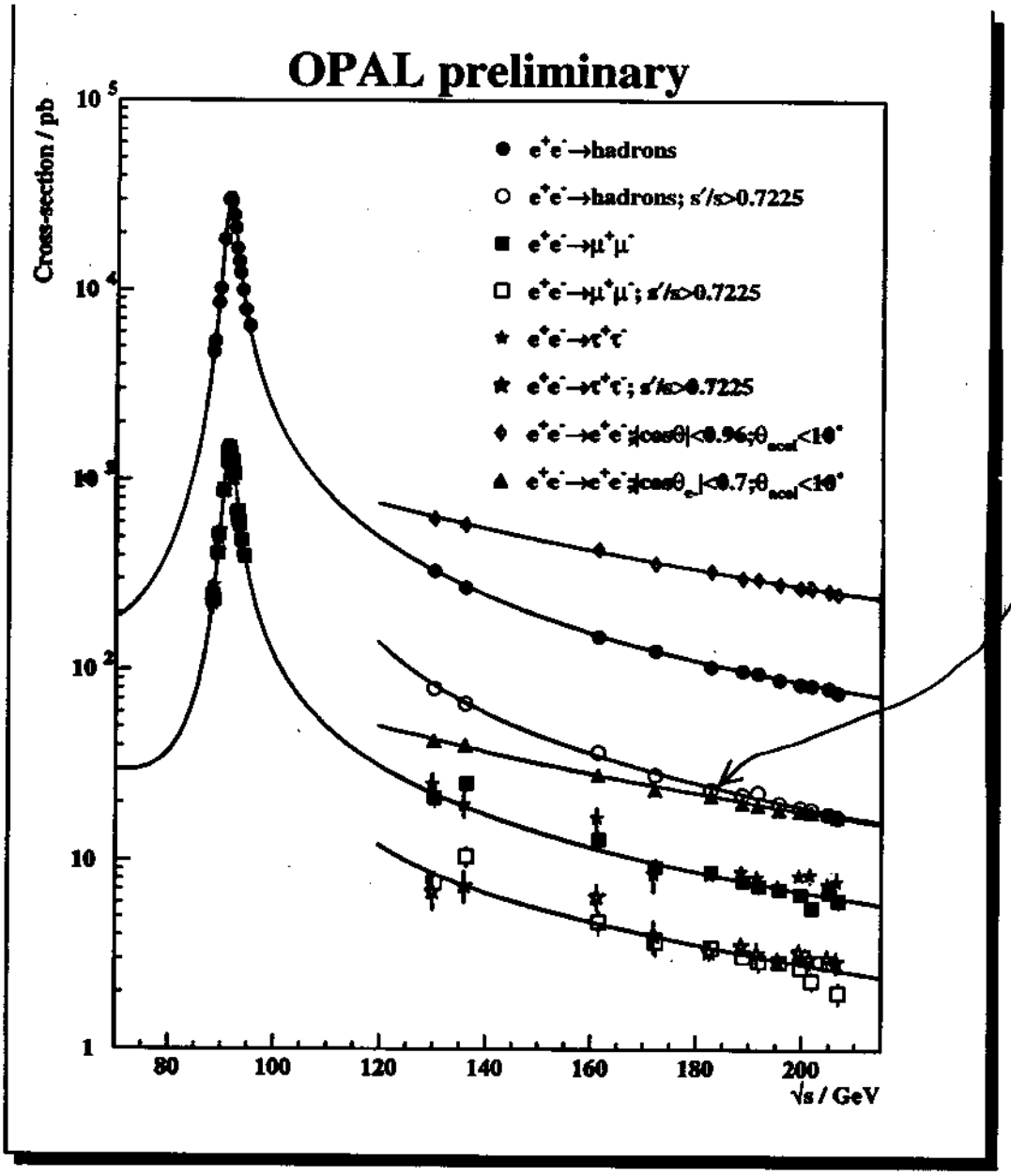






$\sqrt{s}$ (GeV) mean	range	$\int \mathcal{L} dt$ (pb^{-1})	$\Delta\mathcal{L}$ (%)
204.8±0.1	202.5 – 205.5	58	0.29
206.6±0.1	>205.5	28	0.33
205.4±0.1	>202.5	87	0.28

Two-Fermion cross-section

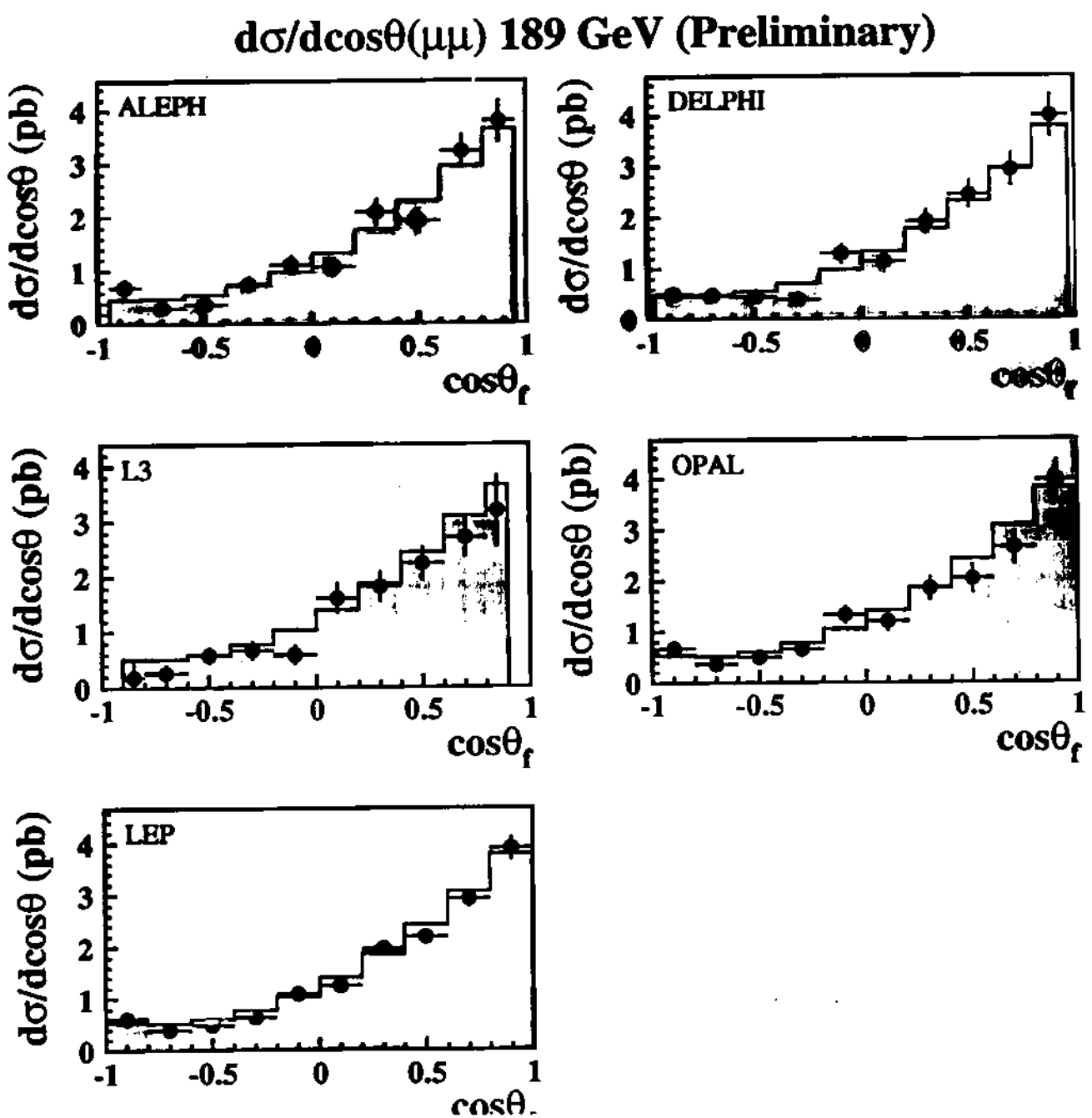


Still good agreement with the SM, except for one..

$$\frac{d\sigma}{d\cos\theta_{\mu^-}}(e^+e^- \to \mu^+\mu^-)$$

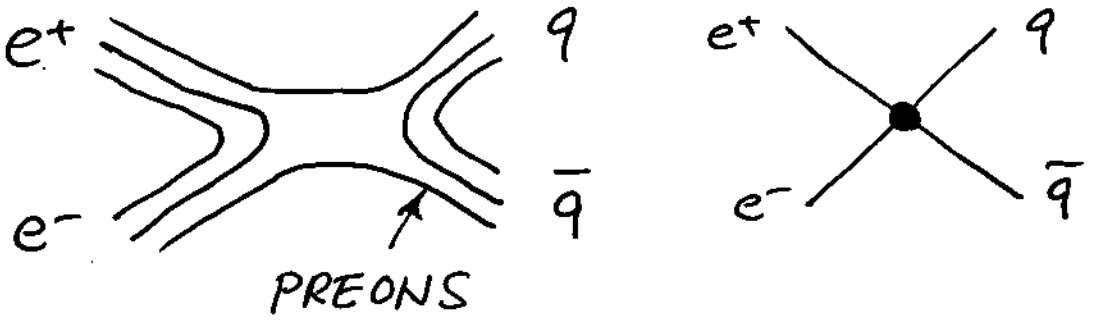
$$\sqrt{s} = 189\ \text{GeV}$$

$$\sqrt{s'}/s > 0.85$$



SEARCH FOR NEW FROM $f\bar{f}$ CROSS SECTIONS

IX. CONTACT INTERACTION (PREON ENERGY SCALE)



HELICITY CONSERVING LAGLANGIAN

$$\mathcal{L}_c = \frac{g^2}{\Lambda^2} \sum_{i,j=R,L} \eta_{ij} [\bar{e}_i \gamma^\mu e_i][\bar{q}_j \gamma^\mu q_j]$$

($\mathcal{L}_c$: CONTACT)

$$\mathcal{L}_{TOTAL} = \mathcal{L}_{SM} + \mathcal{L}_c$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\Big|_{SM} + C_1(s,t)\frac{g^2}{\Lambda^2} + C_2(s,t)\frac{g^4}{\Lambda^4}$$

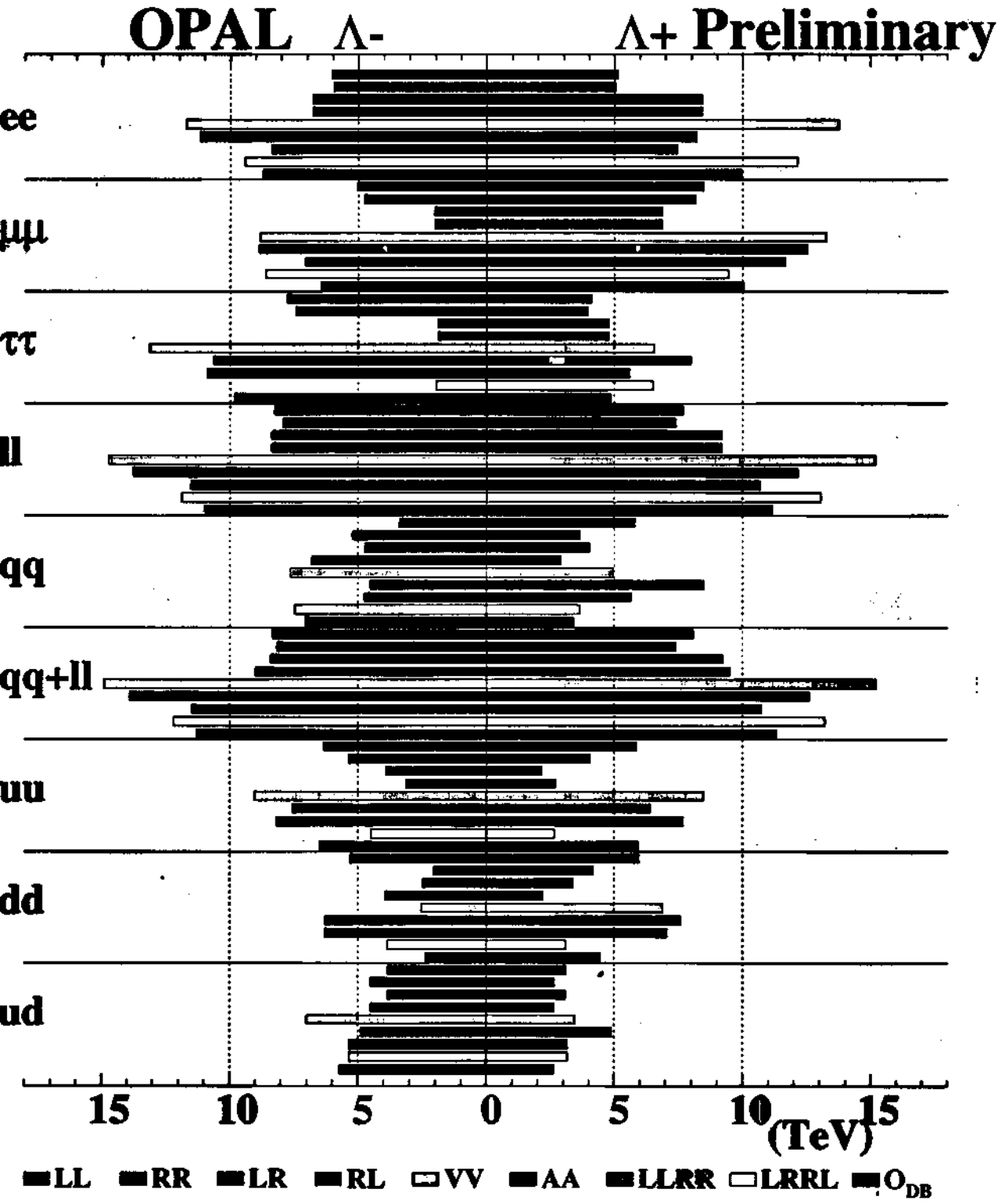
INTERFERENCE CONTACT

AT LEP2

$\frac{d\sigma}{d\Omega}\Big|_{SM}$ IS SMALL

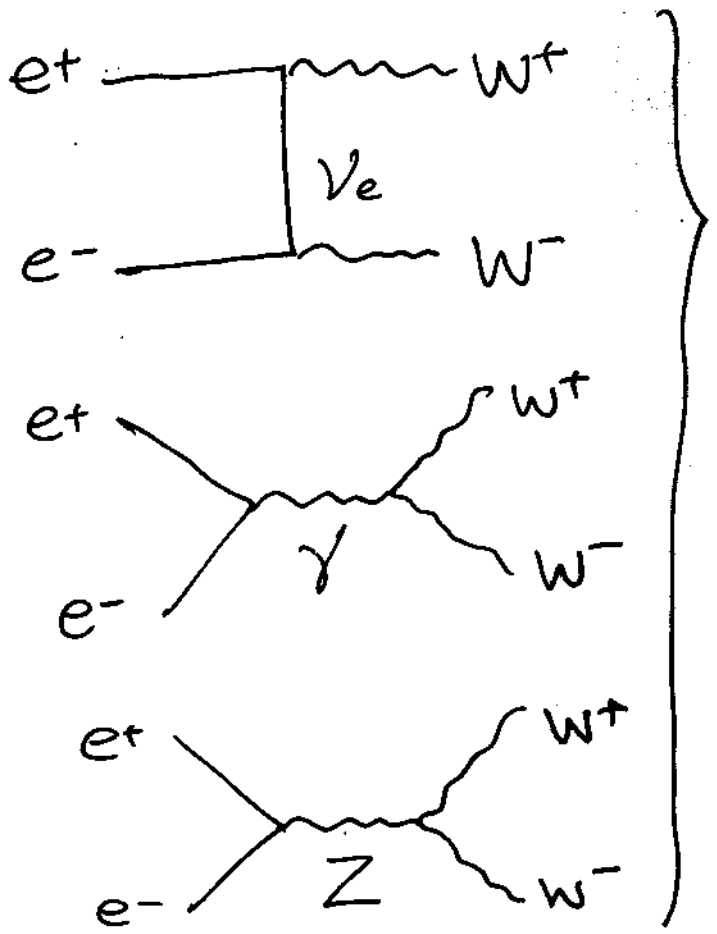
RELATIVELY LARGE EFFECT CAN BE SEEN.

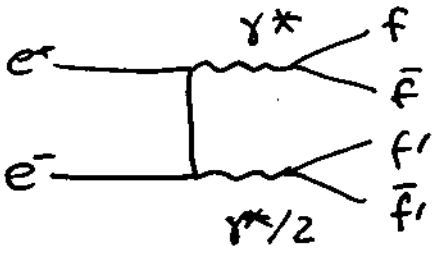
$\frac{g^2}{4\pi} = 1 \qquad \eta_{ij} = \pm 1, 0$



(2) W-BOSON PHYSICS

(A) W^+W^- CROSS SECTION





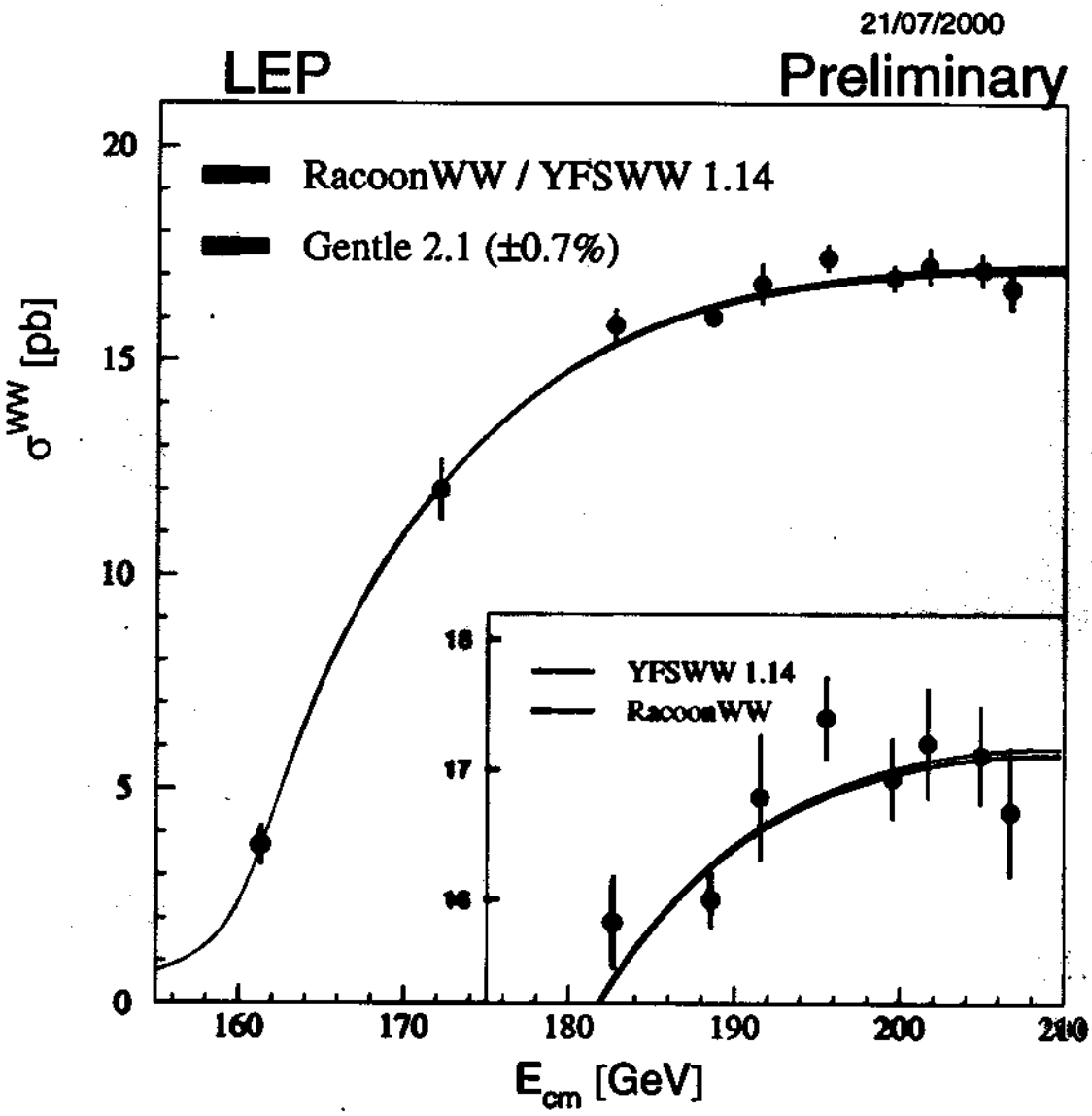
+ ....

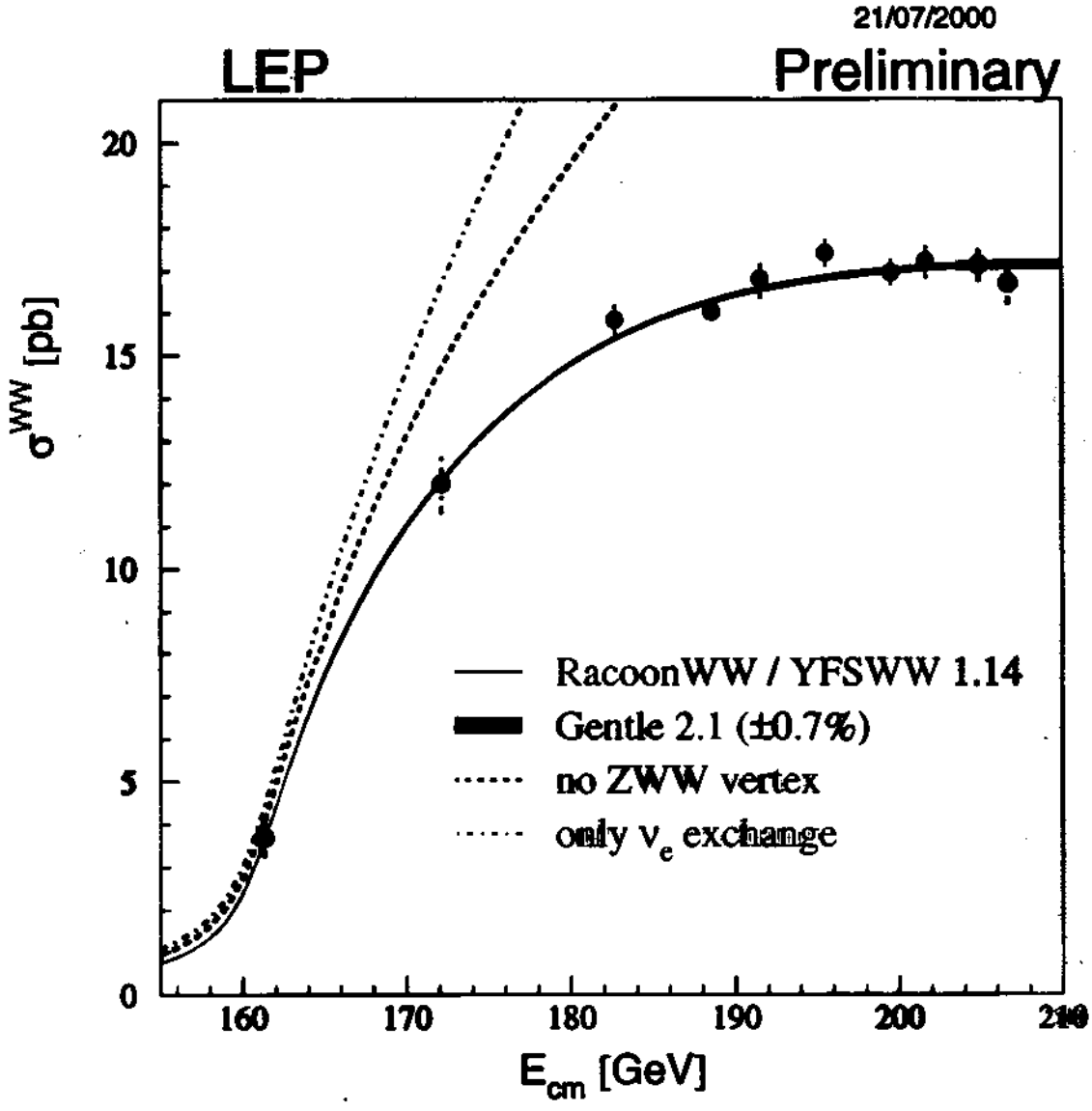
INTERFERENCE

$W^+ \to e^+\nu_e$, $\mu^+\nu_\mu$, $\tau^+\nu_\tau$ EACH $\sim 1/9$

$W^+ \to u\bar{d}$, $c\bar{s}$ EACH $\sim 1/3$

(NEGLECTING CKM-MIXING)


21/07/2000
LEP
Preliminary
RacoonWW / YFSWW 1.14
Gentle 2.1 (±0.7%)
YFSWW 1.14
RacoonWW
σ^{WW} [pb]
E_{cm} [GeV]
0
5
10
15
20
160
170
180
190
200
210


21/07/2000
LEP
Preliminary
σ^{WW} [pb]
20
15
10
5
0
160
170
180
190
200
210
E_{cm} [GeV]
RacoonWW / YFSWW 1.14
Gentle 2.1 (±0.7%)
no ZWW vertex
only ν_e exchange

(B) W-BOSON MASS MEASUREMENT

- EVENT SELECTION SHOUD BE DESIGNED NOT TO BIAS m_W MEASUREMENT

- KINEMATICAL FIT ($m_{W_1} = m_{W_2}$)

  $q\bar{q}q\bar{q}$ CHANNEL 5C FIT

  USE A COMBINATION OF MAX. $P(\chi^2)$

  $q\bar{q}\ell\nu$ CHANNEL 2C FIT
  ($\ell = e, \mu$)

  $q\bar{q}\tau\nu$ CHANNEL
  ENERGY RESCALING
  ($E_{jj} \rightarrow \sqrt{s}/2$)

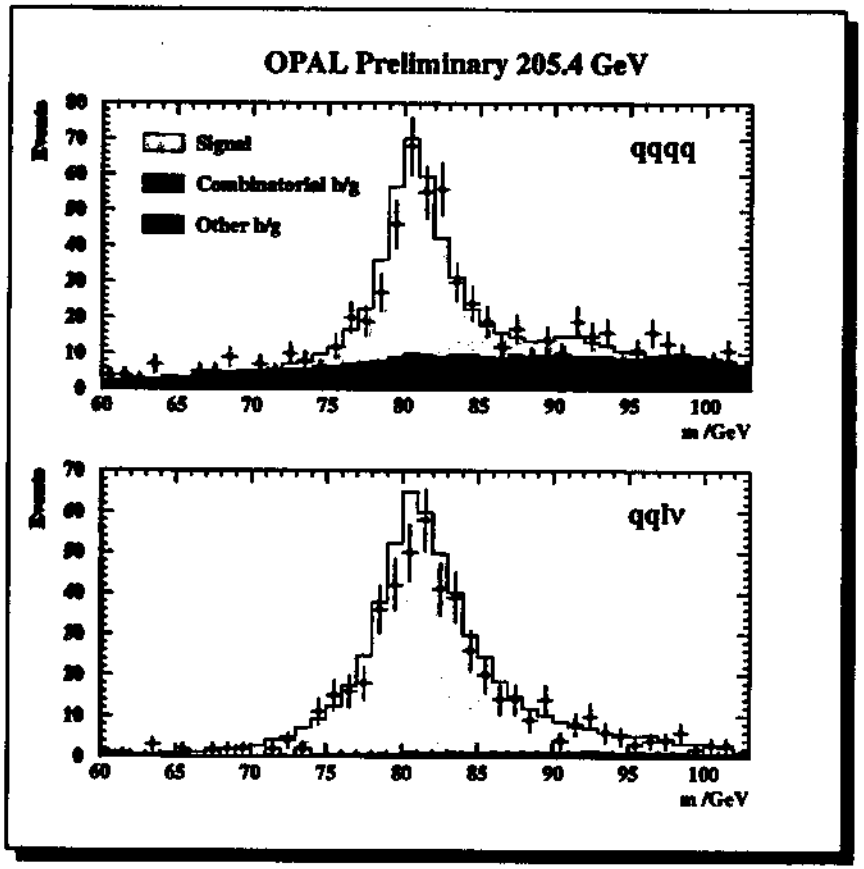
  $\ell\nu\ell\nu$ CANNOT BE USED

- FIT MASS DISTRIBUTION WITH A EXPECTED FUNCTION FORM (m_W)

- CALCULATE BIAS FROM MC'S CORRECT IT (MAINLY FROM RADIATIONS)

Four-Fermion Processes

Event at $\sqrt{s}$ = 208.4 GeV



Mass Reconstruction is fine.

($M_{CMW} = 80.42$ GeV)

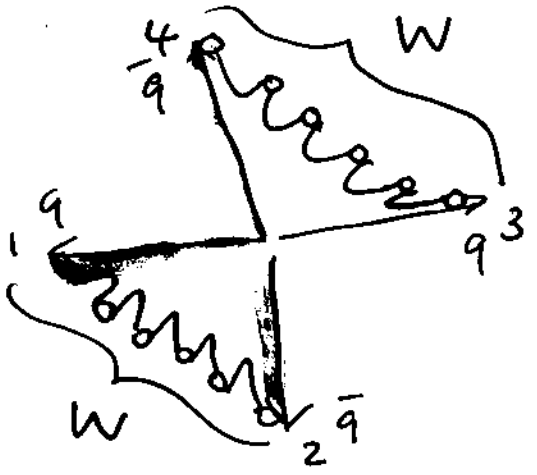
COLOUR RECONNECTION

(IMPORTANT SOURCE OF SYSTEMATIC ERROR)

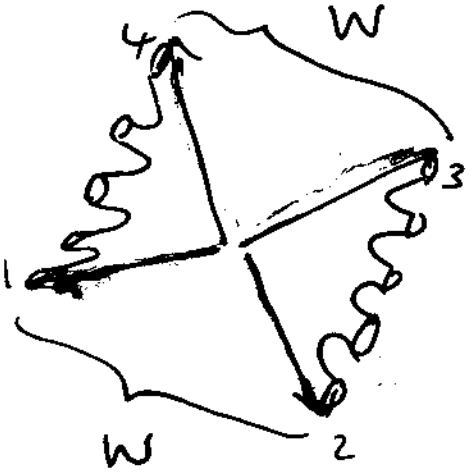
$e^+e^- \to W^+W^- \to \underbrace{q\bar{q}}_{W}\, l\nu$

NO OTHER CHOICE

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



Normal



Colour reconnection

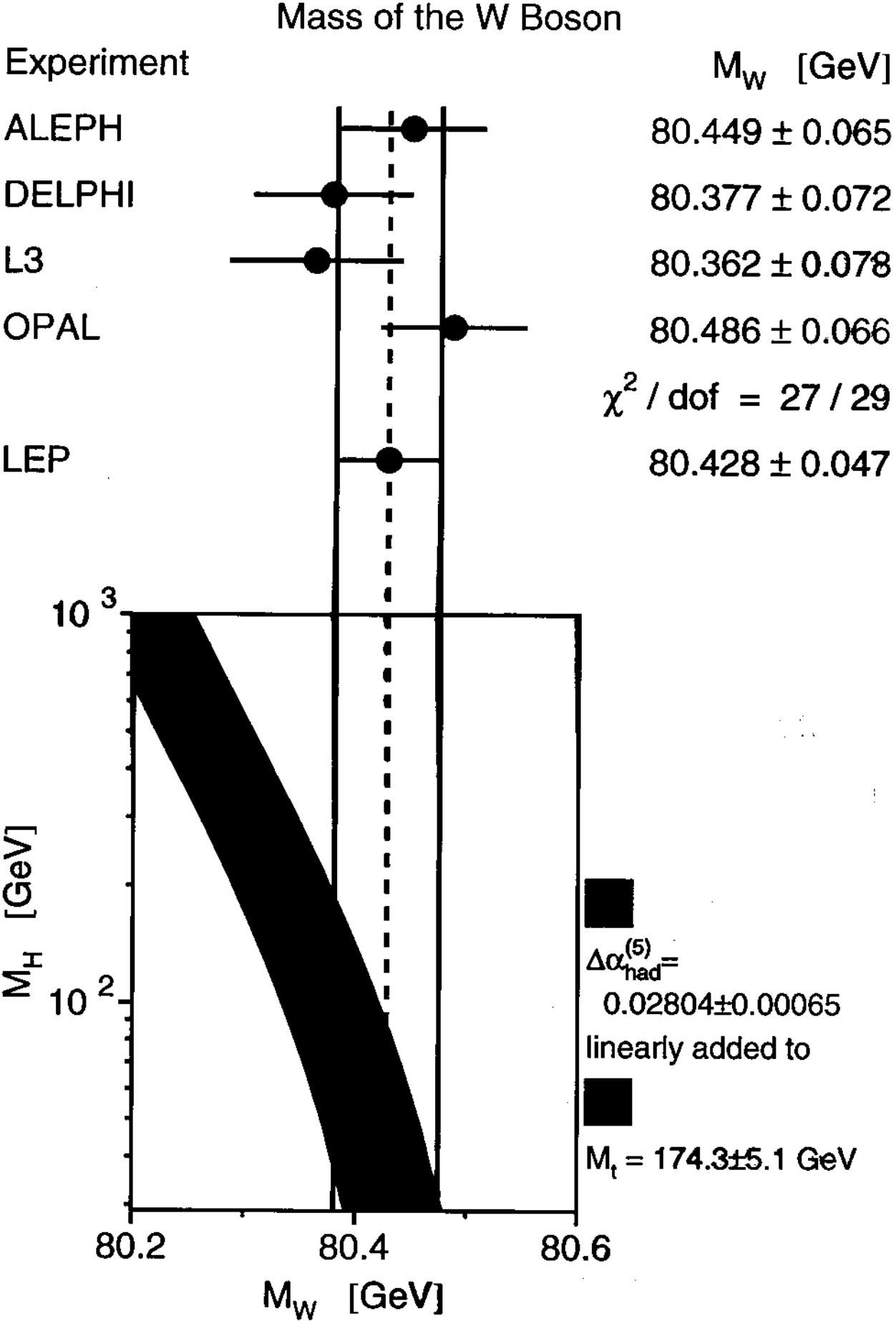
2-3 colour singlet

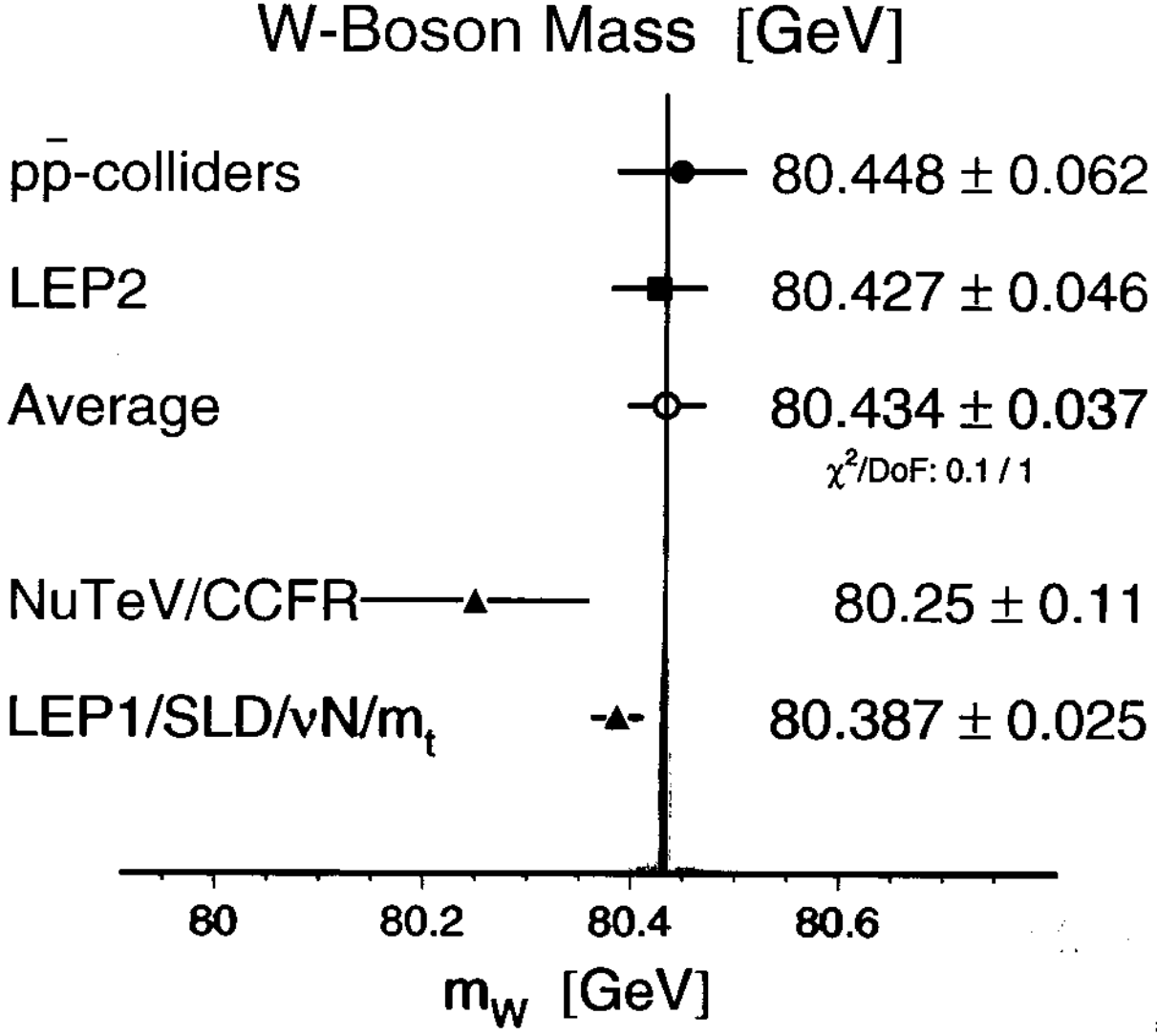
4-1 colour singlet

PARTICLE ASIGNMENT TO JETS

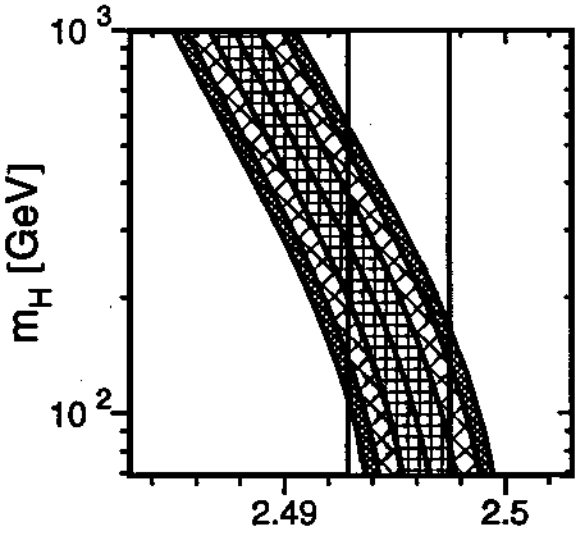
DIFFERS { REAL EVENTS
MC (WITHOUT COLOUR RECONNEC.)

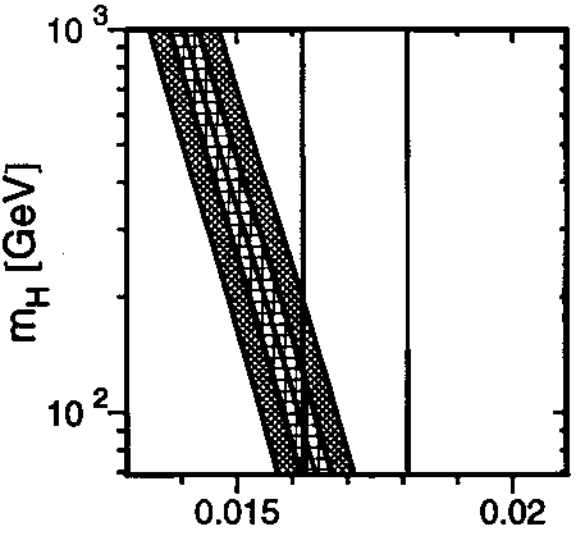
$$\Delta M^{CR}_{syst.} \simeq 30\,MeV$$

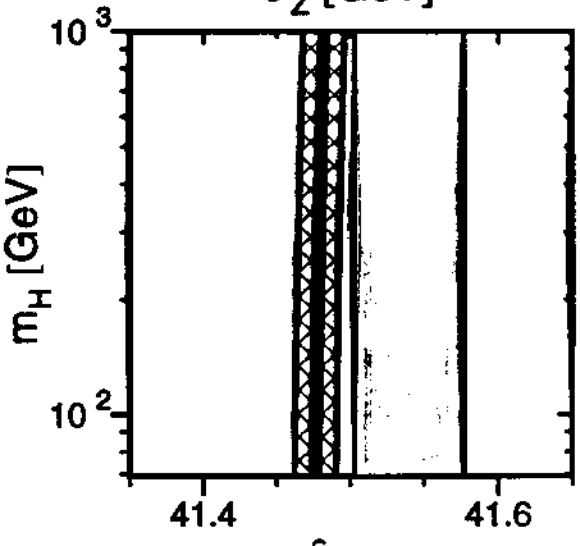

Mass of the W Boson
Experiment
M_W [GeV]
ALEPH
80.449 ± 0.065
DELPHI
80.377 ± 0.072
L3
80.362 ± 0.078
OPAL
80.486 ± 0.066
χ^2 / dof = 27 / 29
LEP
80.428 ± 0.047
10^3
10^2
M_H [GeV]
$\Delta\alpha^{(5)}_{had}$=
0.02804±0.00065
linearly added to
M_t = 174.3±5.1 GeV
80.2
80.4
80.6
M_W [GeV]

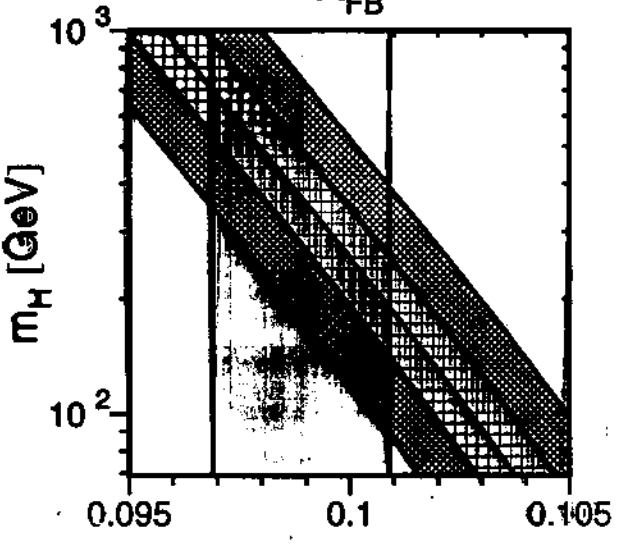

W-Boson Mass [GeV]
p$\bar{p}$-colliders
80.448 ± 0.062
LEP2
80.427 ± 0.046
Average
80.434 ± 0.037
χ^2/DoF: 0.1 / 1
NuTeV/CCFR
80.25 ± 0.11
LEP1/SLD/νN/m_t
80.387 ± 0.025
80
80.2
80.4
80.6
m_W [GeV]

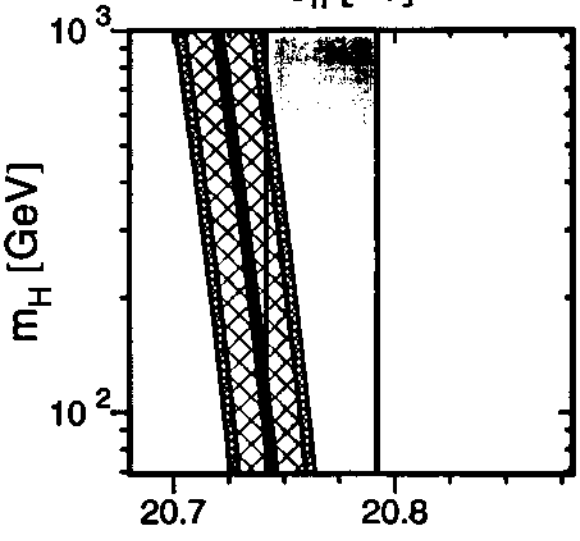
Preliminary

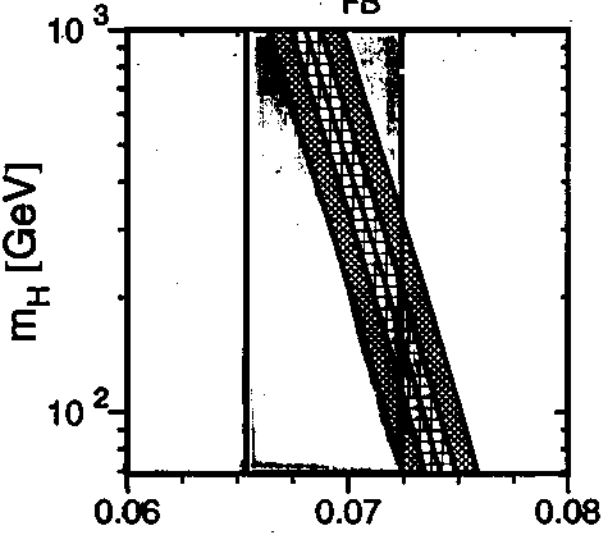


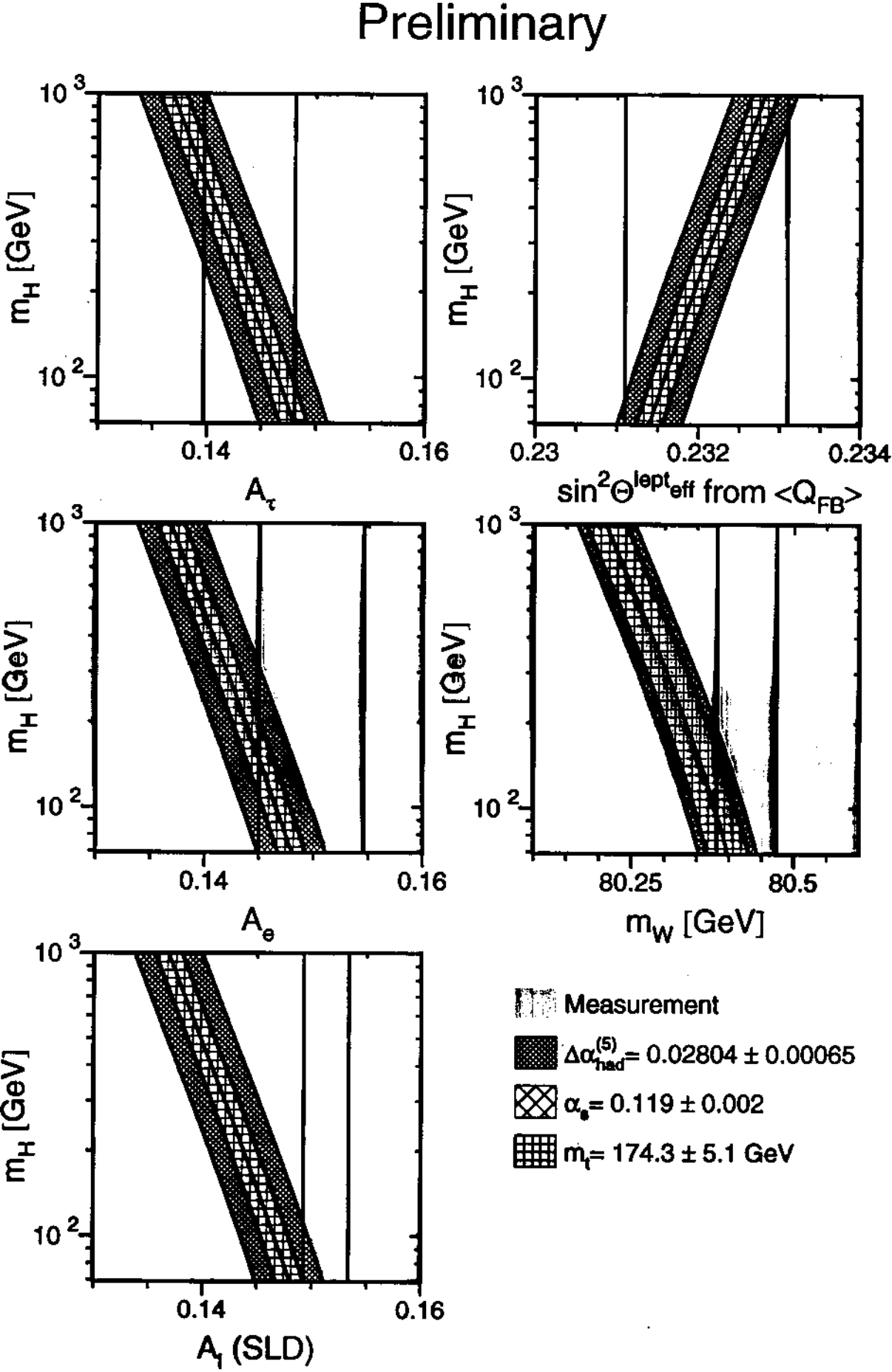


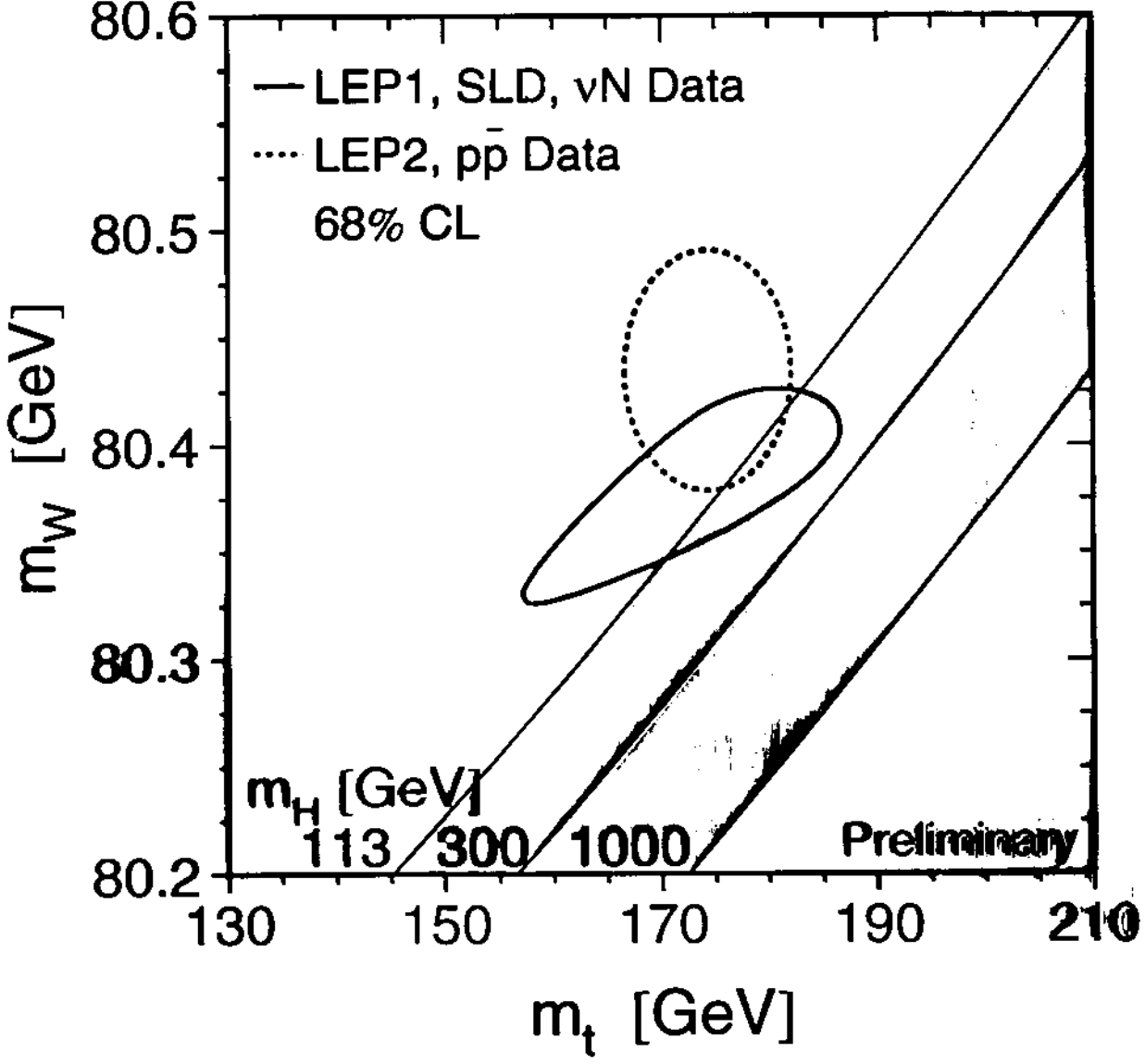


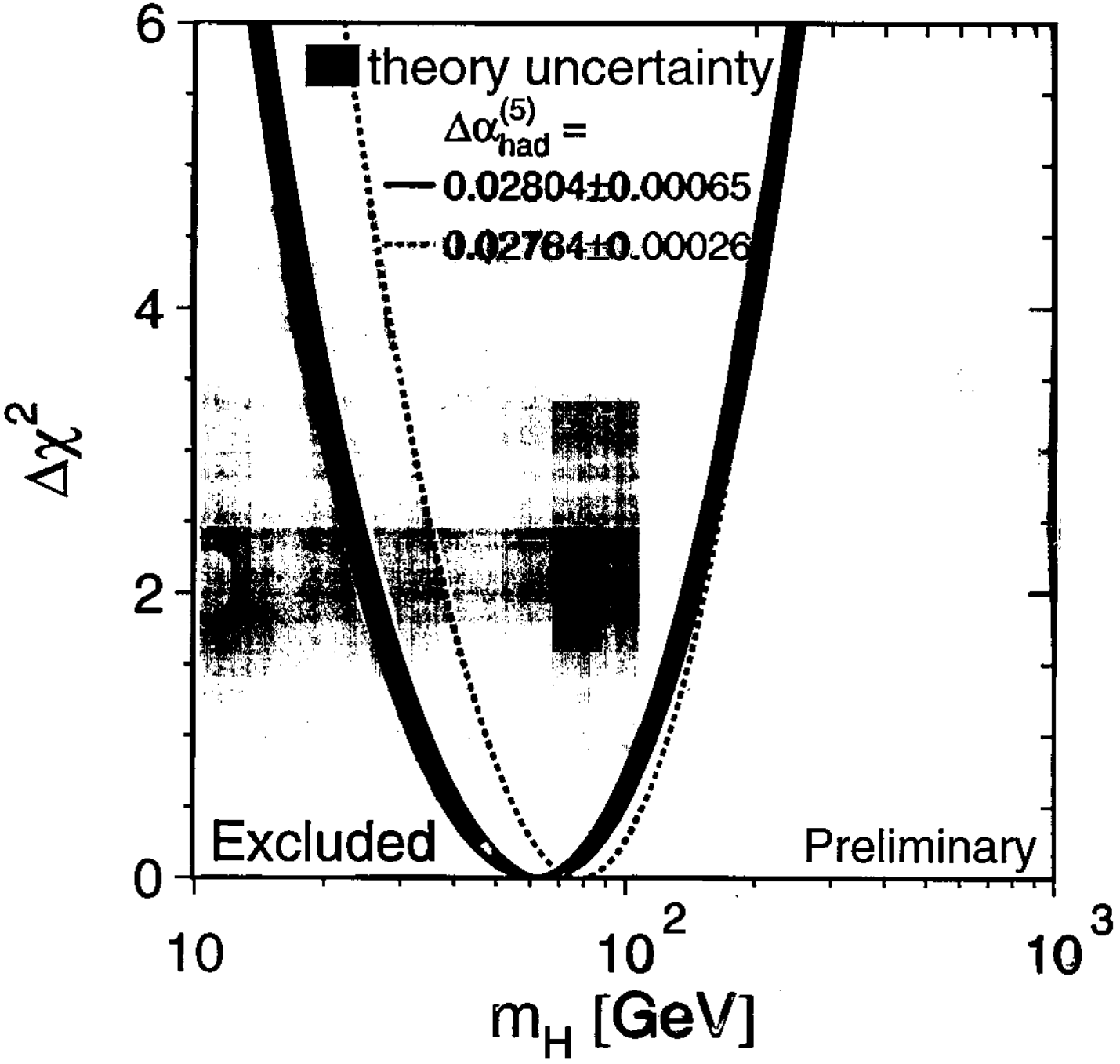







Preliminary
10^3
10^2
m_H [GeV]
0.14
0.16
A_τ
0.23
0.232
0.234
$\sin^2\Theta^{lept}_{eff}$ from $<Q_{FB}>$
A_e
80.25
80.5
m_W [GeV]
A_l (SLD)
Measurement
$\Delta\alpha^{(5)}_{had} = 0.02804 \pm 0.00065$
$\alpha_s = 0.119 \pm 0.002$
$m_t = 174.3 \pm 5.1$ GeV


LEP1, SLD, νN Data
LEP2, pp̄ Data
68% CL
m_H [GeV]
113
300
1000
Preliminary
m_W [GeV]
m_t [GeV]
80.6
80.5
80.4
80.3
80.2
130
150
170
190
210


theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02804±0.00065
0.0278±0.00026
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]
0
2
4
6
10
10^2
10^3

GLOBAL ELECTRO-WEAK FIT

$\Rightarrow m_{H_{SM}} < 170\ GeV$ @ 95% CL

INCLUDING BESII R-MEAS. $\Rightarrow \alpha$ (Z. Zhao's TALK)

$m_{H_{SM}} < 210\ GeV$ @ 95% CL

HIGGS IS HIDING AROUND THE CORNER.

SEE ATUL GURTU (Bombay) ICHEP2000

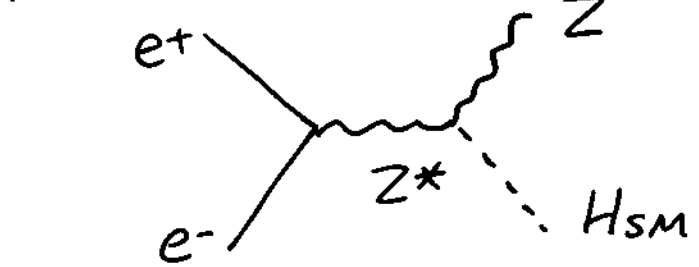
2 HIGGS BOSONS

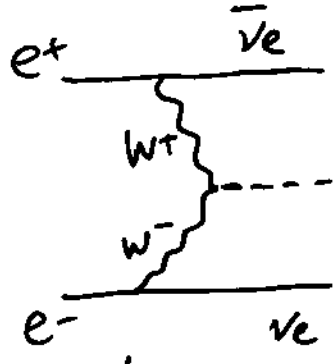
① SEARCH FOR SM HIGGS BOSON

ONLY ONE HIGGS DOUBLET IN SM

4 FIELDS
- 2 CHARGED − 2 = 0 ← EATEN BY W^+, W^-
- 2 NEUTRAL − 1 = 1 : PHYSICAL HIGGS ← EATEN BY Z

PRODUCTION





(≲ 10% AT LEP2)

DECAY

$H_{SM} \rightarrow b\bar{b}$ ~85%
$\tau^+\tau^-$ ~8%
$c\bar{c}$
gg
WW^*

} for $M_{H_{SM}} = 100$ GeV

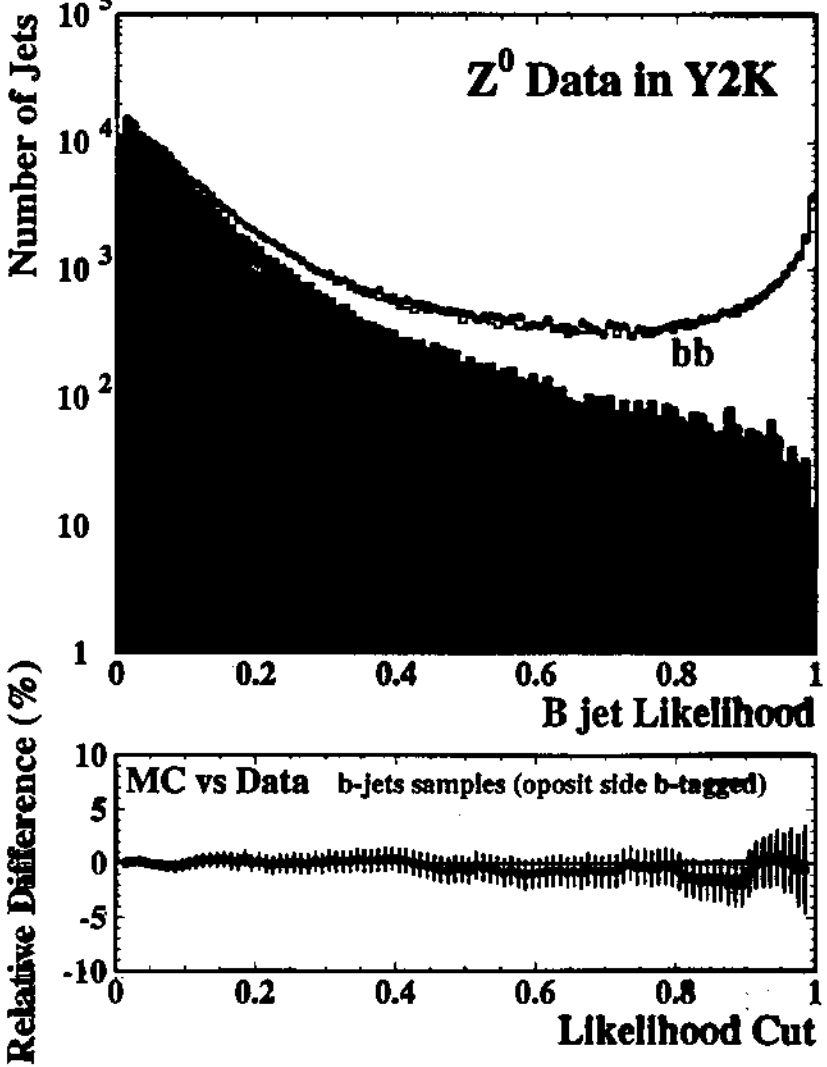
WW^* { INCREASES WITH M_H
$B(WW^*) \simeq B(\tau\tau)$ @ $M_H \simeq 110$ GeV

Various checks for b-tagging

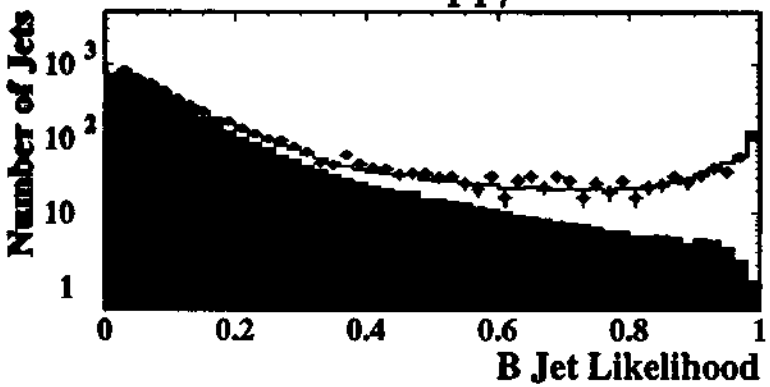
OPAL Preliminary

$At\sqrt{s} = 200 - 209$ GeV

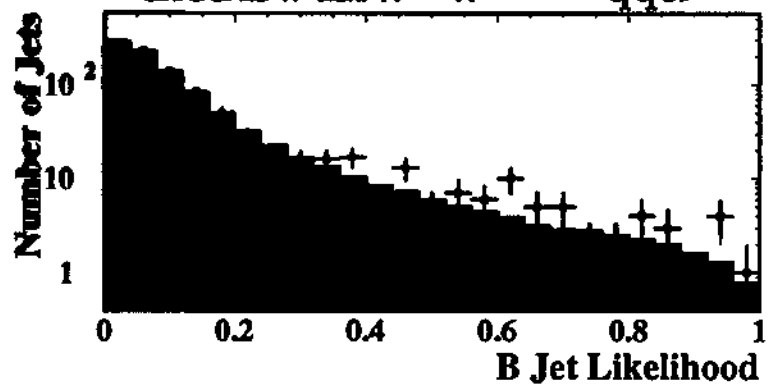
checks in Z^0 calibration data



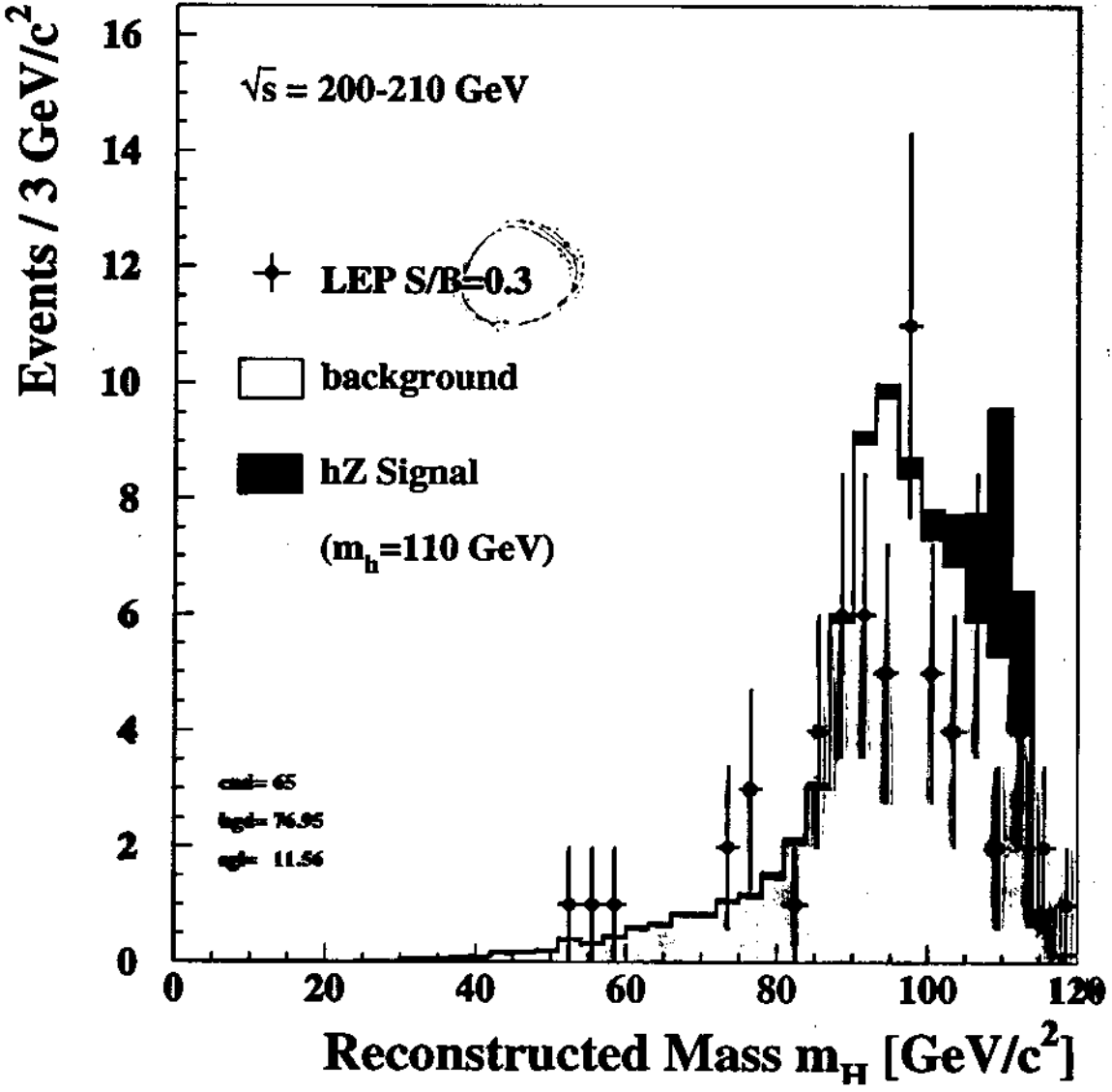
checks with $q\bar{q}\gamma$ events

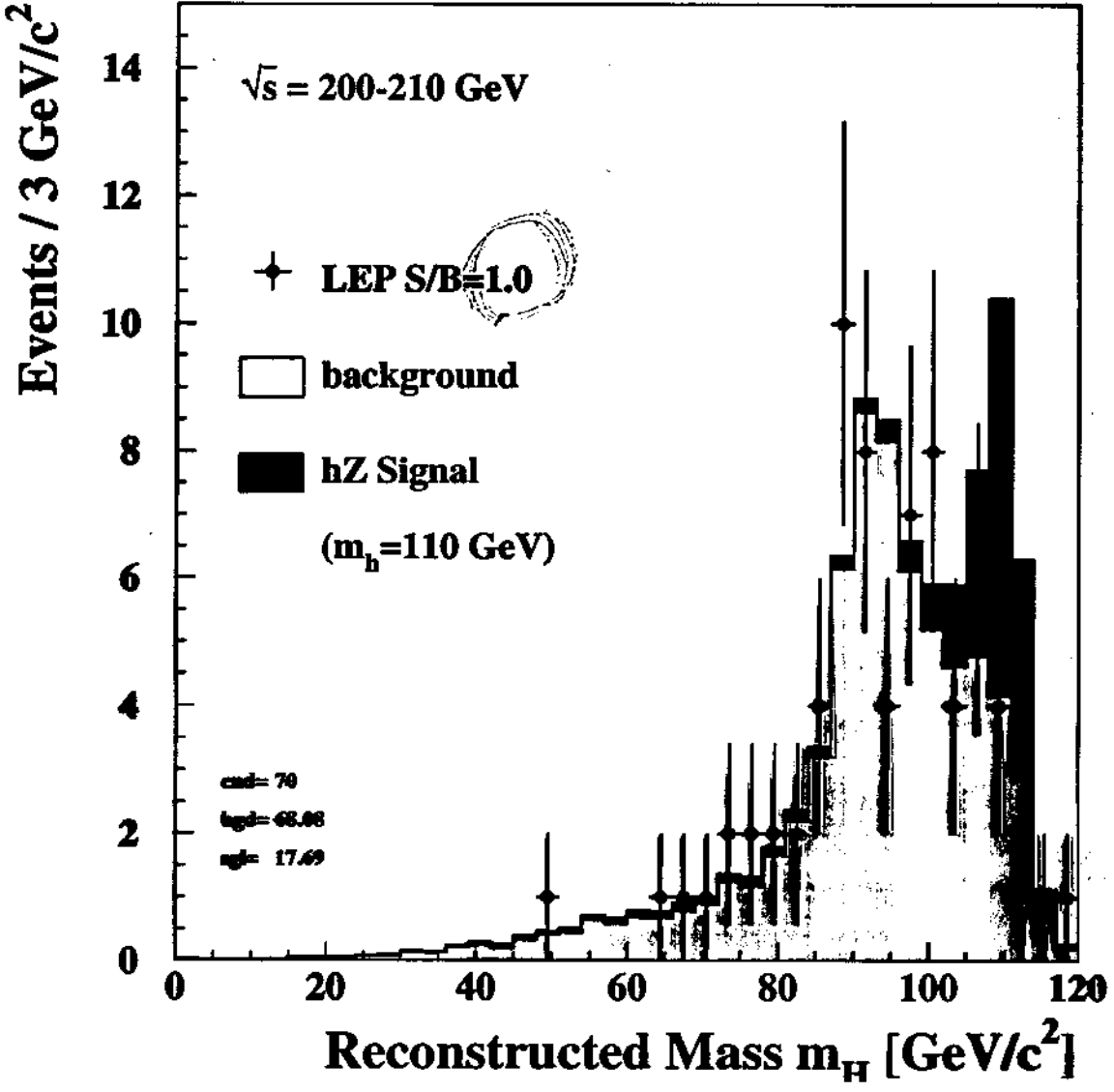


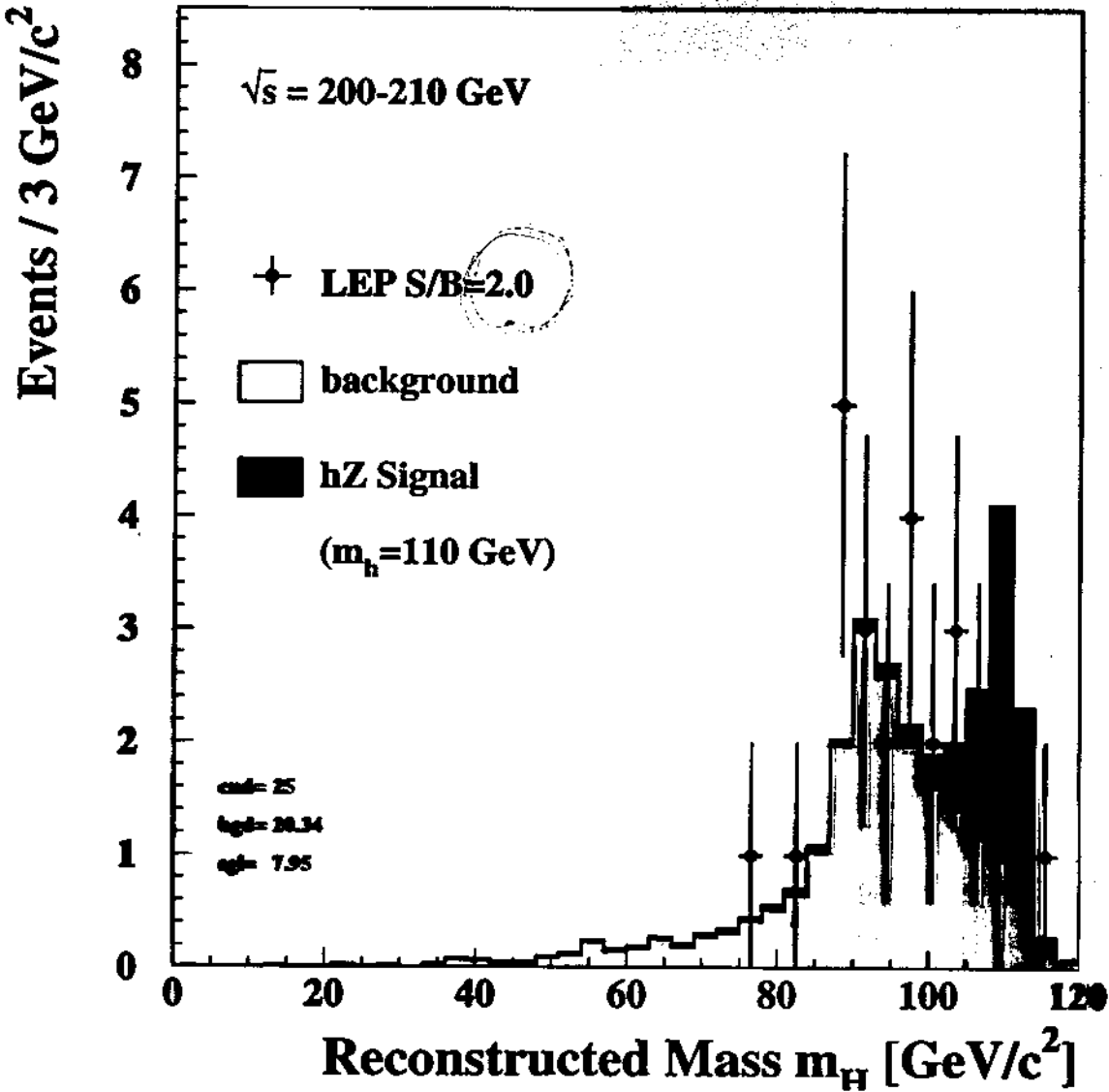
checks with $W^+W^- \rightarrow q\bar{q}\ell\nu$

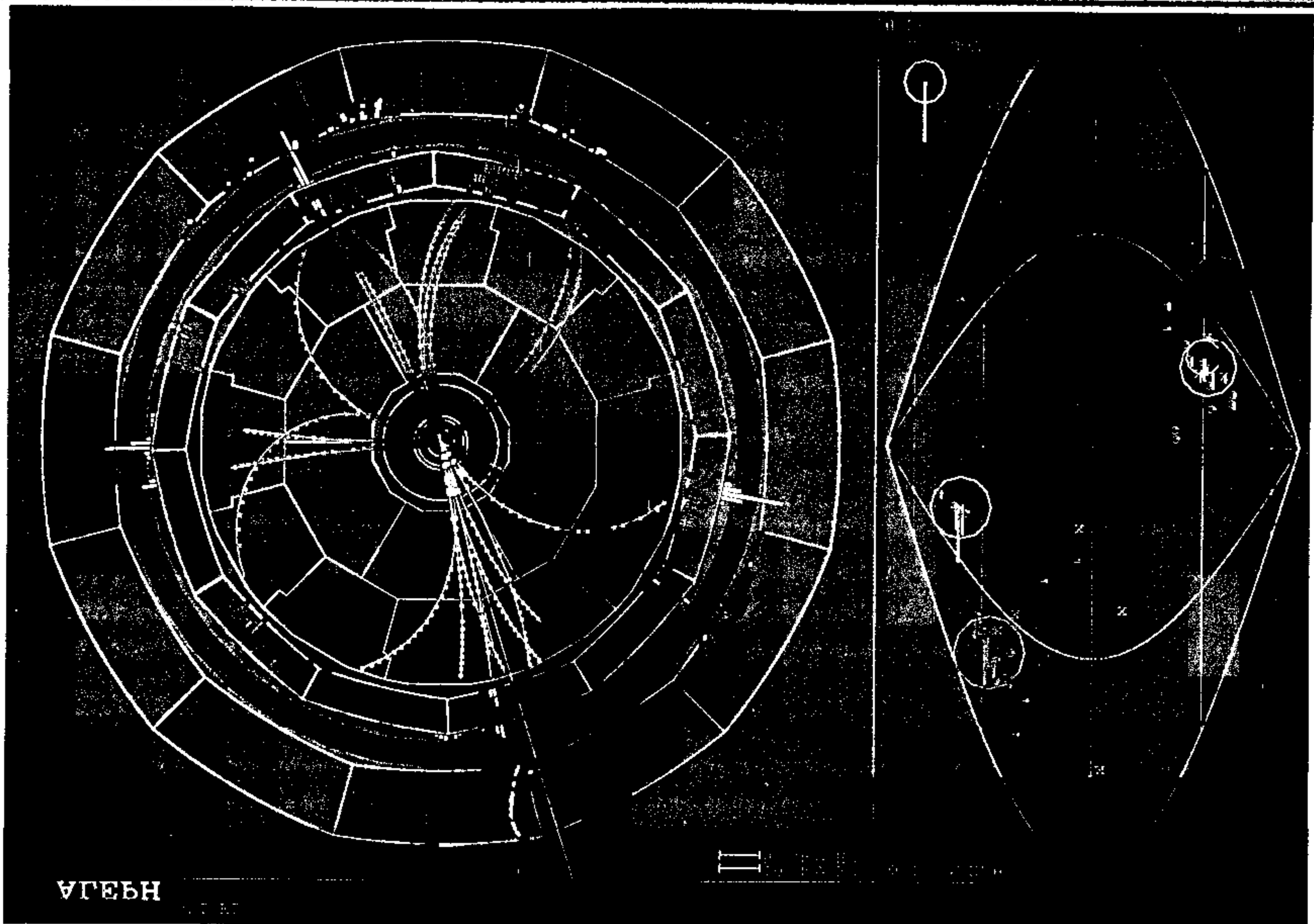


b-tagging works well as usual

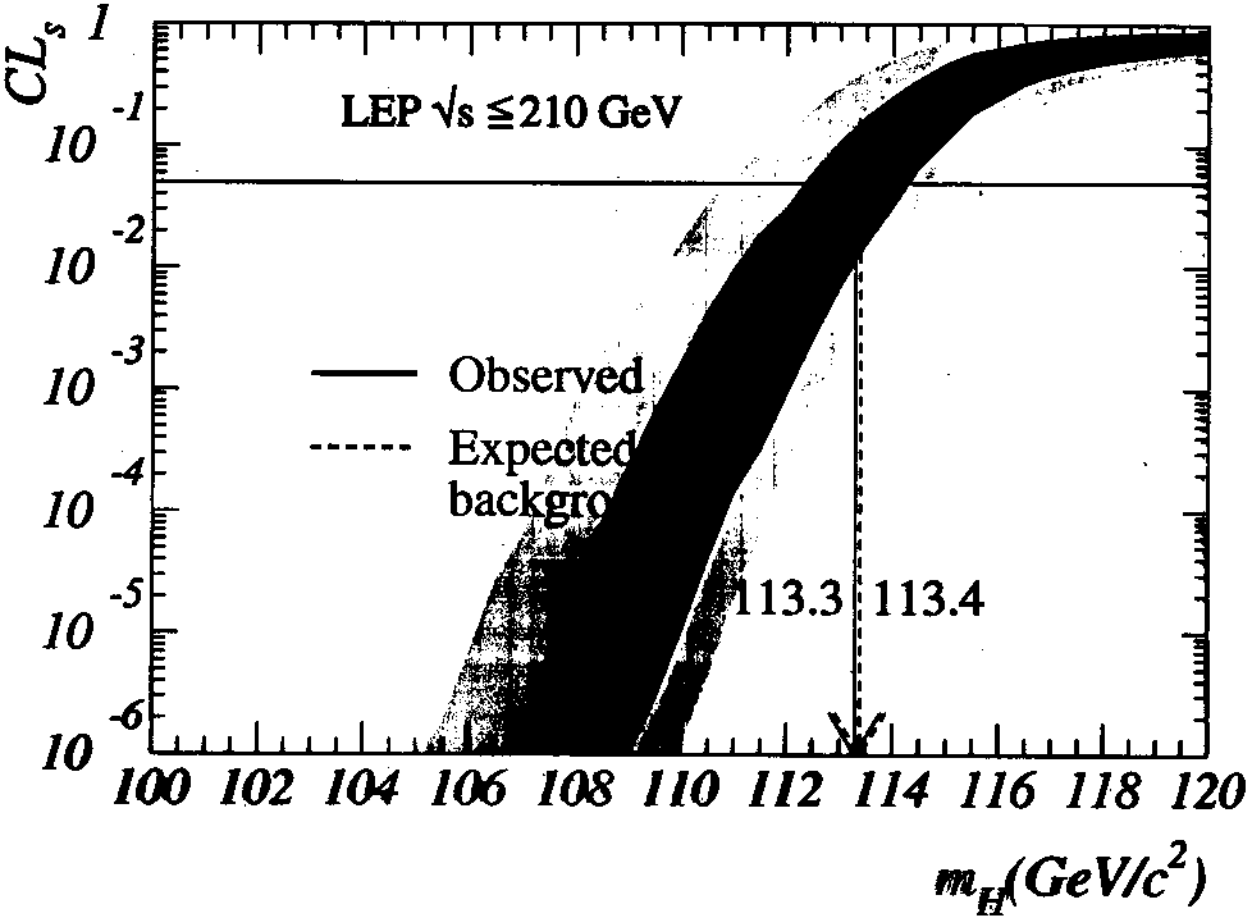

√s = 200-210 GeV
LEP S/B=0.3
background
hZ Signal
(m_h=110 GeV)
cand= 65
bgd= 76.95
sgd= 11.56
Events / 3 GeV/c²
Reconstructed Mass m_H [GeV/c²]
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
120


√s = 200-210 GeV
LEP S/B=1.0
background
hZ Signal
(m_h=110 GeV)
cnd= 70
bgd= 68.08
sgd= 17.69
Events / 3 GeV/c²
Reconstructed Mass m_H [GeV/c²]
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120


√s = 200-210 GeV
LEP S/B=2.0
background
hZ Signal
(m_h=110 GeV)
Events / 3 GeV/c²
Reconstructed Mass m_H [GeV/c²]
0
1
2
3
4
5
6
7
8
0
20
40
60
80
100
120



SM Higgs bbqq candidate

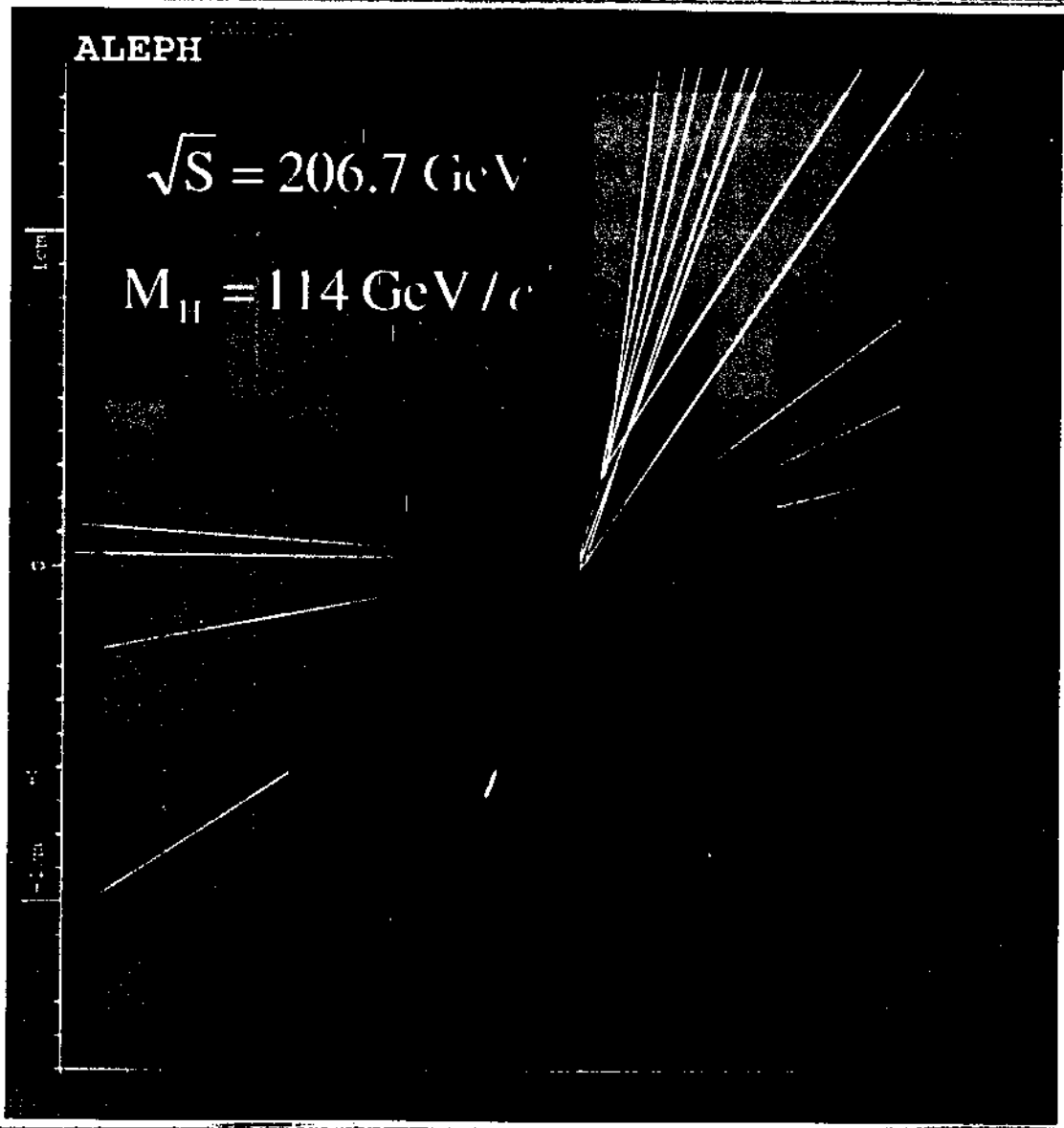


LEP COMBINED HIGGS BOSON MASS LIMIT

$m_{H_{SM}} > 113.3$ GeV

@ 95% CL

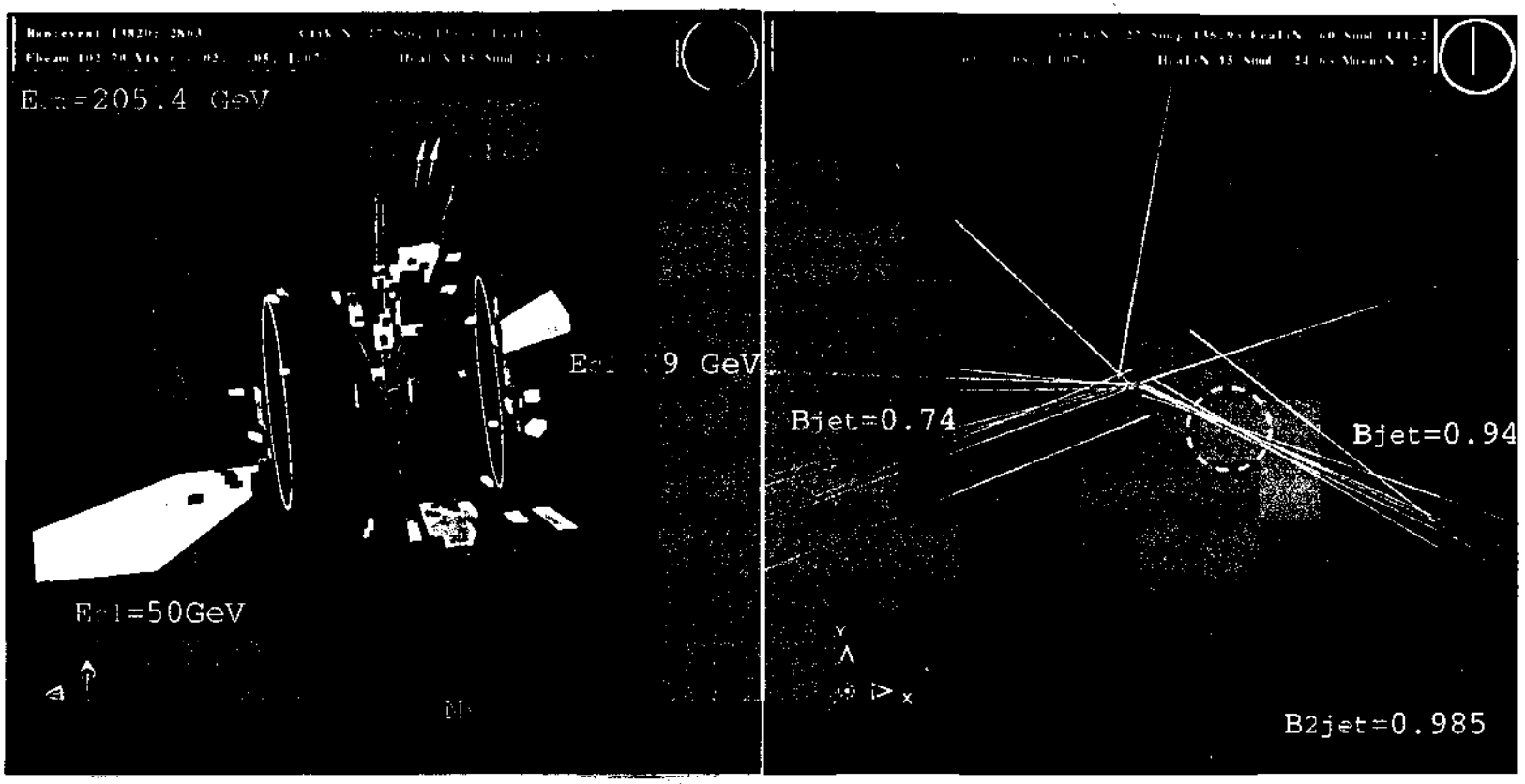
SM Higgs bbqq candidate - vertex region



SM Higgs

Highest Mass Candidate $M_{\mathrm{Higgs}} = 124$ GeV

$$e^+e^- \rightarrow H^0 e^+e^- \rightarrow b\bar{b}e^+e^-$$



one electron is poorly measured.

good b-tag

(2) SEARCH FOR MSSM HIGGS BOSONS

SUSY NEEDS AT LEAST 2 HIGGS DOUBLETS $\Rightarrow$ 8 FIELDS

4 CHARGED $-2 = 2$ $\quad H^+ H^-$

4 NUETRAL $-1 = 3$ $\quad h^\circ, H^\circ, A^\circ$

$\uparrow$ EATEN BY $W^\pm$ & Z

ESSENTIAL PARAMETERS

m_A , $\tan\beta = \frac{v_2}{v_1}$ $\leftarrow$ VACUUM EXPECTATION VALUES

- $m_{h^\circ} < m_{Z^\circ}$ TREE LEVEL
- $m_{h^\circ} \lesssim 130$ GeV HIGHER ORDER CORRECTIONS

(1990 OKADA, YAMAGUCHI. YANAGIDA)

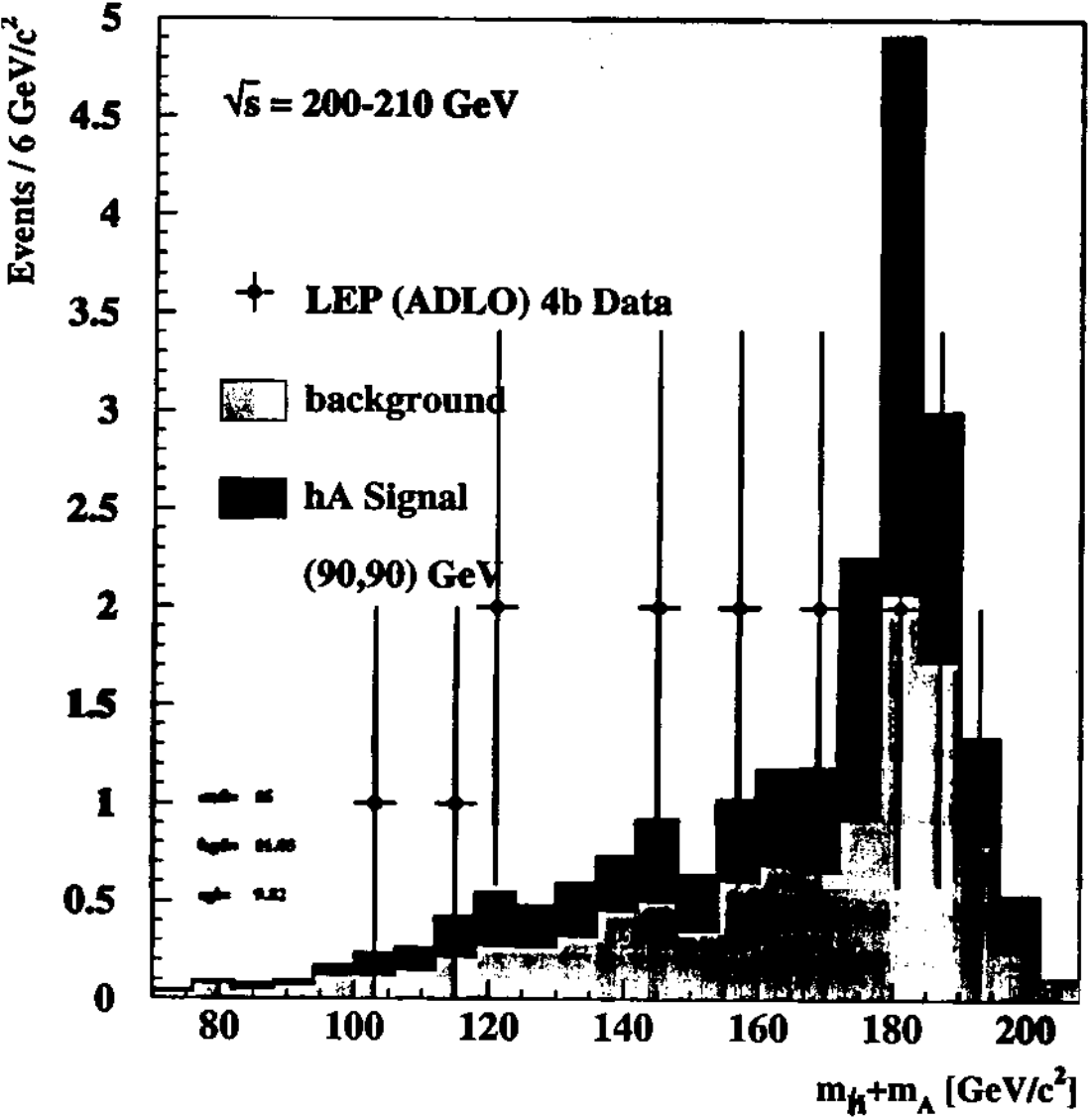
PRODUCTION

$e^+e^- \rightarrow Z h^\circ \quad \sigma = \sigma_{SM} \sin^2(\alpha-\beta)$

$e^+e^- \rightarrow A^\circ h^\circ \quad \sigma = \sigma_{SM} \cos^2(\alpha-\beta) \cdot \bar{\beta}^3$

DECAY

$A^\circ, h^\circ \rightarrow b\bar{b}$ OR $\tau^+\tau^-$

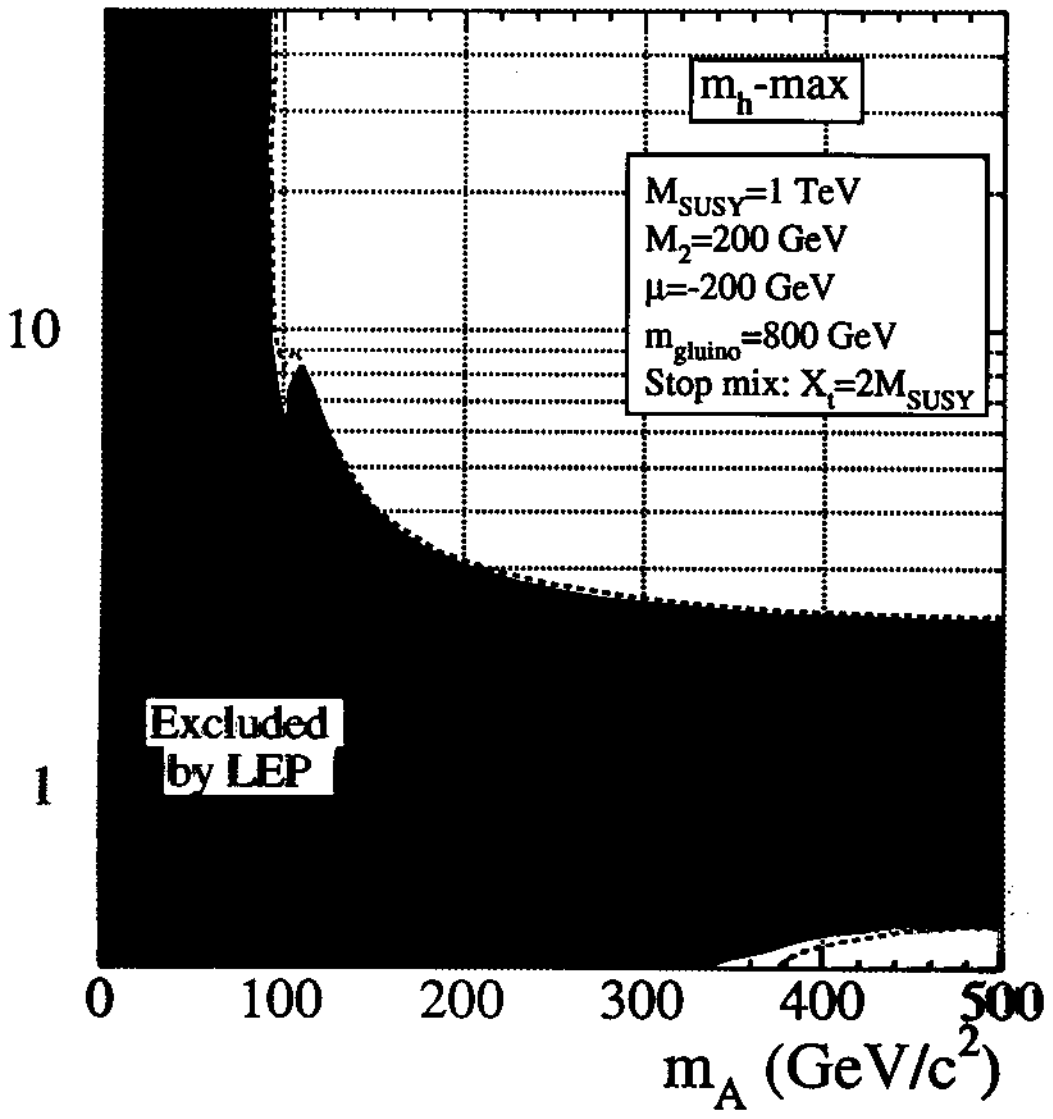


$e^+e^- \to h^\circ A^\circ$

$h^\circ \to b\bar{b}$

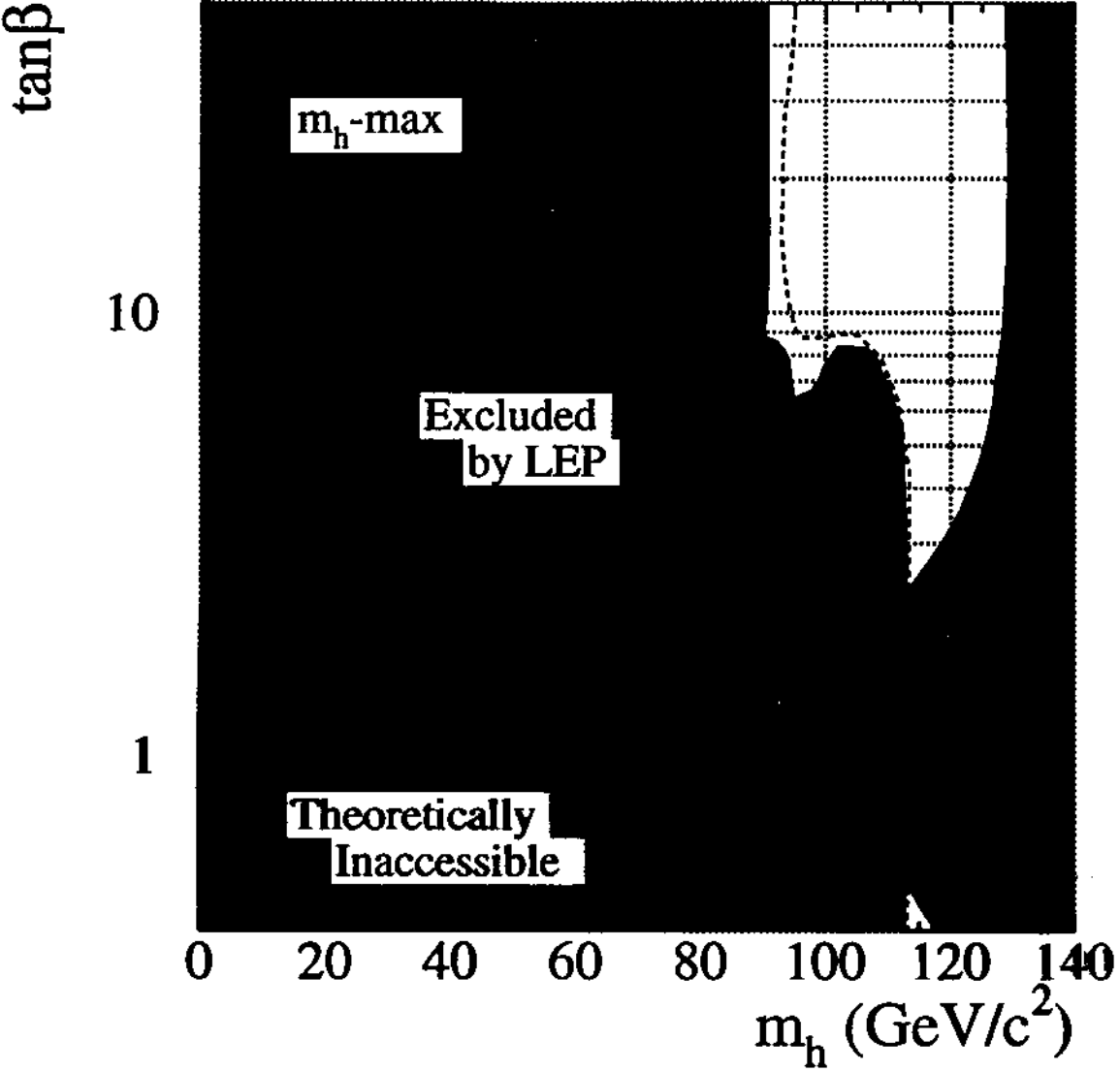
$A^\circ \to b\bar{b}$

LEP COMBINED PLOT



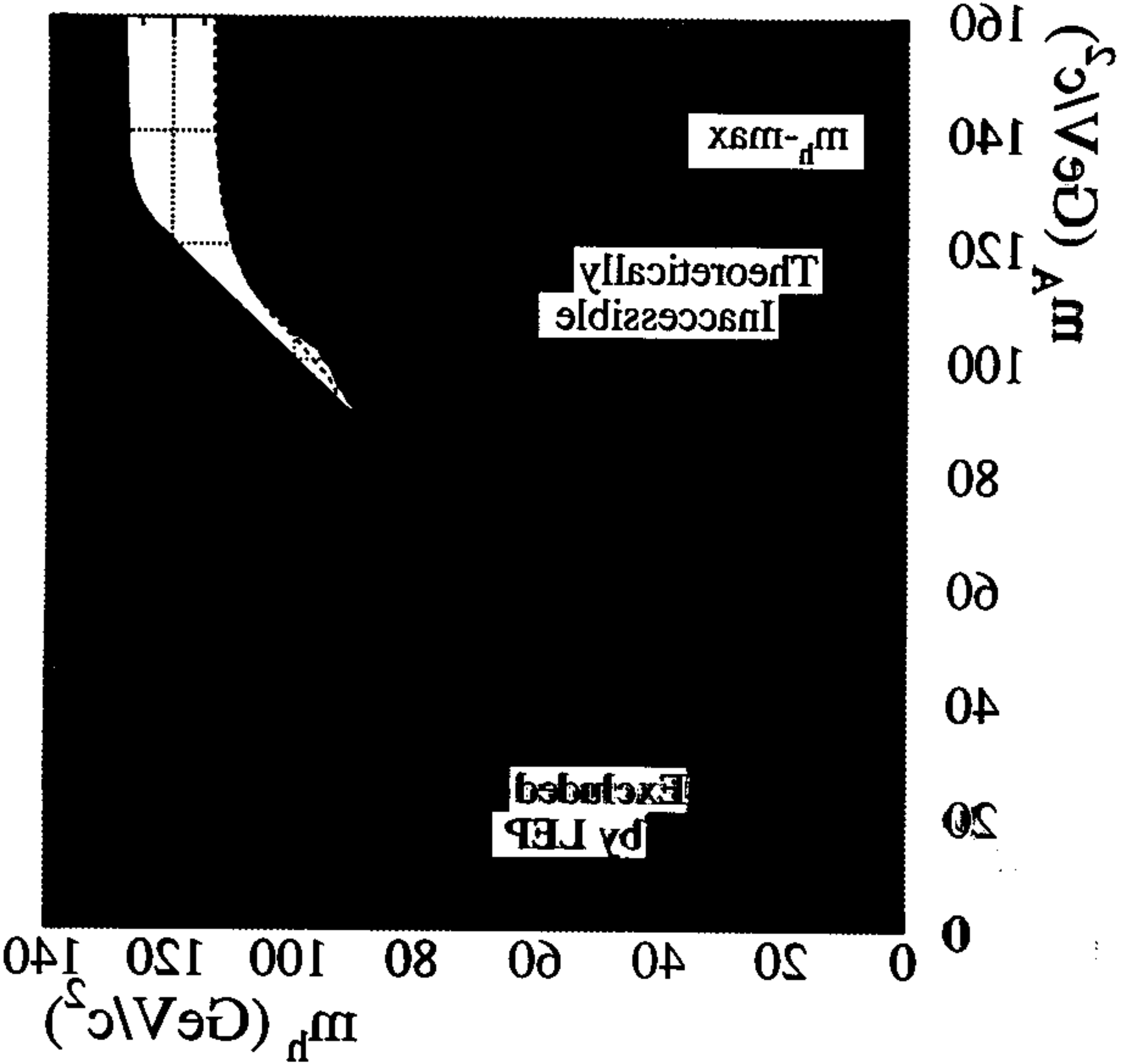
LEP COMBINED

95% C.L.



SMALL tanβ REGION

IS EXCLUDED



m_h-max
Theoretically
Inaccessible
Excluded
by LEP
0
20
40
60
80
100
120
140
160
m_A (GeV/c^2)
m_h (GeV/c^2)

3 SEARCHES FOR SUSY

SUPERSYMMETRIC PARTNERS

J = 0	J = ½	J = 1	J = 3/2	J = 2
sfermions: $\begin{bmatrix}\tilde{\nu}_L\\ \tilde{l}_L\end{bmatrix}$ $\tilde{\nu}_R$ $\tilde{l}_R$	$\begin{bmatrix}\nu_L\\ l_L\end{bmatrix}$ ν_R l_R $l = e, \mu, \tau$			
$\begin{bmatrix}\tilde{q}_L\\ \tilde{q}'_L\end{bmatrix}$ $\tilde{q}_R$ $\tilde{q}'_R$	$\begin{bmatrix}q_L\\ q'_L\end{bmatrix}$ q_R q'_R $q = u, c, t$ $q' = d, s, b$			
~inos: $\begin{bmatrix}H_1^0\\ H_1^-\end{bmatrix}$ $\begin{bmatrix}H_2^+\\ H_2^0\end{bmatrix}$	$\tilde{g}$ $\tilde{\gamma}$ $\tilde{Z}$ $\tilde{W}^+$ $\tilde{H}_1^0$ $\tilde{H}_2^+$ $\tilde{H}_1^-$ $\tilde{H}_2^0$ Goldstino $\tilde{G}_{1/2}$	g γ Z W^+ eaten	massive ↑ gravitino $\tilde{G}_{3/2}$	graviton G

$\tilde{\chi}_1^+$ $\tilde{\chi}_2^+$: CHARGINOS

$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$: NEUTRALINOS

SUSY BREAKING

1) GRAVITY MEDIATED

$$M_{SUSY} \simeq \frac{\Lambda^2_{Hidden}}{M_{Pl}}$$

$M_{SUSY} \sim M_{EW}$ $\quad \Lambda_{hidden} \sim 10^{12}$ GeV

- $m_{\tilde{G}_{3/2}} \simeq O(TeV)$
- $\tilde{\chi}^0_1$, $\tilde{\nu}$ LSP CANDIDATES

2) GAUGE MEDIATED

- NO FCNC
- $m_{\tilde{G}_{3/2}} \ll 1$ GeV $\quad \tilde{G}_{3/2}$: LSP

① $\tilde{\chi}^0_1$: NLSP

② $\tilde{\tau}_1$: NLSP

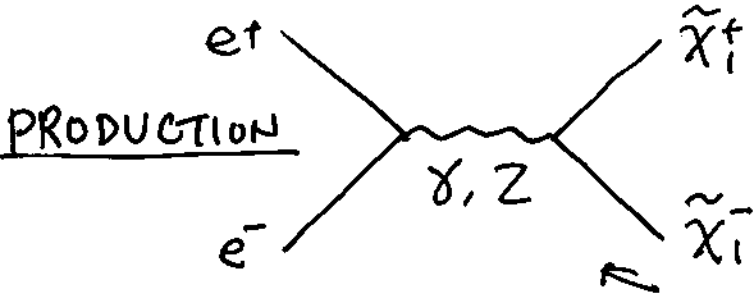
3) ANOMARY MEDIATED

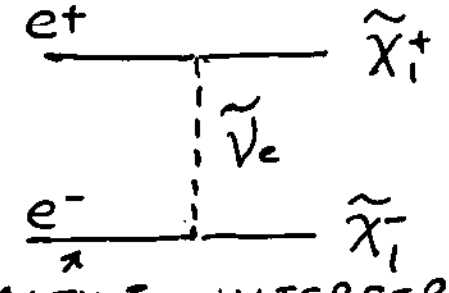
① GAUGINOS + HIGGSINOS

(A) CHARGINOS

MIXTURE OF $\tilde{W}^{\pm}$, $\tilde{H}^{\pm}$

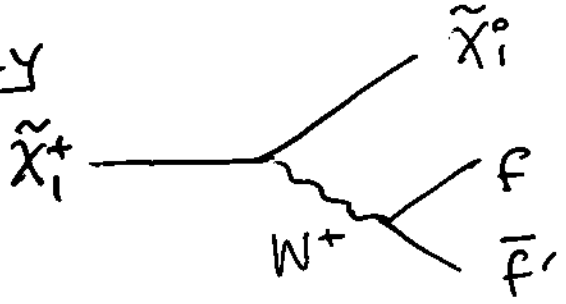
PRODUCTION

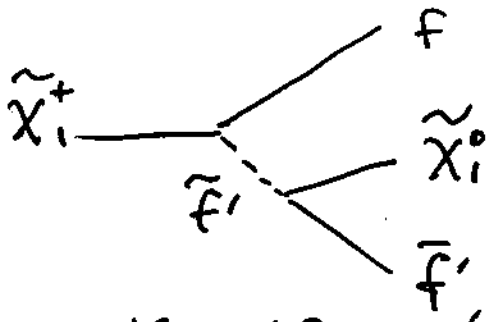




NEGATIVE INTERFERENCE

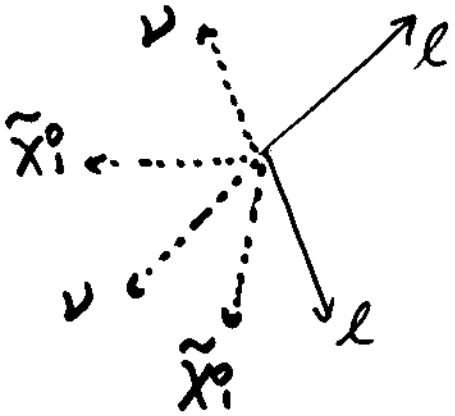
DECAY

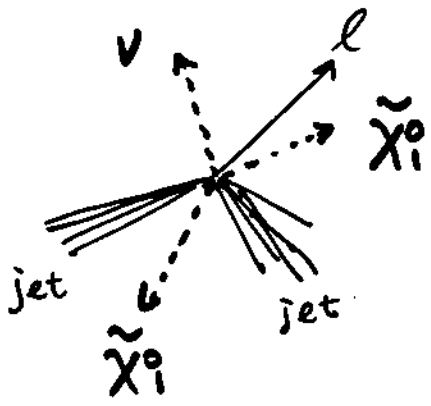


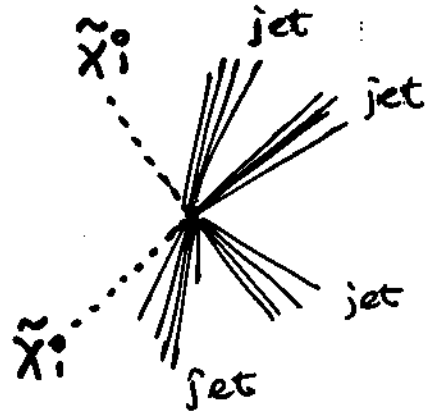


IN GENERAL CROSS SECTION IS LARGE (> 1 pb)

EVENT TOPOLOGY







BACKGROUND DEPENDS ON $\Delta M = M_{\tilde{\chi}_1^+} - M_{\tilde{\chi}_1^0}$

ΔM LARGE ... W^+W^-

ΔM SMALL ... two photon processes

Chargino cross section limit

Luminosities (pb^{-1}) in plots:

$\sqrt{s}$ (GeV)	192	196	200	202
ALEPH	29	80	86	42
DELPHI	26	77	83	40
L3	30	84	83	37
OPAL	29	73(74)	66(75)	11(38)

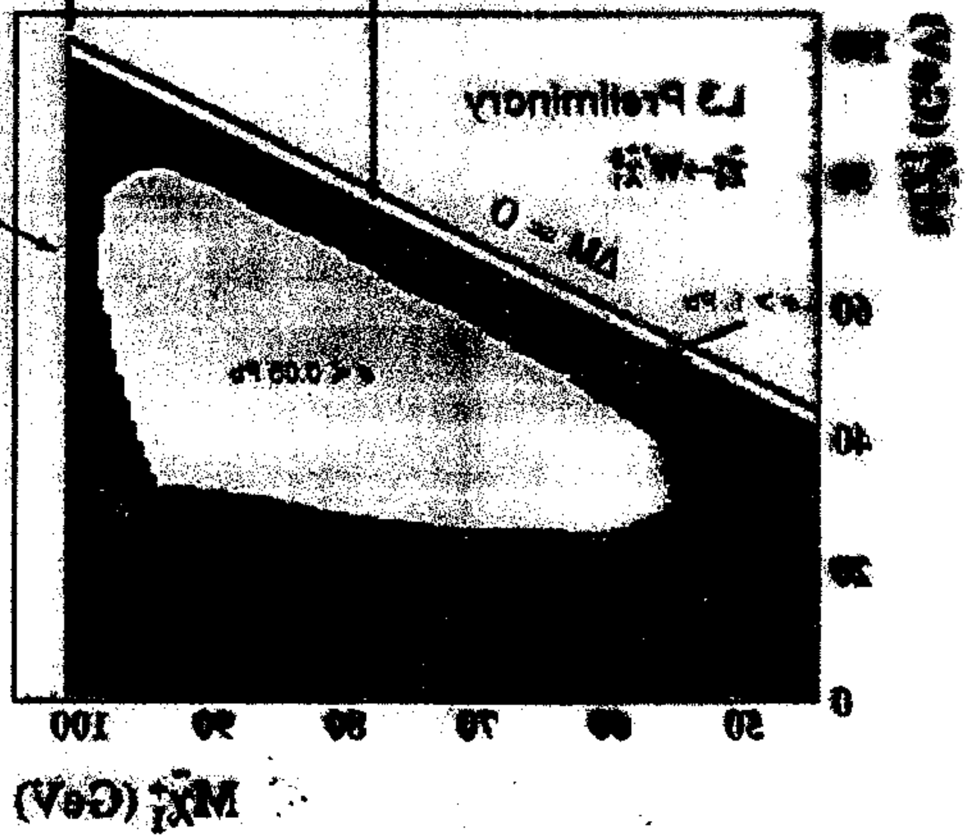
difference at kinematic limit

Full of 1999 data are combined with one in 2000

kinematic limit

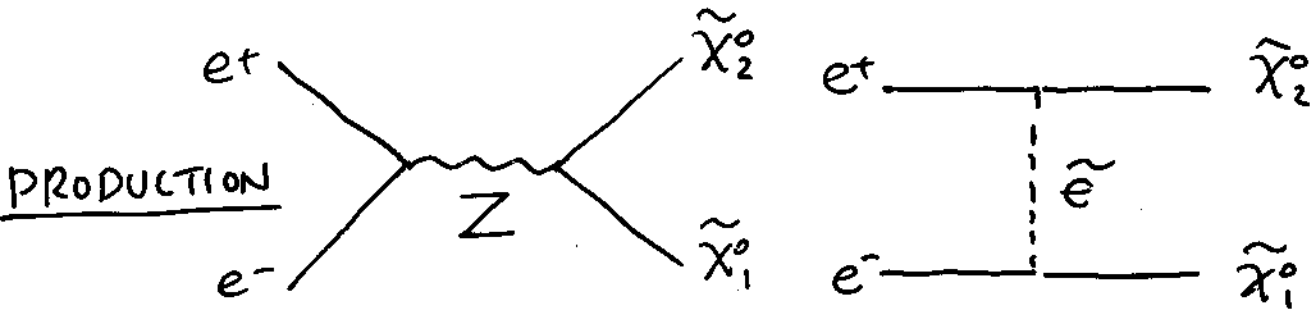
Small ΔM region No sensitivity

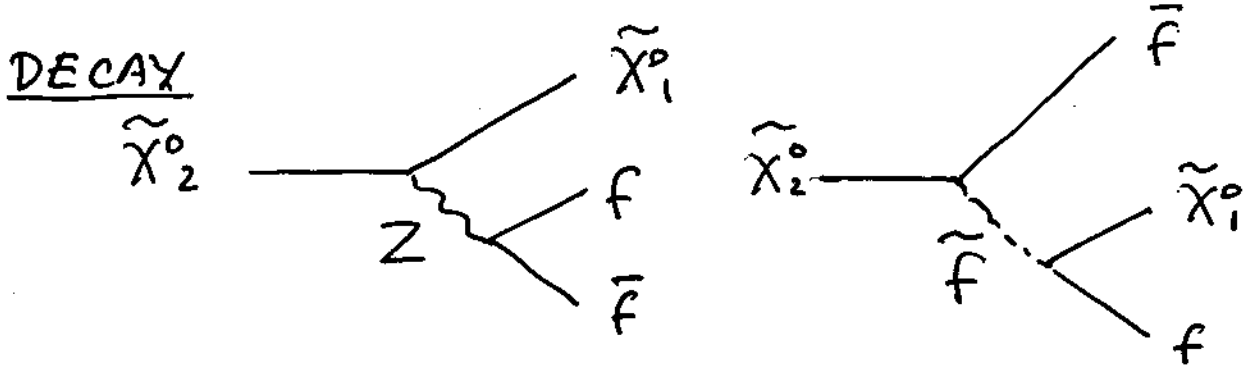
limit is set up to the kinematic limit

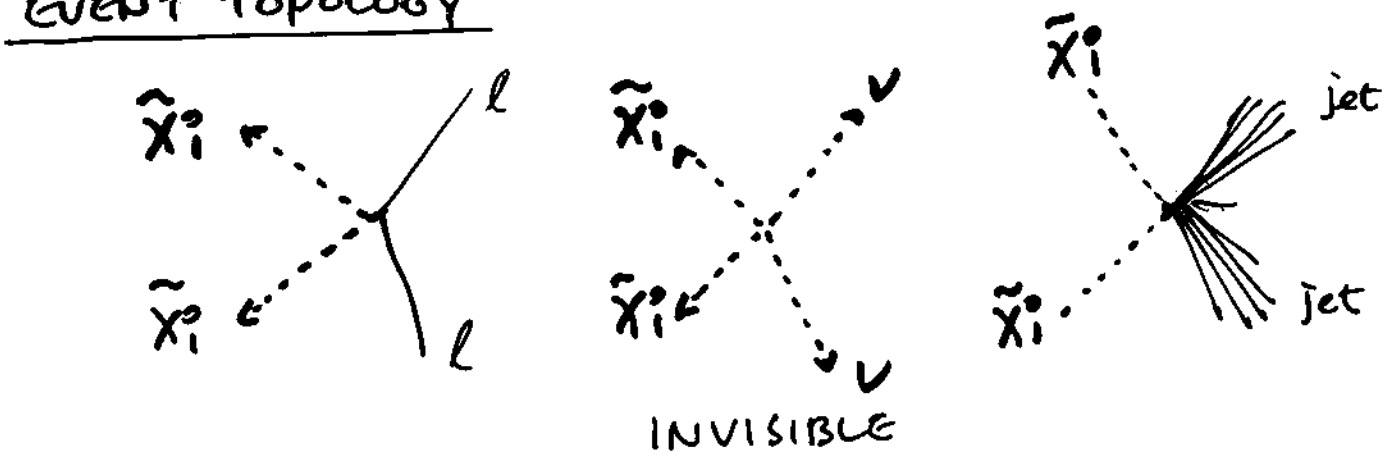


ICHEP2000
NAGA-1

(B) NEUTRALINOS







BACKGROUND DEPENDS ON $\Delta M = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$

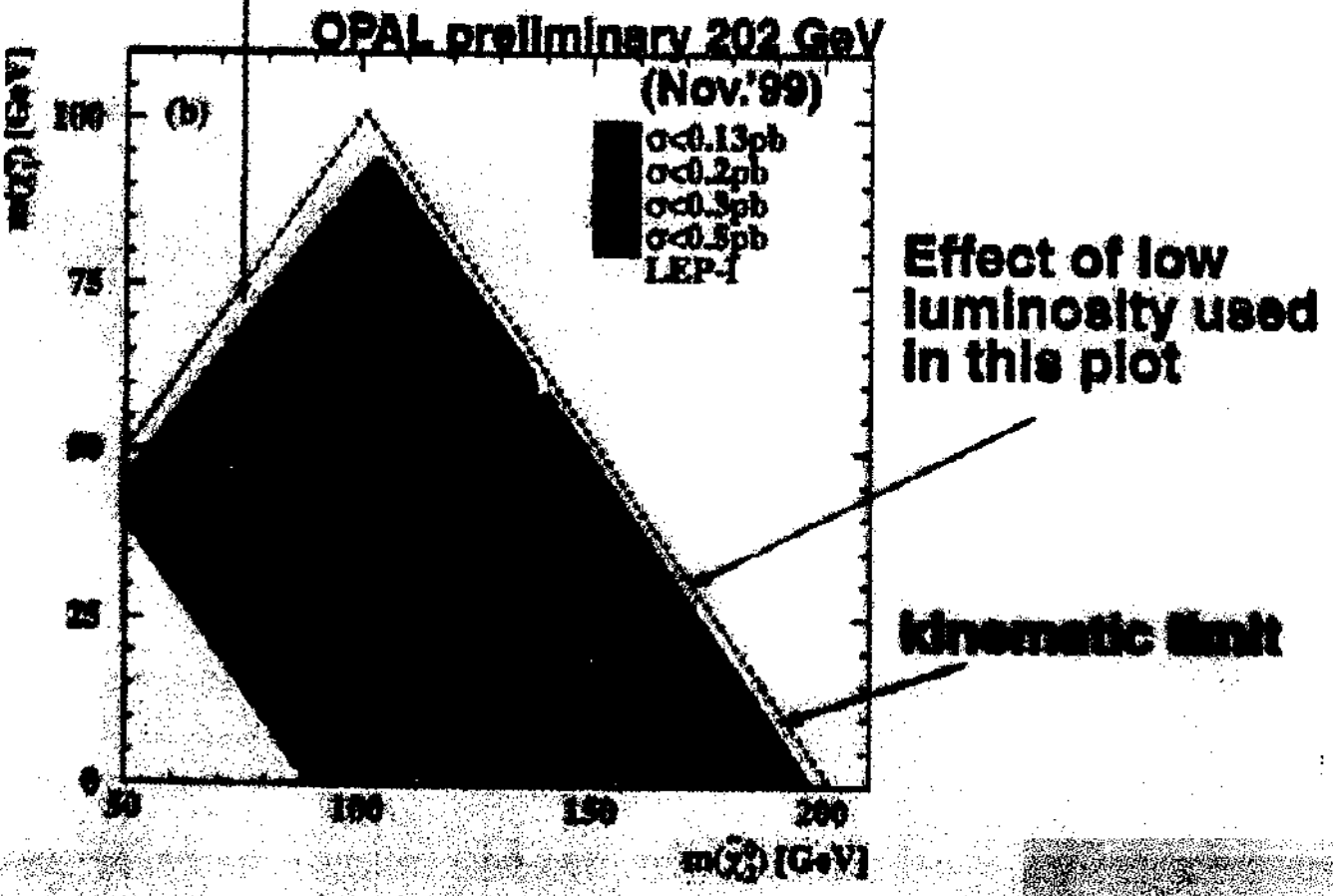
ΔM LARGE W^+W^- Z^0Z^0 ↳ $\nu\bar{\nu}$

ΔM SMALL TWO PHOTON PROCESSES

Neutralino Cross-section Limit

Small ΔM region
no sensitivity

$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^{(*)}) = 100\%$
is assumed.



Effect of low luminosity used in this plot

Kinematic limit

Cross section limit for Chargino
Neutralino

⇓

CMSSM interpretation

PHYSICS INTERPRETATION BASED ON CMSSM

↳ CONSTRAINT

ASSUMPTIONS

- GAUGINOS HAVE A COMMON MASS ($m_{1/2}$) AT GUT SCALE
- SFERMION HAVE A COMMON MASS (m_0) AT GUT SCALE
- MASSES RUN WITH Q^2 FROM GUT TO EW SCALE (RENORMALIZATION GROUP EQ.)

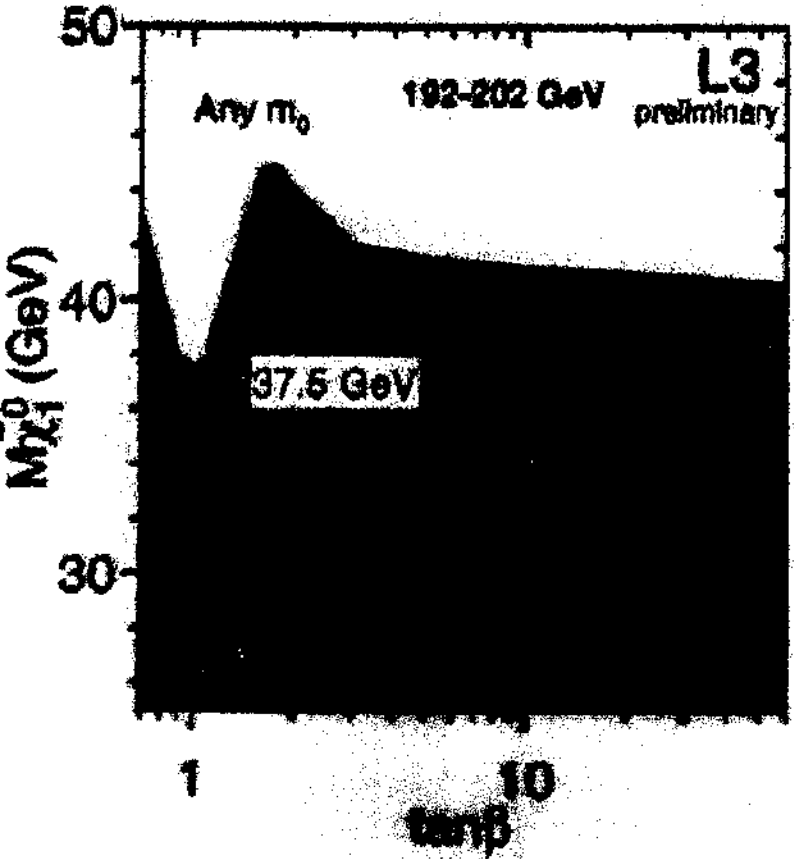
MSSM PARAMETERS

- M_2 = SU(2) GAUGINO MASS @ EW SCALE
- μ = HIGGSINO MIXING PARAMETER
- $\tan\beta = v_2/v_1$
- m_0 = COMMON SCALAR MASS @ GUT SCALE

⇒ MASS LIMIT OF $M_{\tilde{\chi}_1^0}$

$\tilde{\chi}_1^0$ IS THE COLD DARK MATER CANDIDATE

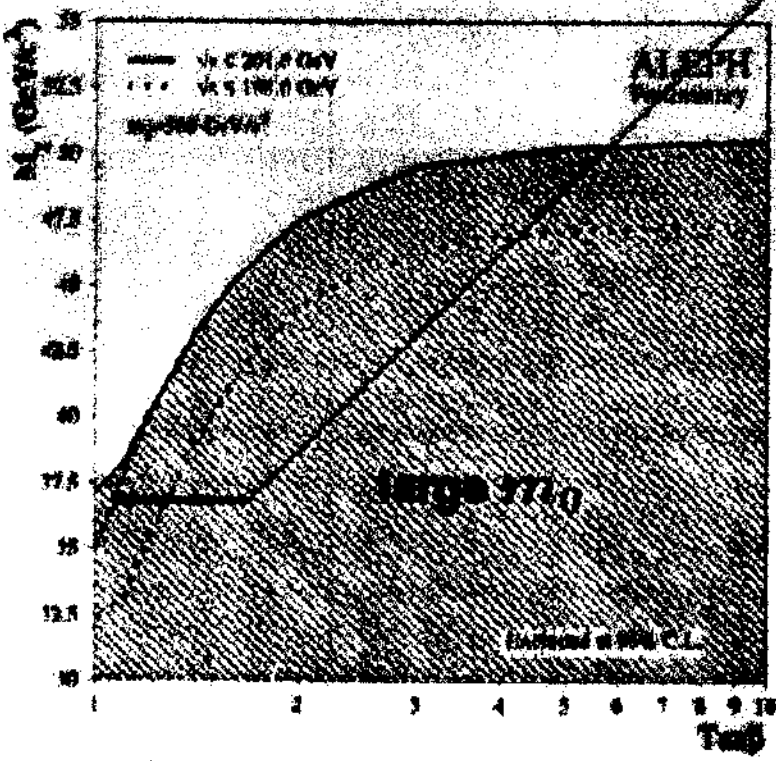
Neutralino mass limits



Chargino, neutralino and slepton results are combined.

slepton results are importnat for small m_0 at large $\tan\beta$:
2 body decays of $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^0$

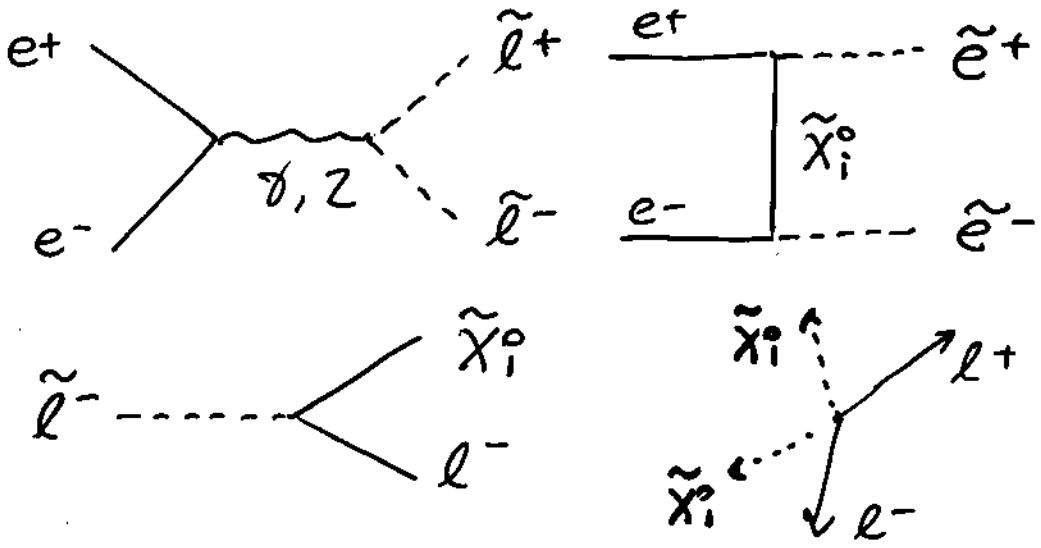
No constraint from neutralino search



	LSP mass limit (GeV)	
	large m_0	any m_0
ALEPH	37	37
DELPHI	36.7	36.3
L3		37.5
OPAL	35.7	31.6(189)

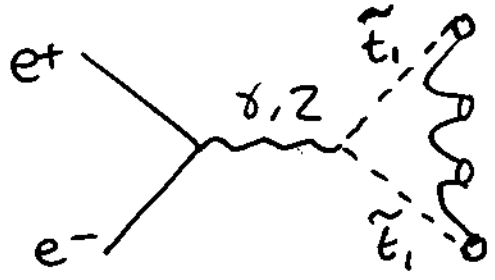
(2) SFERMIONS

(A) SCALAR LEPTONS



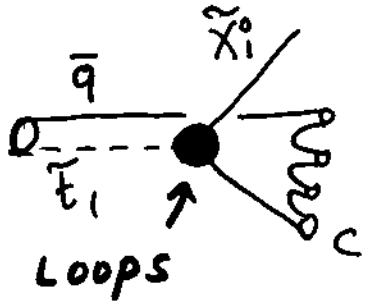
(B) STOP. SBOTTOM

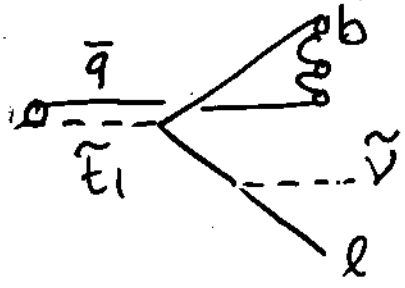
CAN BE LIGHER THAN OTHER $\tilde{q}$'s
(LEFT-RIGHT MIXING)

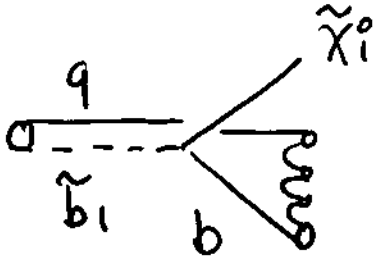


FORM STOP-HADRON

SIMILAR FOR $\tilde{b}_1$

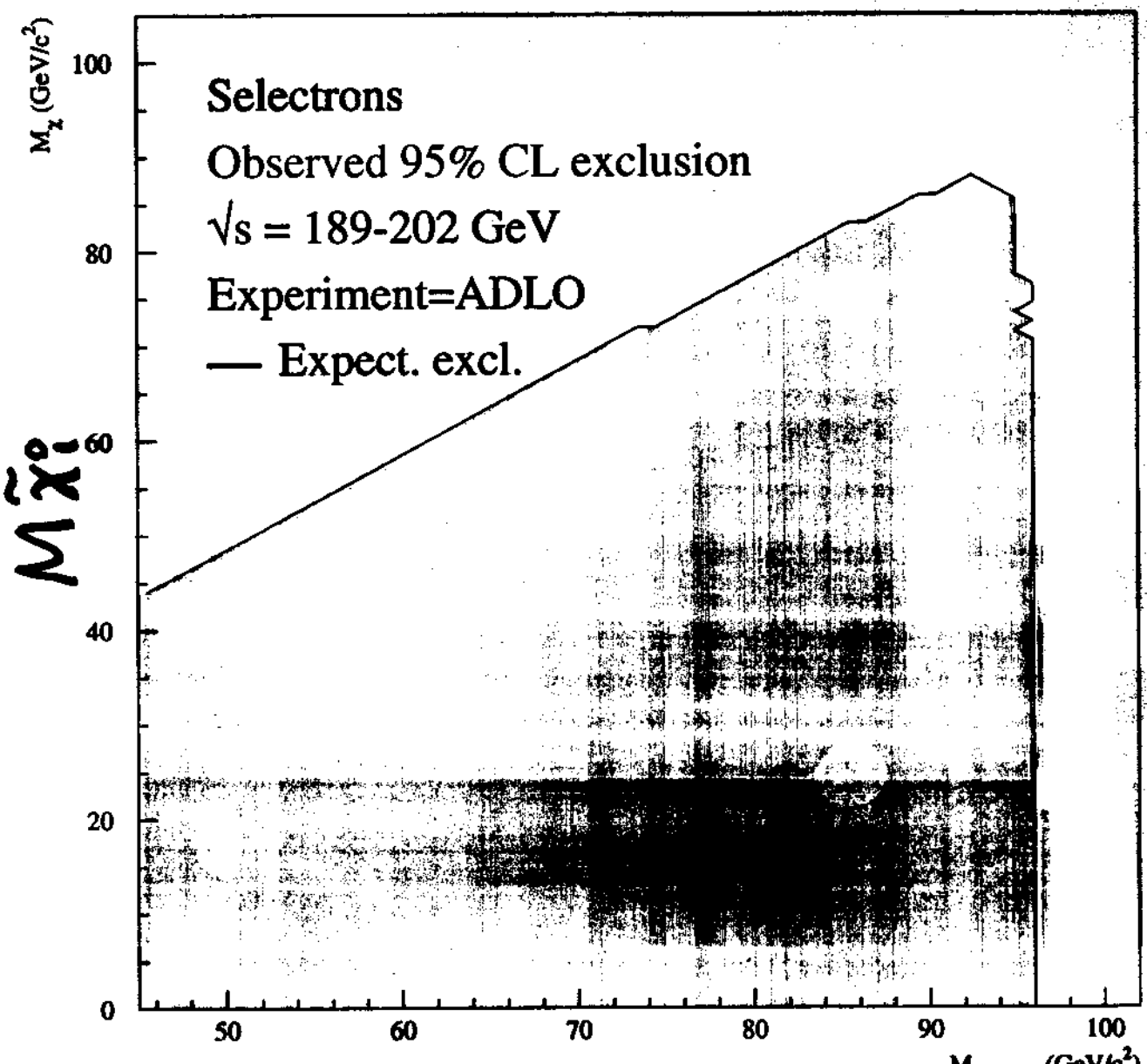






(IN GENERAL JETS ARE VERY NARROW)

$e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$



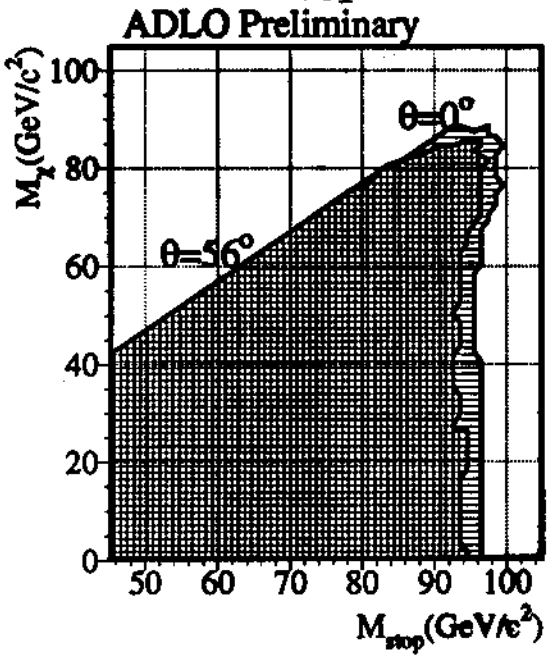
$M_{\tilde{\chi}^0_1}$

$M_{\tilde{e}}$

Stop search

- No evidence for excess ⇒ derive mass limits:
- Consider two values for $\tilde{t}$ mixing angle: $\theta_{mix} = 0°$ (purely $\tilde{t}_L$ state), $\theta_{mix} = 56°$ (smallest σ)

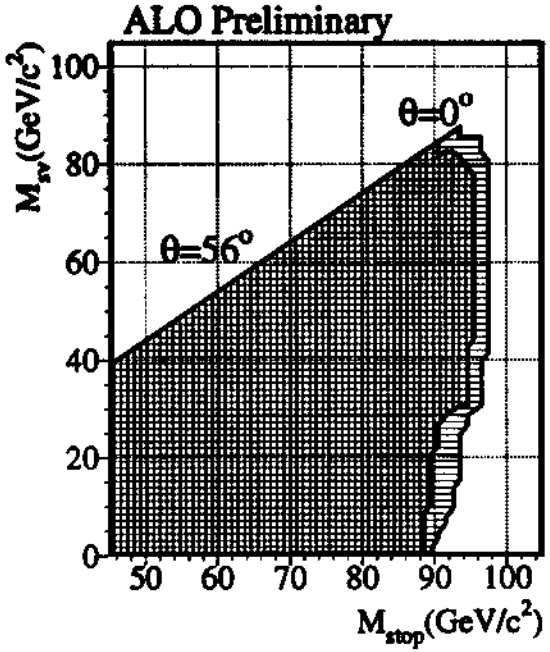
$\tilde{t} \to c\tilde{\chi}_1^0$:



$\theta_{mix} = 0°$:$m_{\tilde{t}} > 95$ GeV ($\Delta m > 15$ GeV)

$\theta_{mix} = 56°$:$m_{\tilde{t}} > 92$ GeV ($\Delta m > 15$ GeV)

$\tilde{t} \to bl\tilde{\nu}$:



$\theta_{mix} = 0°$:$m_{\tilde{t}} > 89$ GeV ($\Delta m > 15$ GeV)

$\theta_{mix} = 56°$:$m_{\tilde{t}} > 89$ GeV ($\Delta m > 15$ GeV)

(3) GAUGE MEDIATED SUSY BREAKING

PHENOMENOLOGY

- $\tilde{G}_{3/2}$ (GRAVITINO) IS THE LSP.
  $M_{\tilde{G}_{3/2}} < 1\,GeV$ or $\ll 1\,GeV$
- THE NEXT LIGHTEST SUSY PARTICLE (NLSP) CAN BE
  $\tilde{\chi}_1^0$ OR $\tilde{l}_R$ (MOST PROBABLY $\tilde{\tau}_1^-$)

SIMPLEST CASES

(1) $e^+e^- \longrightarrow \tilde{G}_{3/2}\,\tilde{\chi}_1^0$
$\hookrightarrow \gamma\,\tilde{G}_{3/2}$

$e^+e^- \longrightarrow \tilde{\chi}_1^0\,\tilde{\chi}_1^0$
$\hookrightarrow \gamma\,\tilde{G}_{3/2}$
$\hookrightarrow \gamma\,\tilde{G}_{3/2}$

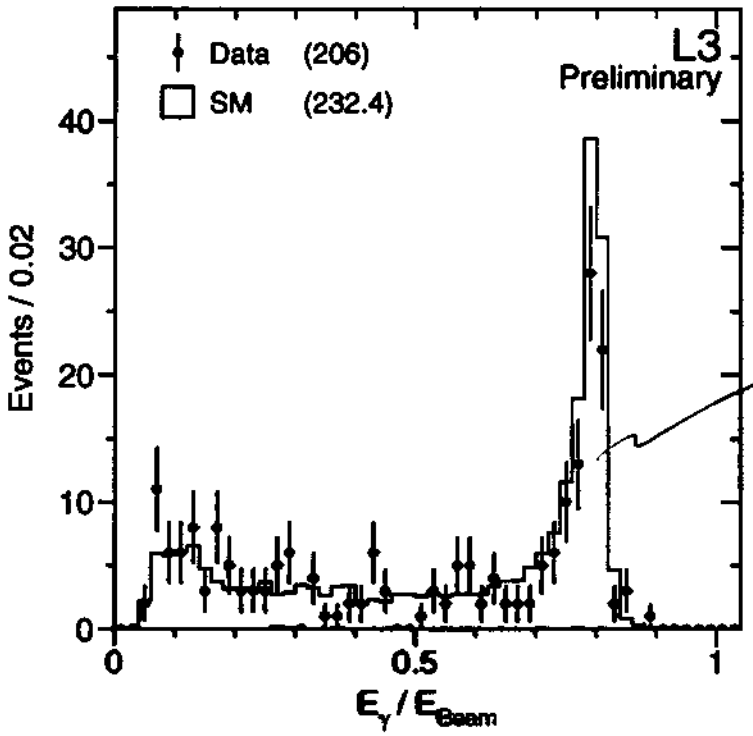
- $\tau_{\tilde{\chi}_1^0}$ DEPENDS ON $M_{\tilde{G}_{3/2}}$
  $l = \beta\gamma\,\tau_{\tilde{\chi}_1^0}$ $\quad O(\mu m) \sim O(km)$

(2) $e^+e^- \longrightarrow \tilde{\tau}_1^+\,\tilde{\tau}_1^-$
$\hookrightarrow \tilde{G}_{3/2}\,\tau^-$
$\hookrightarrow \tilde{G}_{3/2}\,\tau^+$

- $\tilde{\tau}$- DEPENDS ON $M_{\tilde{G}_{3/2}}$

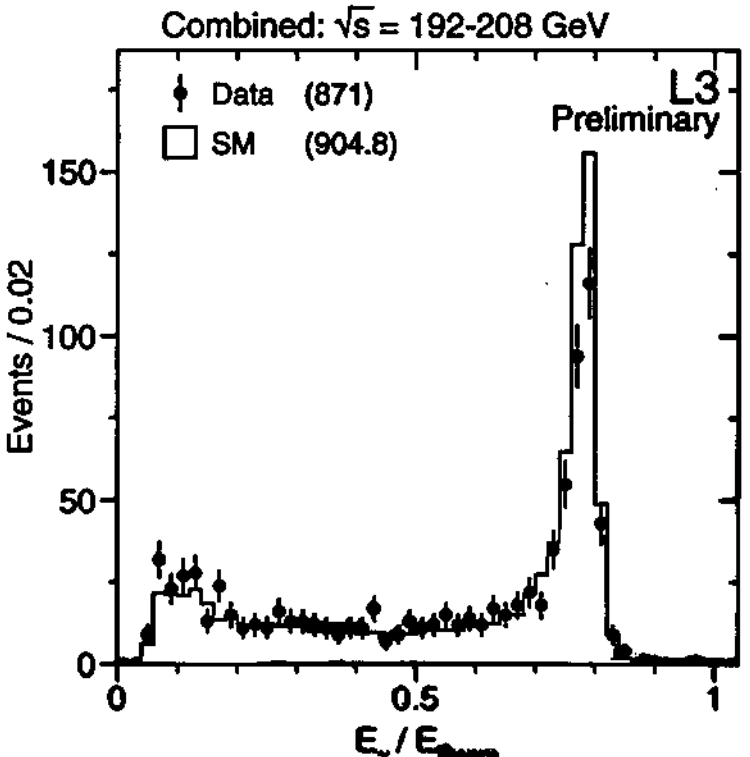
γ + missing energy

$\sqrt{s} = 202 - 208$ GeV, $\int \mathcal{L}\,dt = 90.7\text{pb}^{-1}$



This year's data confirm continue to show a slight disagreement in the shape of the differential cross section.

$\sqrt{s} = 192 - 208$ GeV, $\int \mathcal{L}\,dt = 323\text{pb}^{-1}$



Single and Multiphoton events

$\gamma(\gamma)$ + missing energy

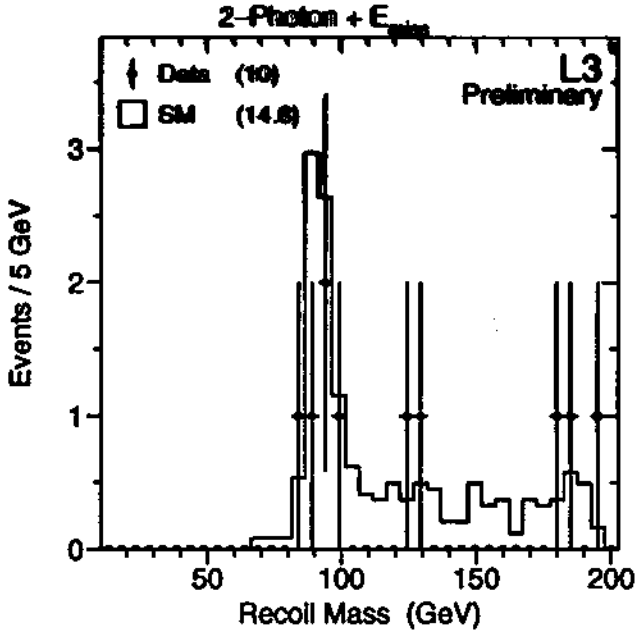
Standard Model Process $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$

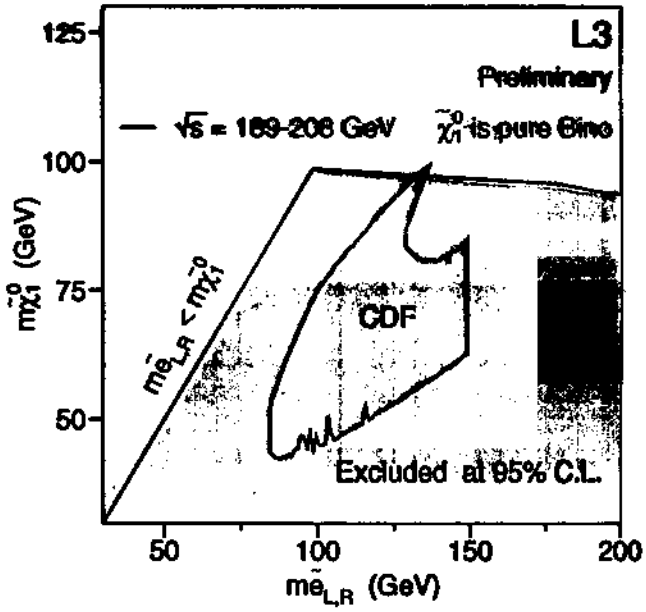
In the GMSB scenario, with $\tilde{G}$ LSP, the possible decay channels are :

$$e^+e^- \to \tilde{\chi}_1^0\tilde{G} \to \tilde{G}\tilde{G}\gamma$$

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tilde{G}\tilde{G}\gamma\gamma$$

$$\sqrt{s} > 202 \text{ GeV } (\theta \geq 14 \text{ deg})$$





Rule out SUSY interpretation of CDF $ee\gamma\gamma$ event

EXTRA DIMENSIONS

1998 Arkani-Hamed, Dimopoulos, Dval: (ADD)

MOTIVATION

EW INTERACTION HAS BEEN PROVEN AT DISTANCE OF $M_{EW}^{-1} \sim 10^{-17}$ cm

BUT GRAVITY HAS NOT BEEN PROVEN AT DISTANCE OF $M_{Pl}^{-1} \sim 10^{-32}$ cm

$\Rightarrow$ M_{EW} IS THE ONLY FUNDAMENTAL SHORT DSTANCE SCALE.

$$M_D \equiv M_{Pl(4+n)} \simeq M_{EW}$$

NEWTON FORCE IN 1+3 DIM

$$F = G_N \frac{m_1 m_2}{r^2} = \frac{1}{M_{Pl}^2} \frac{m_1 m_2}{r^2}$$

SCALE of EXTRA D. $\downarrow$

THIS IS VALID ONLY FOR $r > R$

AT $r < R$

$$F = \frac{1}{M_D^{n+2}} \frac{m_1 m_2}{r^{n+2}}$$

n : extra dim

$\downarrow$

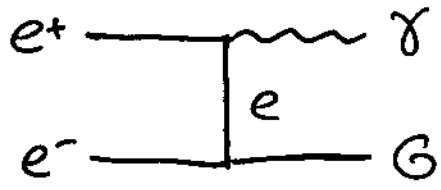
AT $r > R$

$$F = \frac{1}{M_D^{n+2}} \frac{1}{R^n} \frac{m_1 m_2}{r^2}$$

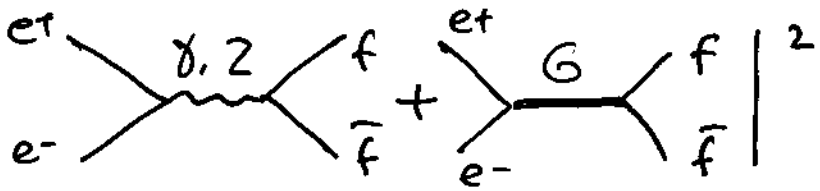
$$M_{Pl}^2 = M_D^{n+2} R^n$$

$n=1$	$R \sim 10^{13}$ m	EXCLUDED
$n=2$	$R \sim 1$ mm	
$n=7$	$R \sim 1$ fm	(Superstring, M-theory $4+n \leq 11$)

GRAVITY INTERACTIONS WE KNOW



$$\sigma \sim \alpha G_N$$
$$\approx 10^{-66}\ \text{cm}^{-2}$$
$$\approx 10^{-30}\ \text{pb}$$



Interference
$\sim \alpha G_N$

MASSLESS GRAVITON LIVES IN 4+n DIMENSION SPACE

$$q_G = (\underbrace{E, p_1, p_2, p_3}_{4\text{ dim}}, \underbrace{q_1, \cdots q_n}_{n\text{-dim}})$$

$$E^2 = p_1^2 + p_2^2 + p_3^2 + \underbrace{q_1^2 + \cdots + q_n^2}_{m_G^2}$$

THERE ARE SO MANY MODES OF GRAVITON IN THE EXTRA DIMENSION

$$\sigma(e^+e^- \to \gamma G) \simeq \alpha G_N \times \frac{M_{Pl}^2}{s}$$
$$\simeq \alpha \frac{1}{s}$$

ALMOST CONTINUOUS MASS

γ IS NOT MONOCHROMATIC

LEP2 Lower 95% CL M_S(Hewett) Limits (TeV)

	$e^+e^- \to \gamma G$					$e^+e^- \to ZG$					
Experiment	n=2	n=3	n=4	n=5	n=6	n=2	n=3	n=4	n=5	n=6	Color coding
ALEPH	1.10	0.86	0.70	0.60	0.52	0.38	0.22	0.17	0.14	0.12	≤184 GeV
DELPHI	1.25	0.97	0.79	0.68	0.59						≤189 GeV
L3	1.02	0.81	0.67	0.58	0.51	0.60	0.38	0.29	0.24	0.21	≤202 GeV
OPAL	1.09	0.86	0.71	0.61	0.53						λ=-1 λ=+1 GL

Virtual Graviton Exchange

Experiment	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	qq	ff	$\gamma\gamma$	WW	ZZ	Combined
ALEPH (Λ_T)	1.17 0.91	0.73 0.75	0.67 0.69	0.59/0.64 0.55/0.59 (68)	1.17 0.94	0.91 0.92			0.84/1.12 (<189) M_S > 0.75/1.00
DELPHI		0.58 0.73	0.56 0.65		0.60 0.76	0.69 0.71			0.60/0.76 (ff) (<202)
L3	0.91 0.98	0.56 0.69	0.58 0.54		0.84 1.00	0.80 0.79	0.68 0.79	1.2 1.2	1.3/1.2 (<202)
OPAL		0.62 0.69	0.59 0.66		0.61 0.68	0.85 0.82		0.59 0.76	0.88/0.96 (<202)

CONCLUSIONS

1) LEP2 COLLIDER IS WORING VERY WELL.

AS WELL AS 4 EXPERIMENTS + PHYSICISTS + ...

2) $113\,\text{GeV} < M_{H_{SM}} < 210\,\text{GeV}$

@95%CL ↑ DIRECT SEARCH

↑ @95%CL PRECISE EW-MEASUREMENTS (+ BES II R)

$90\,\text{GeV} < M_{h_{MSSM}} \lesssim 130\,\text{GeV}$

@95%CL ↑ DIRECT SEARCH

↑ THEORY

3) ALL THE EXCITEMENTS ARE POSTPONED TO THE EARLY NEXT CENTURY

AT { LHC, JLC ...

OPEN QUESTIONS AFTER THE LEP ERA

- IS THERE A HIGGS ?
  LIGHT HIGGS ?
- IS THERE SUSY ?
- WHY THE NUMBER OF LEPTON-QUARK GENERATIONS IS 3 ?
- WHY $SU(3)_c \times SU(2)_L \times U(1)_Y$?
- WHY SPACE-TIME DIMENSION IS $3+1$?
- WHY $M_{EW} \ll M_{Pl}$?
- WHY WE EXIST ?
- WHY THE UNIVERSE EXISTS ?