united nations educational, scientific and cultural organization
international atomic energy agency
the **abdus salam** international centre for theoretical physics
ICTP 40th Anniversary

H4.SMR/1574-26

"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

The LEP Legacy

Giorgio Giacomelli

University of Bologna and INFN

The LEP legacy

G. Giacomelli
University of Bologna and INFN

7th School, ICTP, Trieste 26/7-6/8 2004

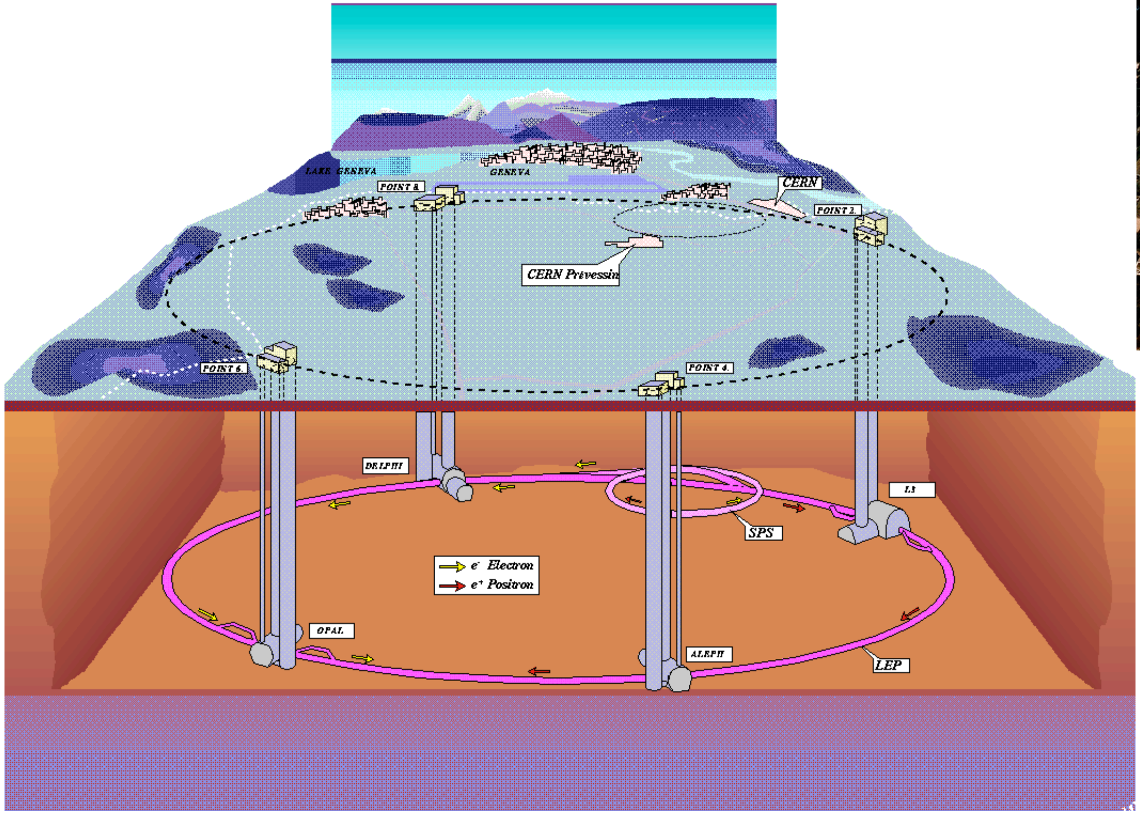
- LEP. Experiments
- Precision EW measurements
- QCD
- New particle searches
- Historical and sociological aspects
- Conclusions

LEP

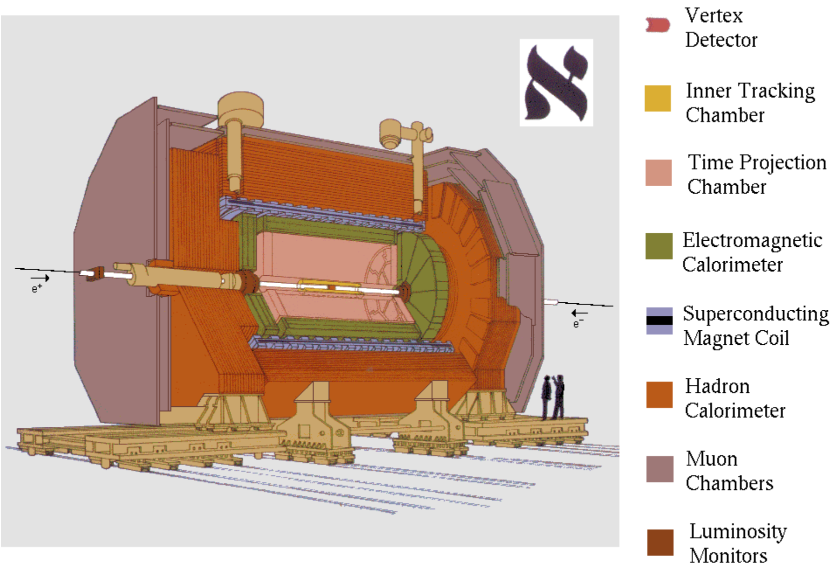
Largest e^+ e^- Collider in the world

c.m. energies up to ~209 GeV

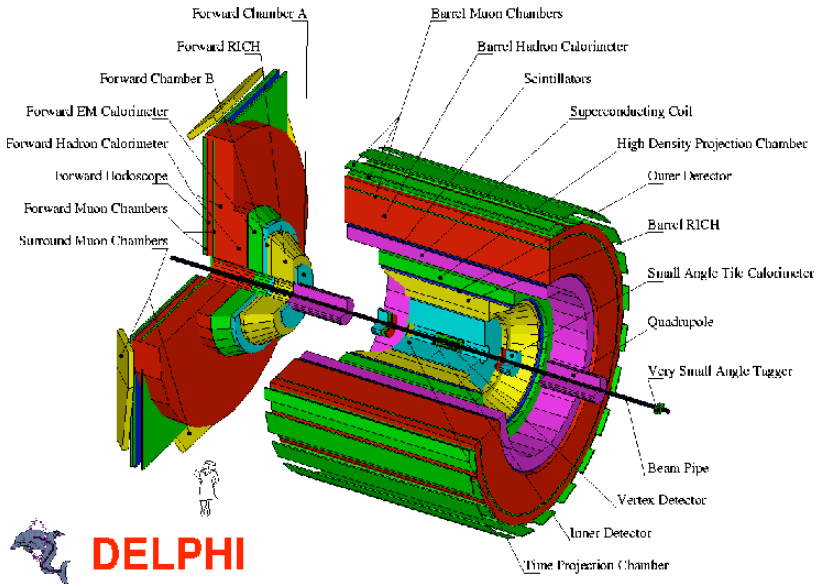
→ LHC

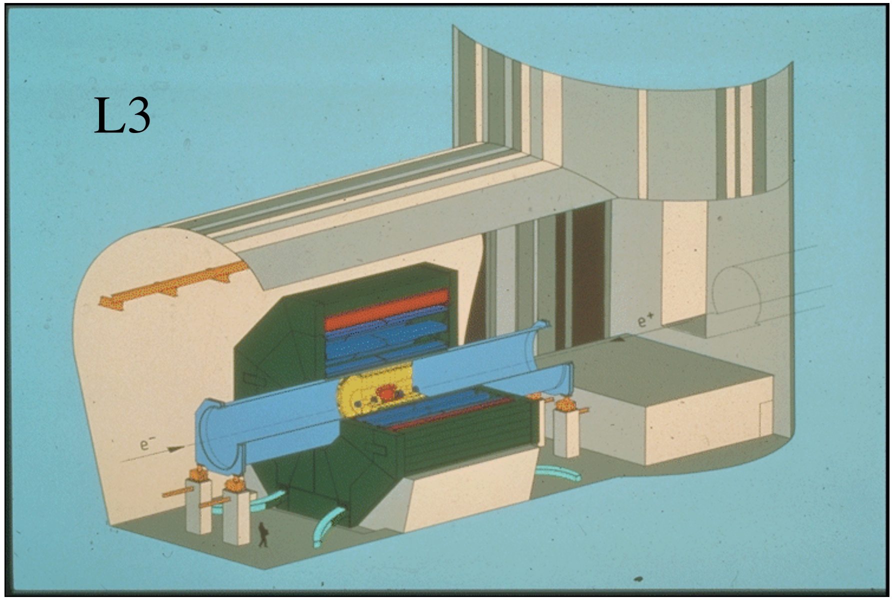


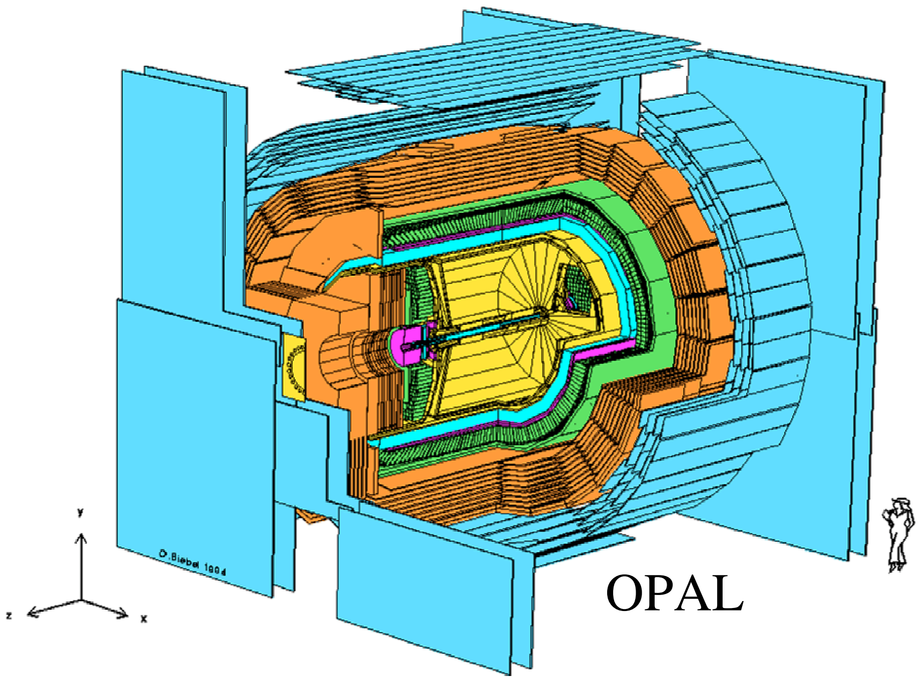
Aleph, Delphi, L3, OPAL

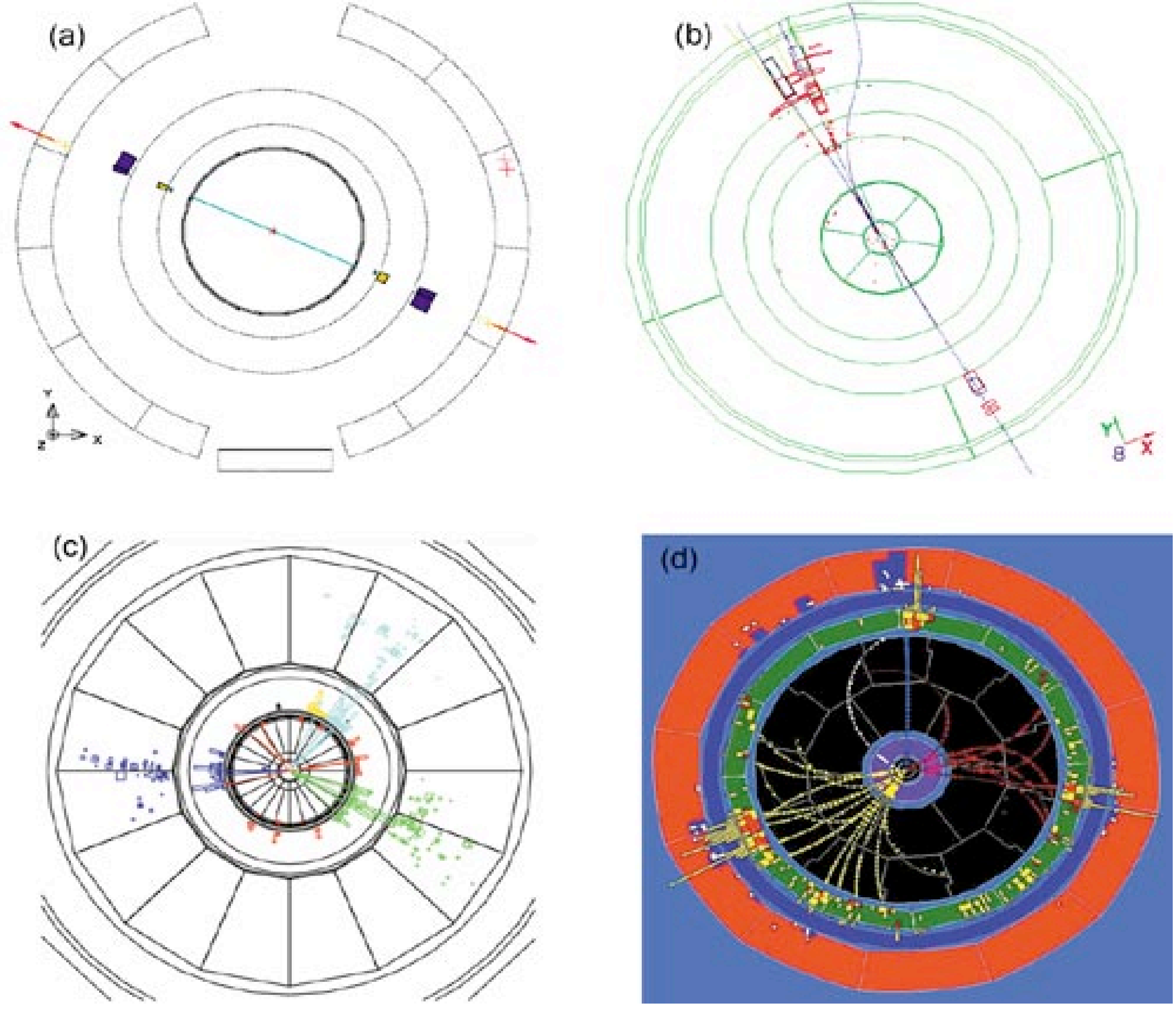


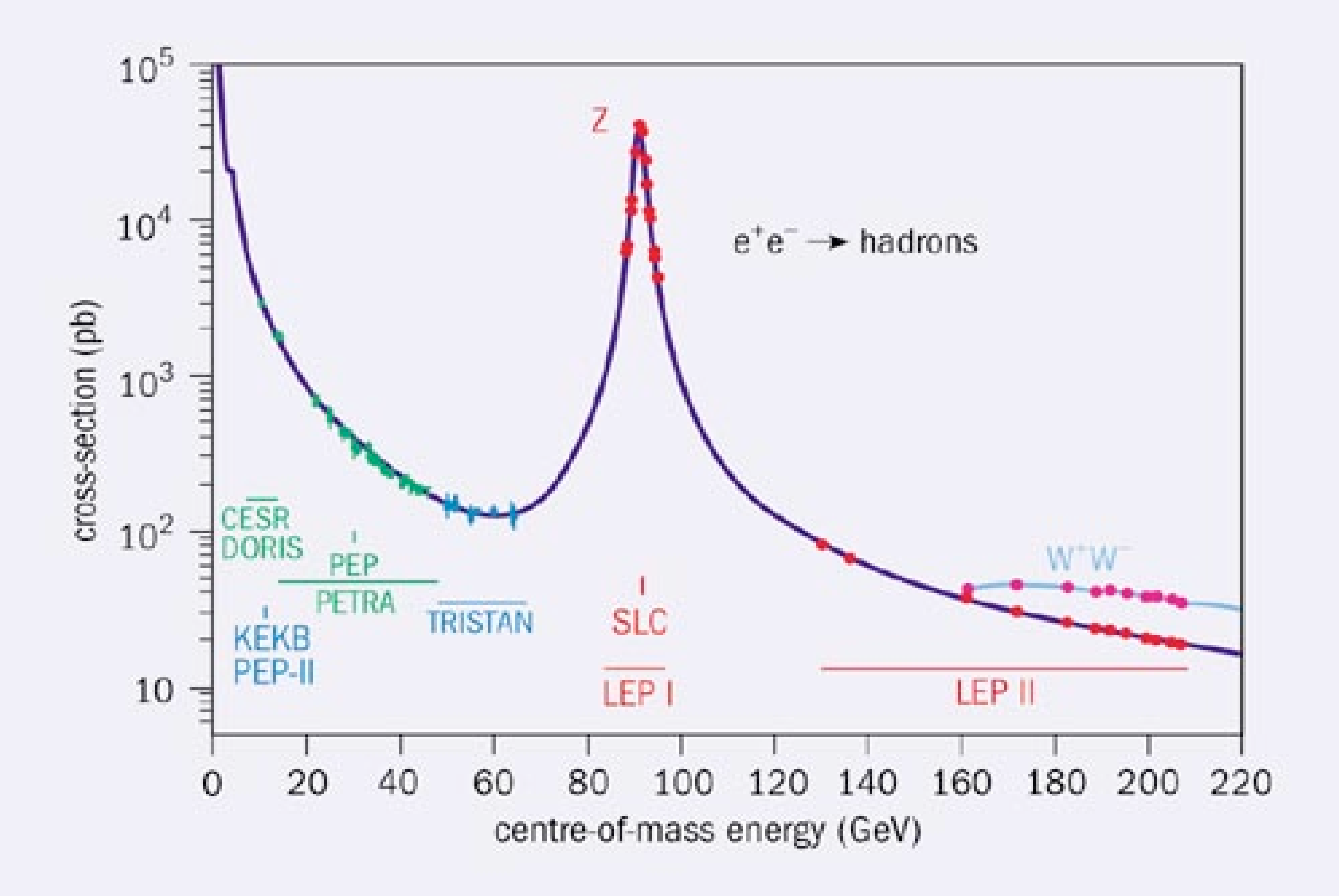
The ALEPH Detector





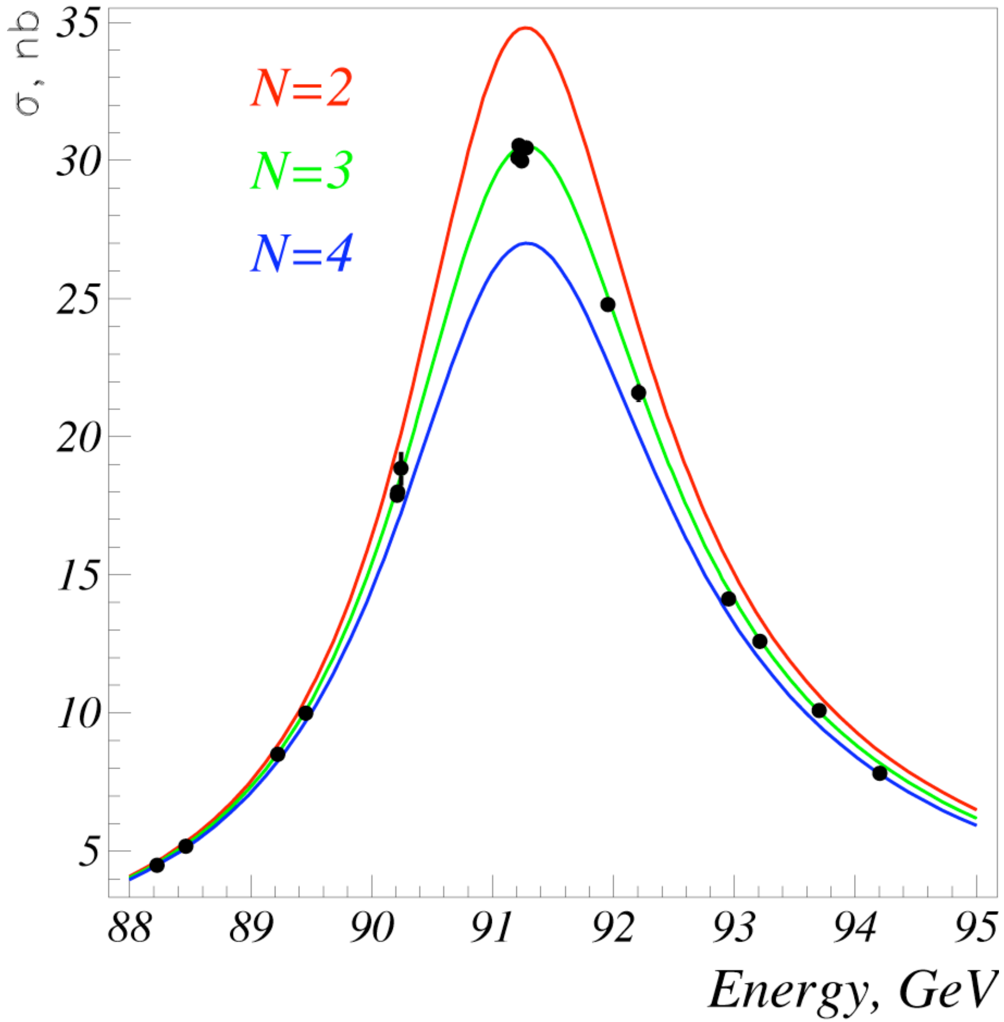



(a)
(b)
(c)
(d)



cross-section (pb)
10⁵
10⁴
10³
10²
10
Z
e⁺e⁻ → hadrons
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
W⁺W⁻
0
20
40
60
80
100
120
140
160
180
200
220
centre-of-mass energy (GeV)

Neutrino generations



$$\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - \Gamma_{ll}(3-\delta_\tau)$$

$$N_\nu = \Gamma_{inv} / \Gamma_\nu$$

$$N_\nu = 2.9841 \pm 0.0083$$

Electroweak Observables

– α , G_F , m_Z ; $1/\alpha(0) = 137$, $1/\alpha(m_Z) = 128$

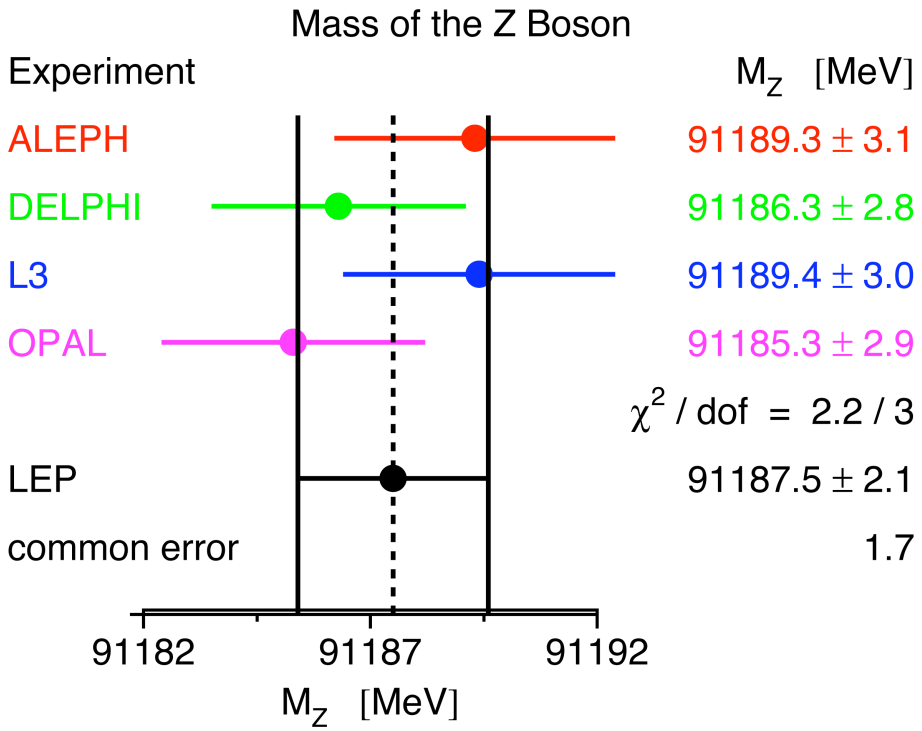
-- positron+electron → fermion+antifermion

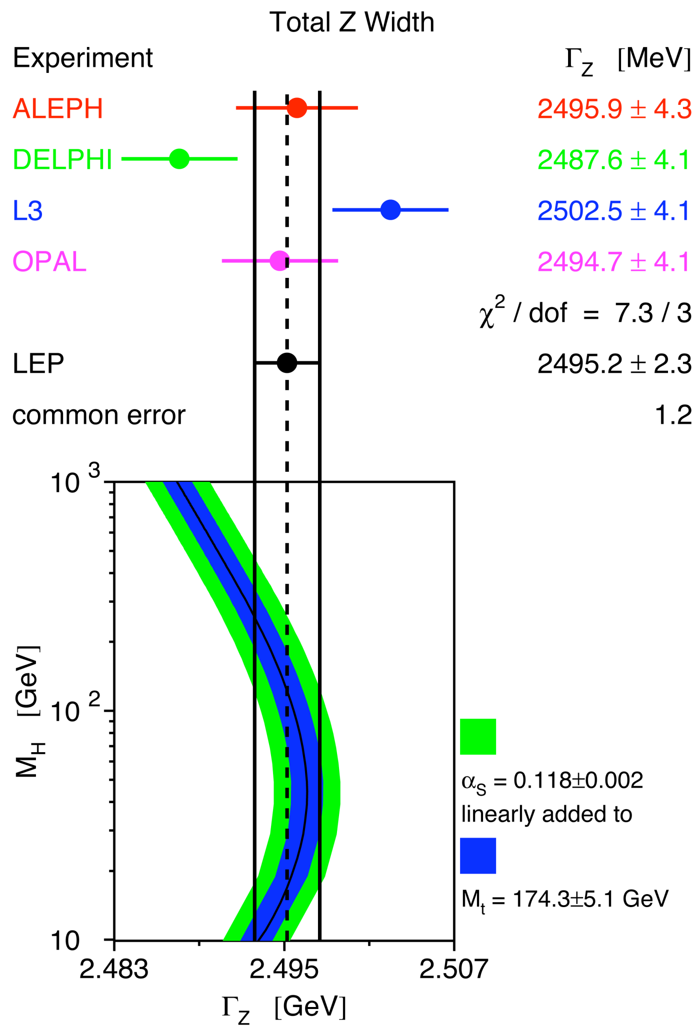
- Total Z width: $\Gamma_Z = 2.4952 \pm 0.0023$ GeV,
- Z peak cross section: $\sigma^0_{had} \equiv \frac{12\pi}{m_Z^2} \cdot \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$,
- Ratios $R_f^0 \equiv \Gamma_{had}/\Gamma_{ff}$ for f = e,μ,τ; also $R_q^0 \equiv \Gamma_{qq}/\Gamma_{had}$ for q = b,c,s,
- Forward backward asymmetries for f = e,μ,τ; b,c,s. At Z pole:

$$A_{FB}^{0,f} \equiv \frac{3}{4} A_e A_f \qquad A_f \equiv \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2},$$

- τ polarisation: $P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{1+\cos^2\theta + 2A_\tau A_e \cos\theta}$.

m_Z and Γ_Z



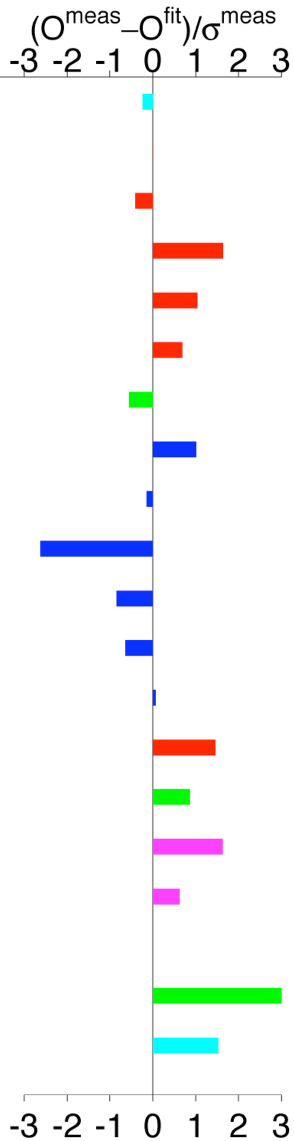


$$m_Z = 91.1875 \pm 0.0021 \text{ GeV}$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

Electroweak Measurements

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.18 ± 0.46	1.52



Interesting to compare with what was known before LEP (EPS89, Madrid):

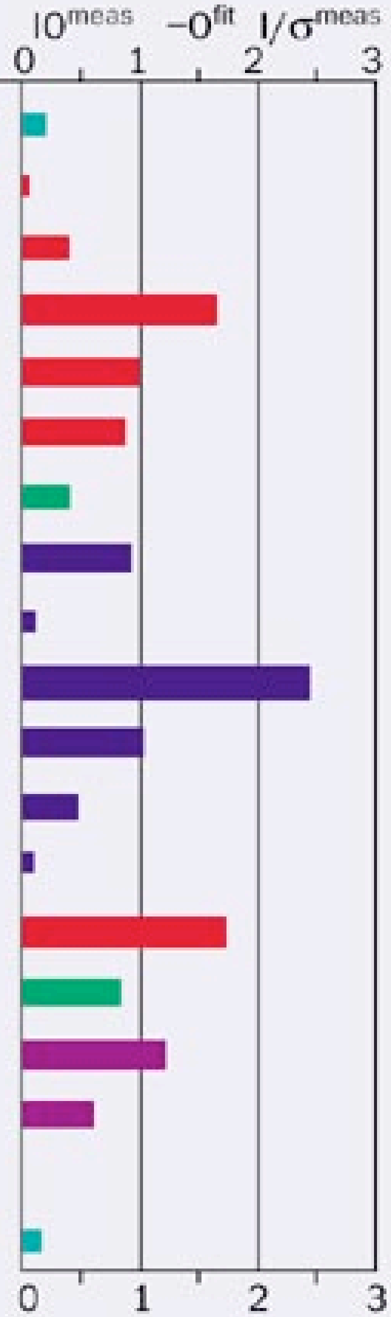
$m_Z = 91.12 \pm 0.16$ GeV $\quad m_W = 80.0 \pm 0.36$ GeV
$\sin^2\theta_W = 0.227 \pm 0.006 \quad N_\nu = 3.0 \pm 0.9$

And with what was foreseen to be measured at LEP:

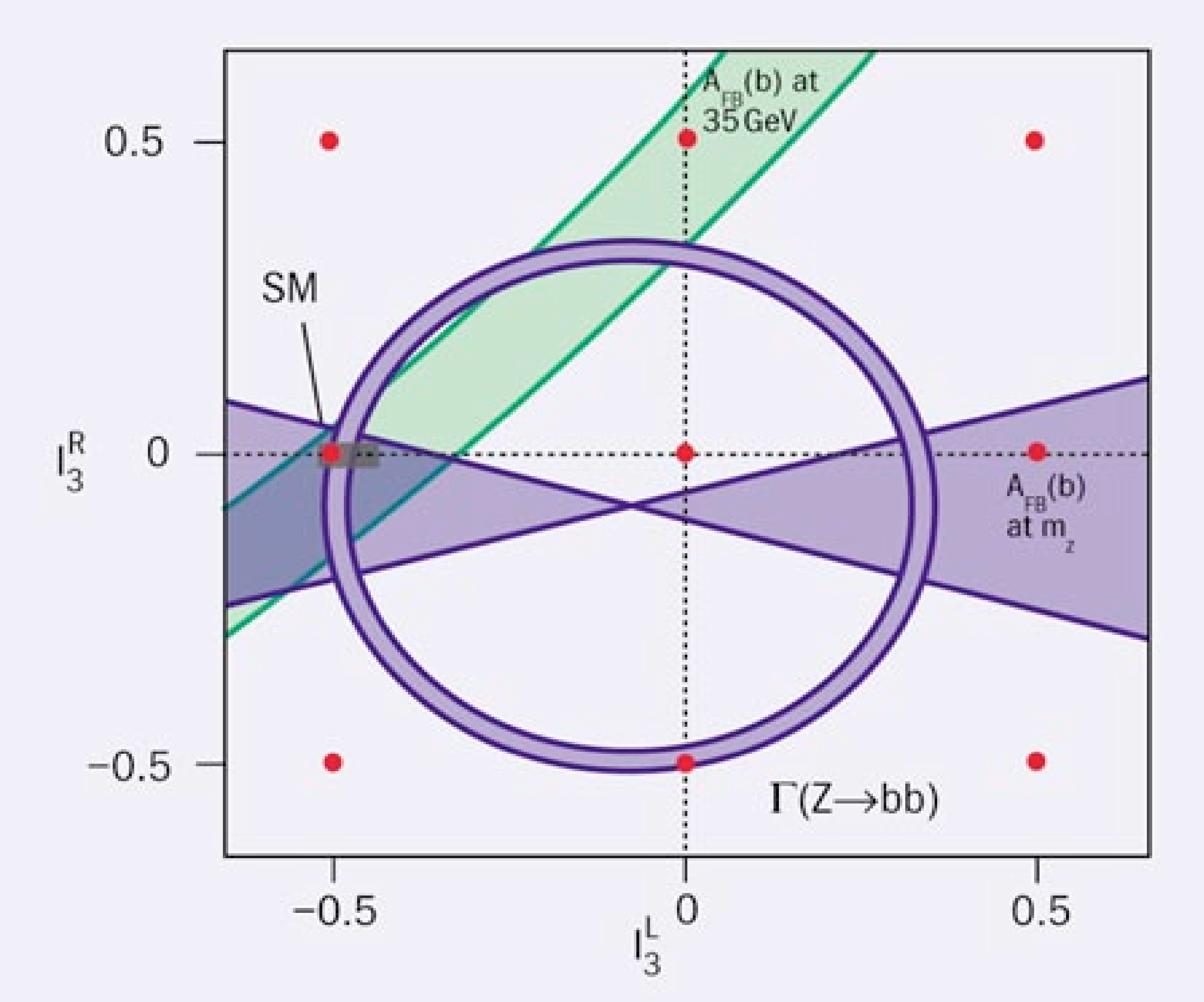
Quantity	Expected error	Achieved
m_Z	50 to 20 MeV	**2.1 MeV**
m_W	100 MeV	**42 MeV**
N_ν	0.3	**0.008**
$A^{0,\mu}_{FB}$	0.0035	**0.0013**
$A^{0,b}_{FB}$	0.0050	**0.0017**
A_τ	0.0110	**0.0043**

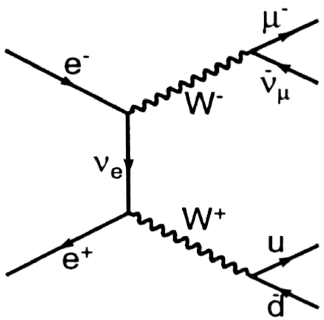
summer 2003

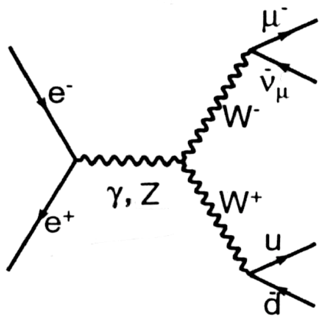
	measurement	fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z (GeV)	91.1875 ± 0.0021	91.1875
Γ_Z (GeV)	2.4952 ± 0.0023	2.4960
σ^0_{had} (nb)	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l (SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\Theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W (GeV)	80.426 ± 0.034	80.385
Γ_W (GeV)	2.139 ± 0.069	2.093
m_t (GeV)	174.3 ± 5.1	174.3
Q_W (Cs)	−72.84 ± 0.46	−72.90



Determination of the weak isospin of the bottom quark

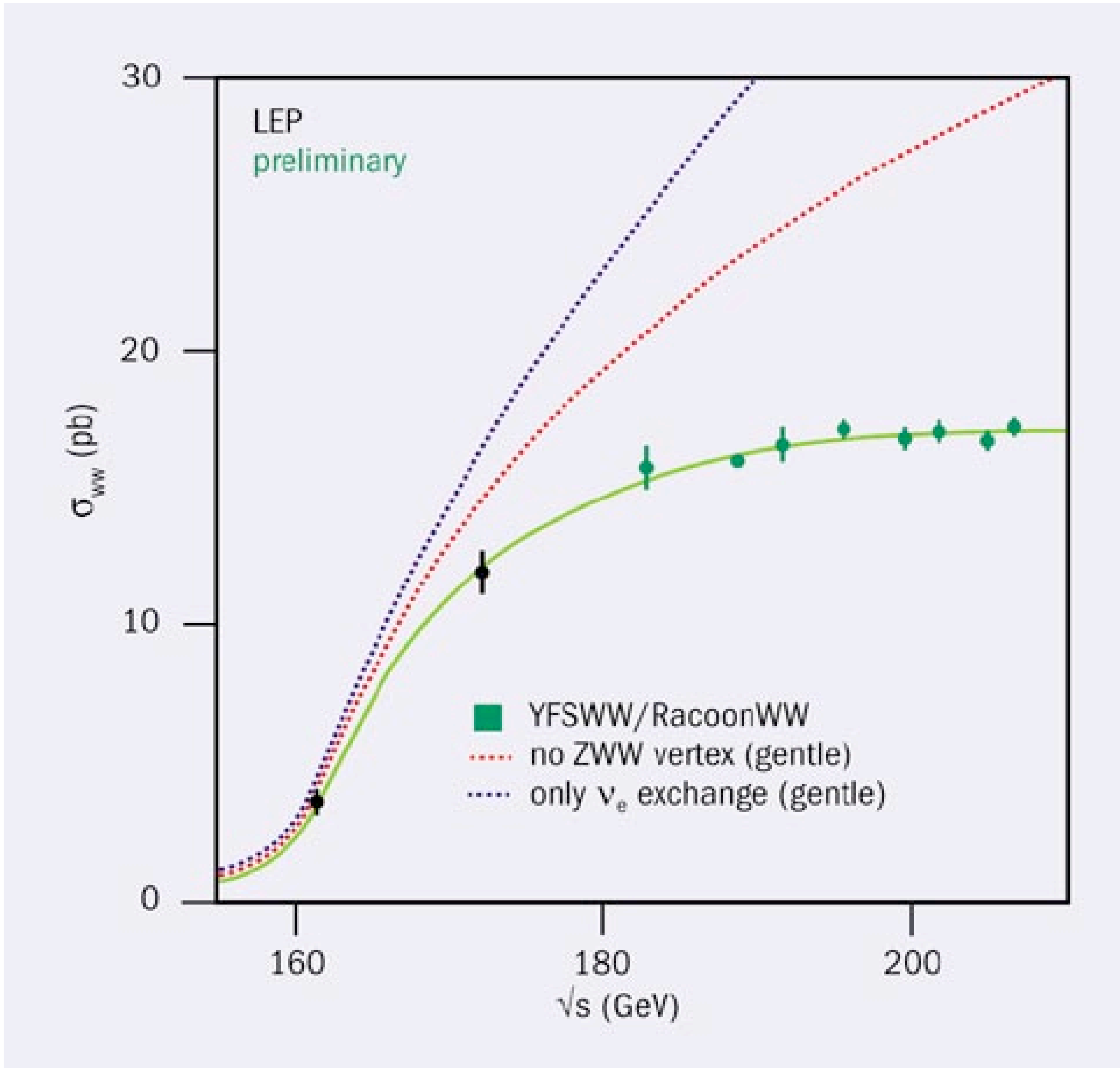






Cross section for the reaction

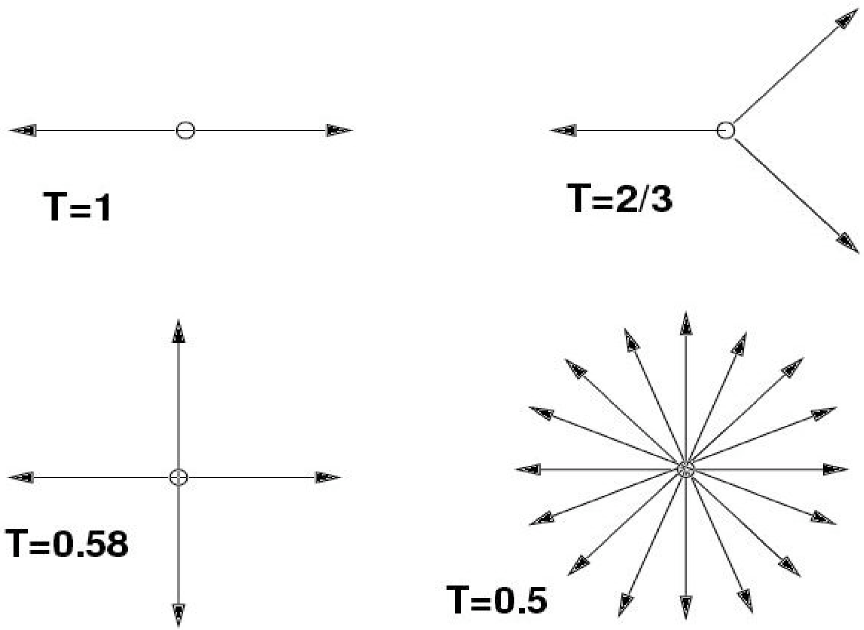
$e^- e^+ \rightarrow W^- W^+$

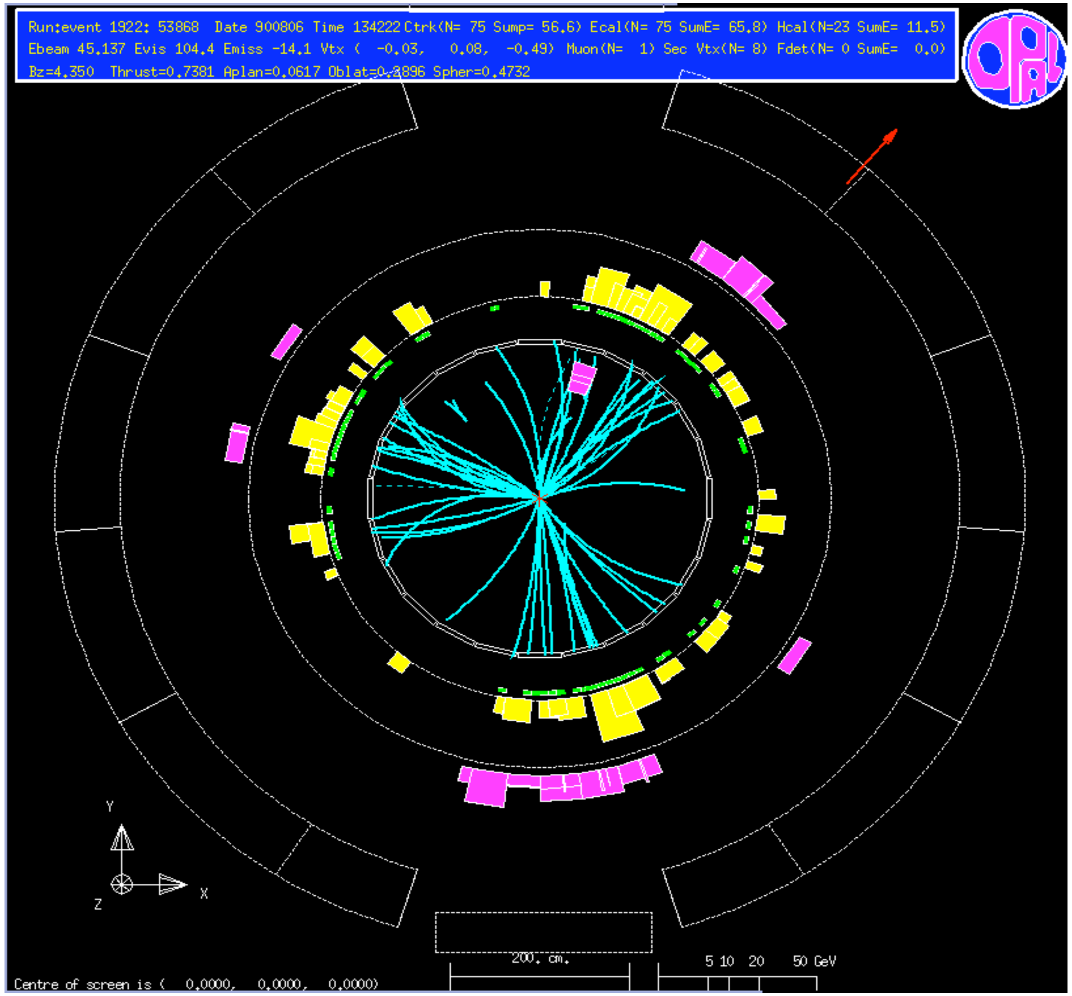


QCD: Event Shapes

Example : Thrust

$$T = \max_{\vec{n}_T} \left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}_T|}{\sum_i |\vec{p}_i|} \right)$$

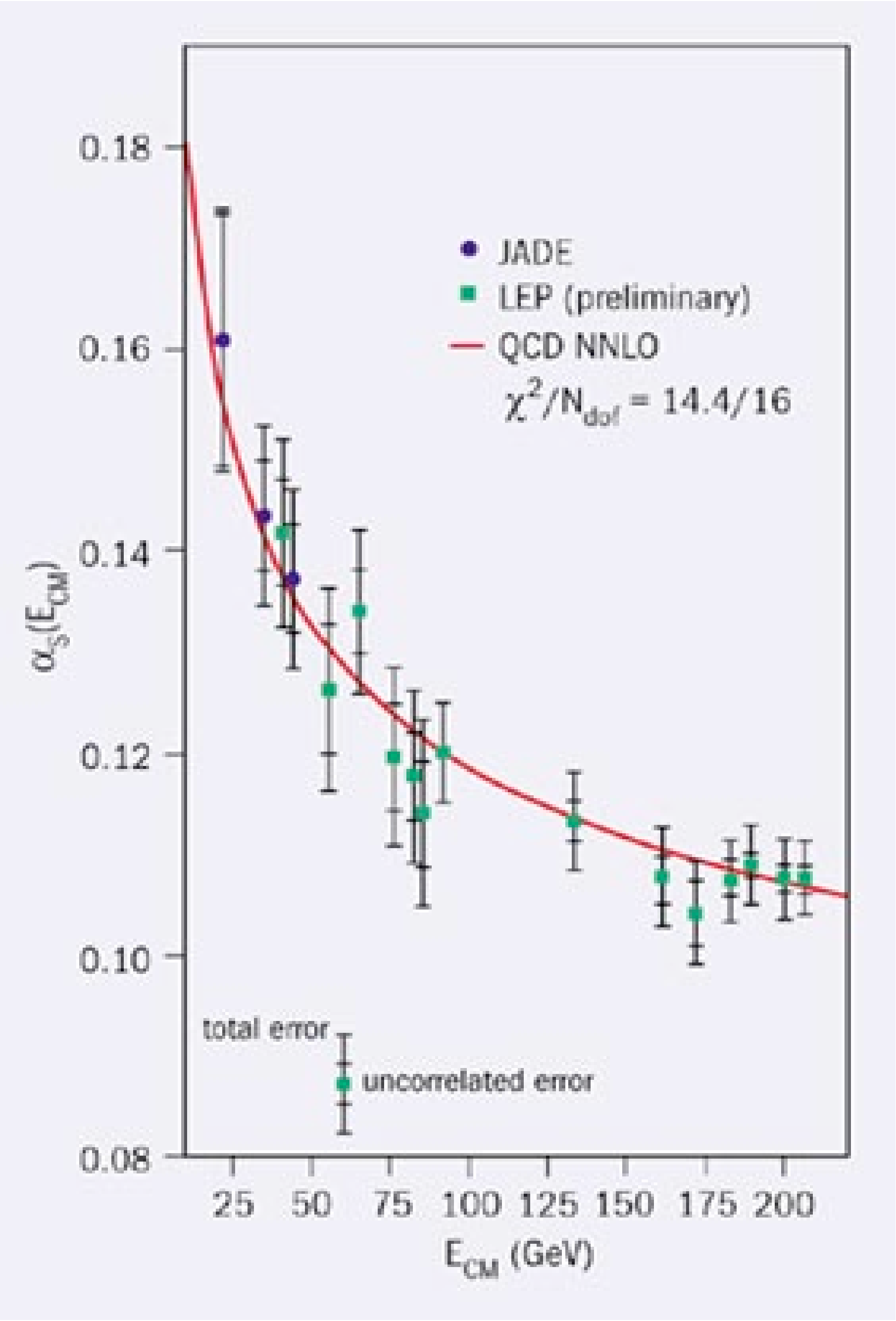




α_S

Measured with many different methods

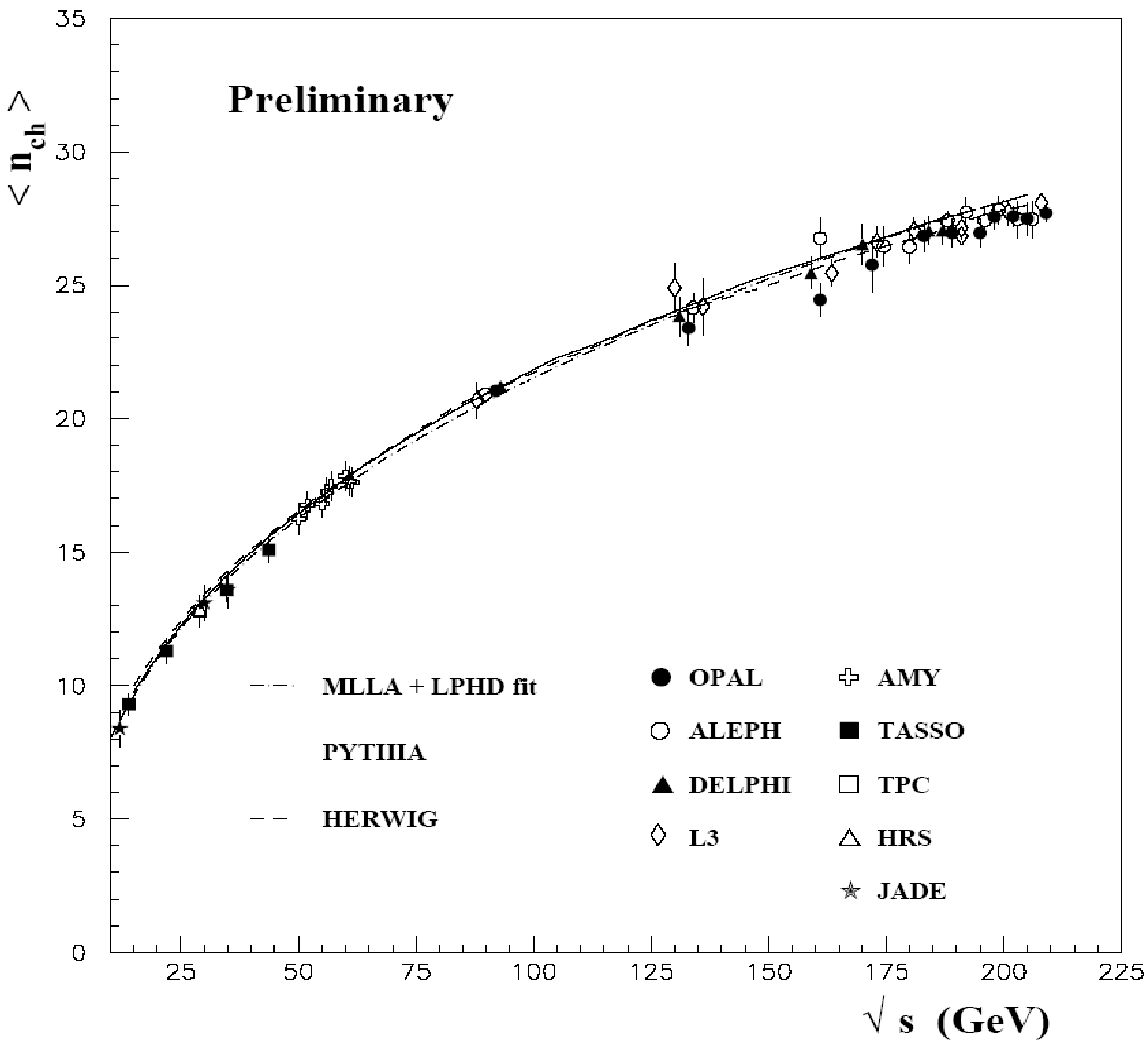
$\alpha_S(m_Z)=0.1176\pm0.0012\pm0.009$



Standard Model (SM) parameters

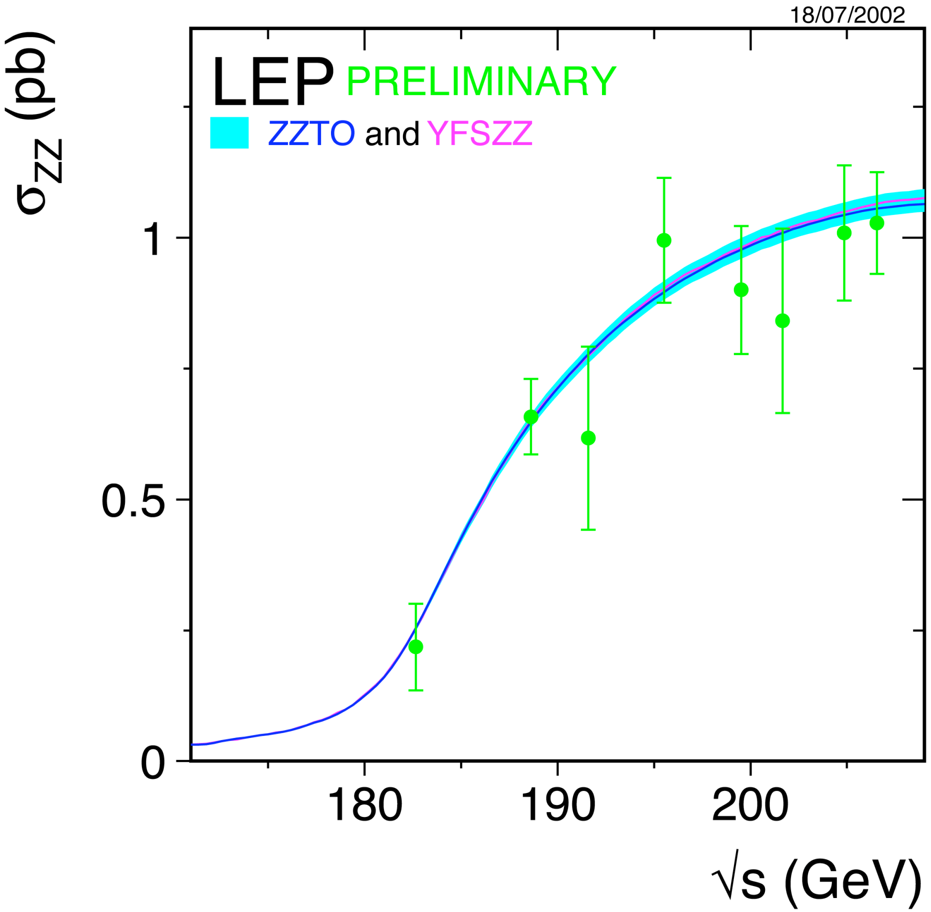
α , G_F , m_Z ; m_t , m_H ; α_S

Average charged hadron multiplicity



Z^0Z^0 production

New SM test. Search for the existence of neutral gauge couplings (ZZZ, ZZg)



Events subdivided in

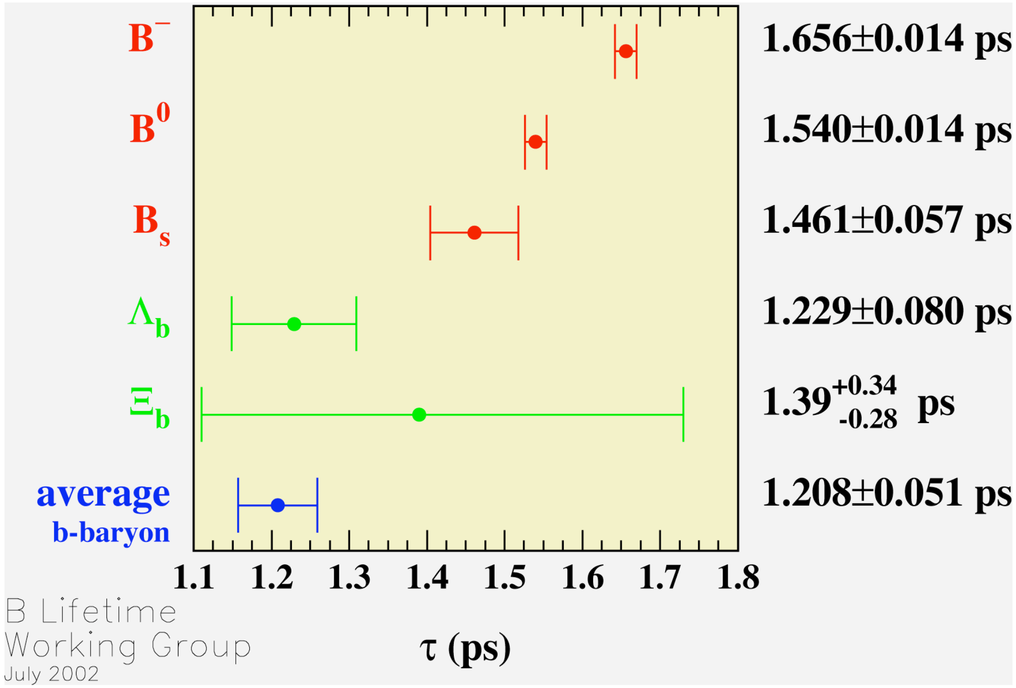
- ZZ → qqqq (4 jets)

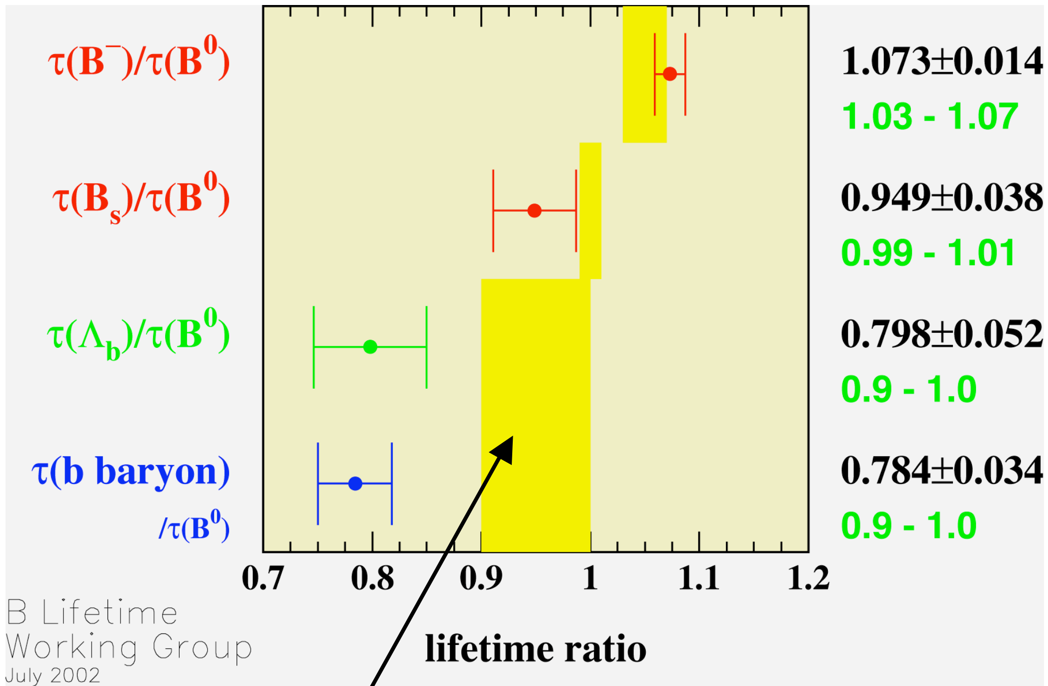
-qqνν (2 jets + missing energy)

-qql⁺l⁻(2jets+2isolated charged leptons)

-4 leptons (limited by low statistics)

B hadron lifetimes





Theoretical predictions
New lattice QCD calculations
seem to better explain these results

Searches

The most important search performed at LEP was the search for the neutral Higgs boson, H^0, of the SM.

Many searches have been performed to look for signs of new Physics beyond the SM:

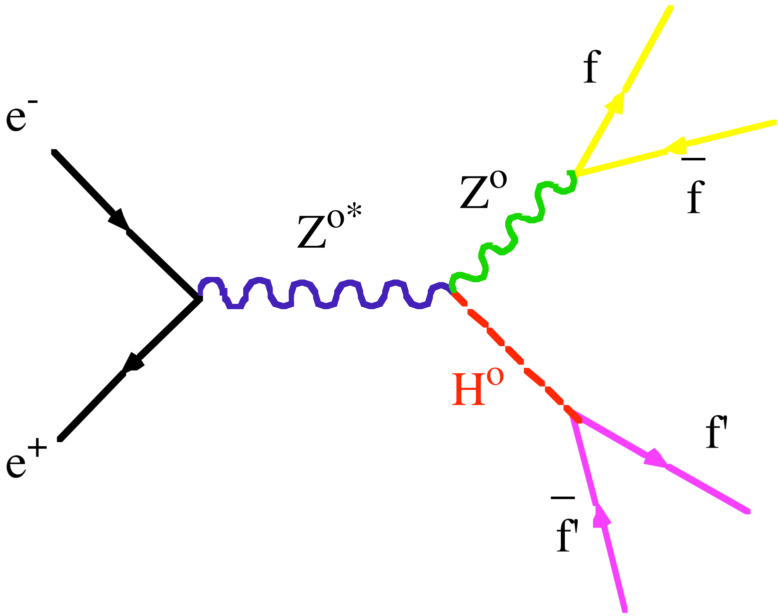
SUSY with and without R-parity violation

Compositeness | Technicolour
Leptoquarks | etc.

Limits:

m>90 GeV for pair production

SM Higgs - Production

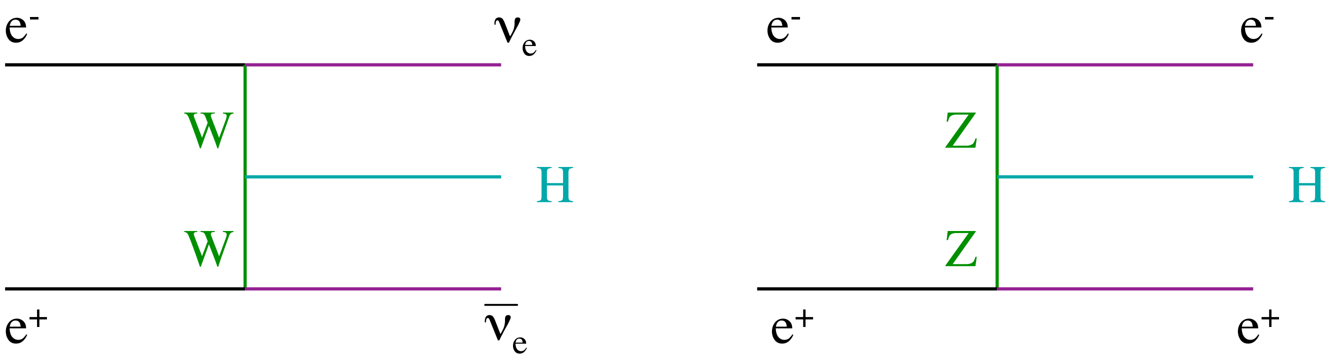


Higgs-Strahlung

Bjorken-Ioffe-Khoze mechanism

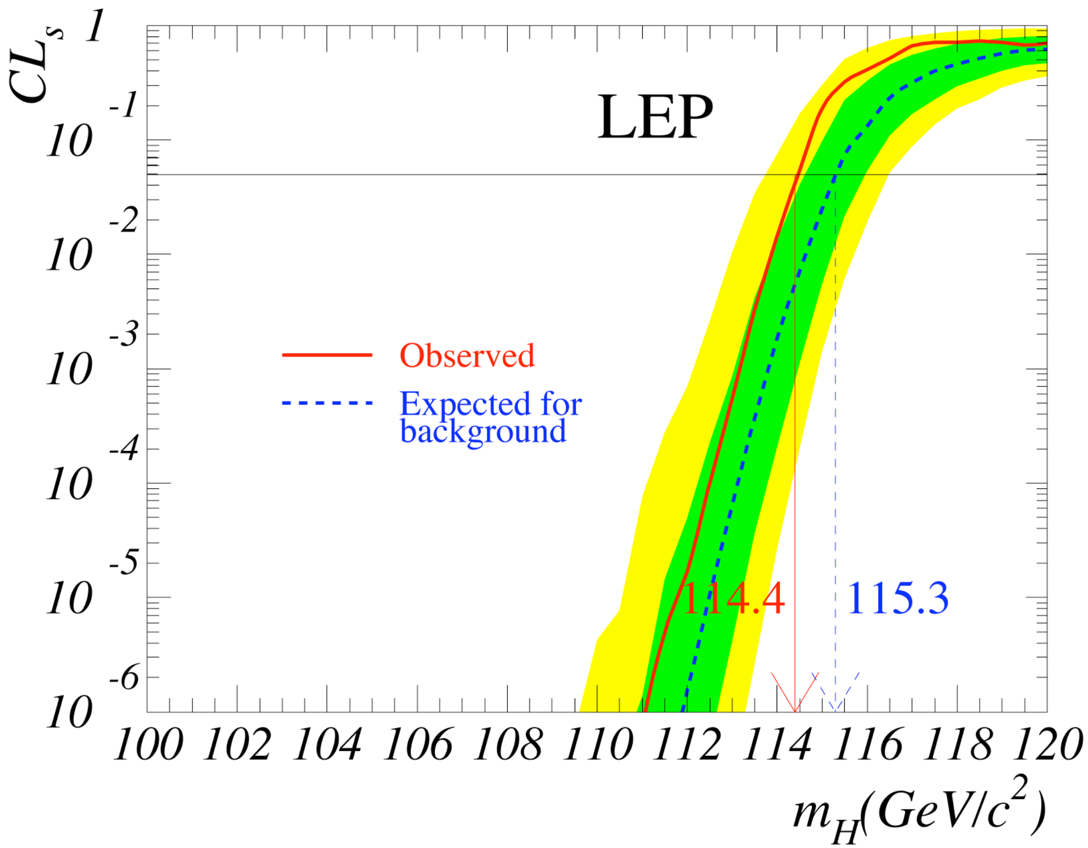
This is the dominant production mechanism at LEP2

WW and ZZ fusion



These processes give a small contribution at LEP energies

Standard Model Higgs



At 95% CL :

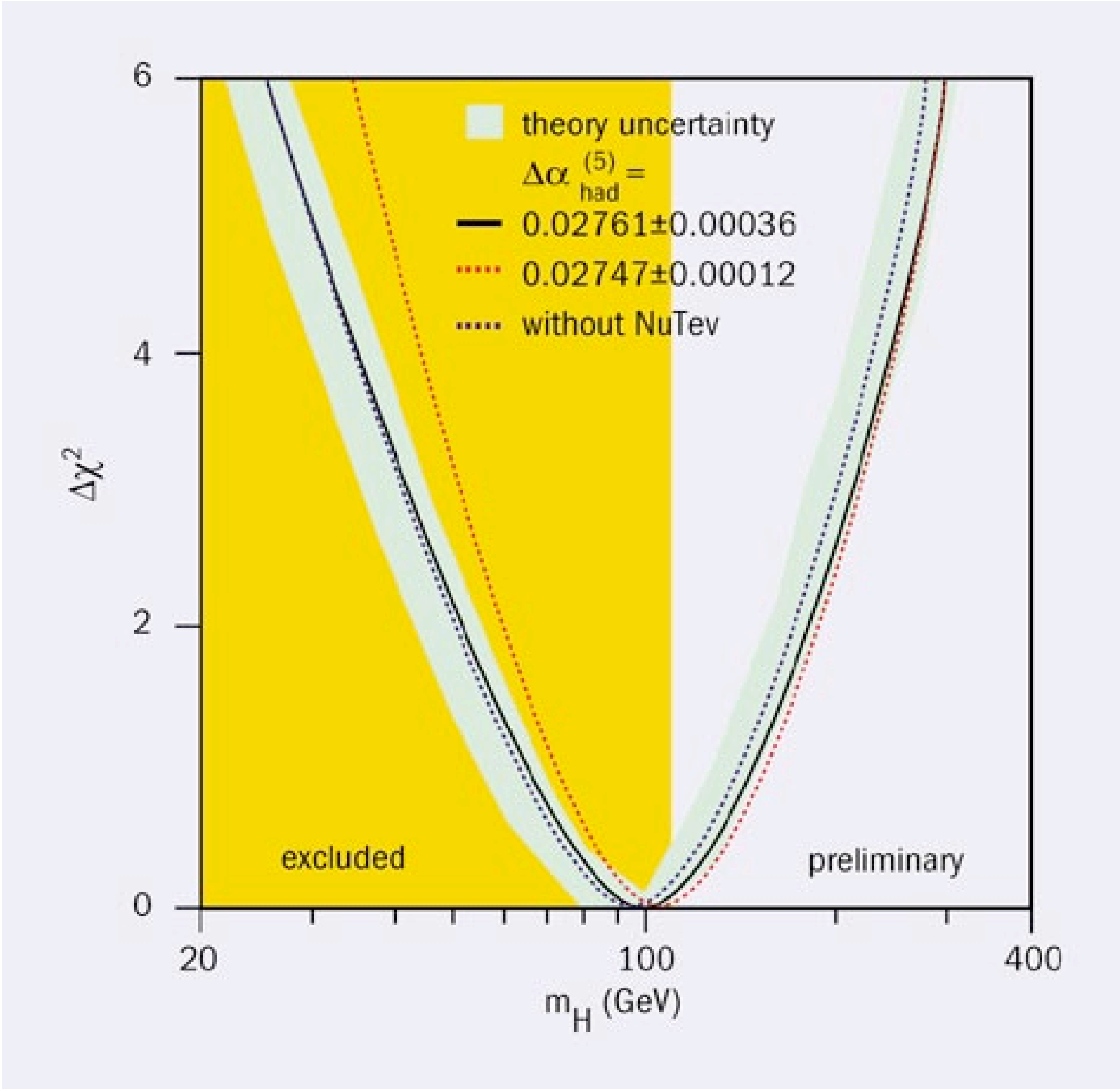
$m_H > 114.4$ GeV(obs.)

$m_H > 115.3$ GeV (exp.)

Higgs boson searches

Escluded by direct search

From best fit of EW data



SUSY

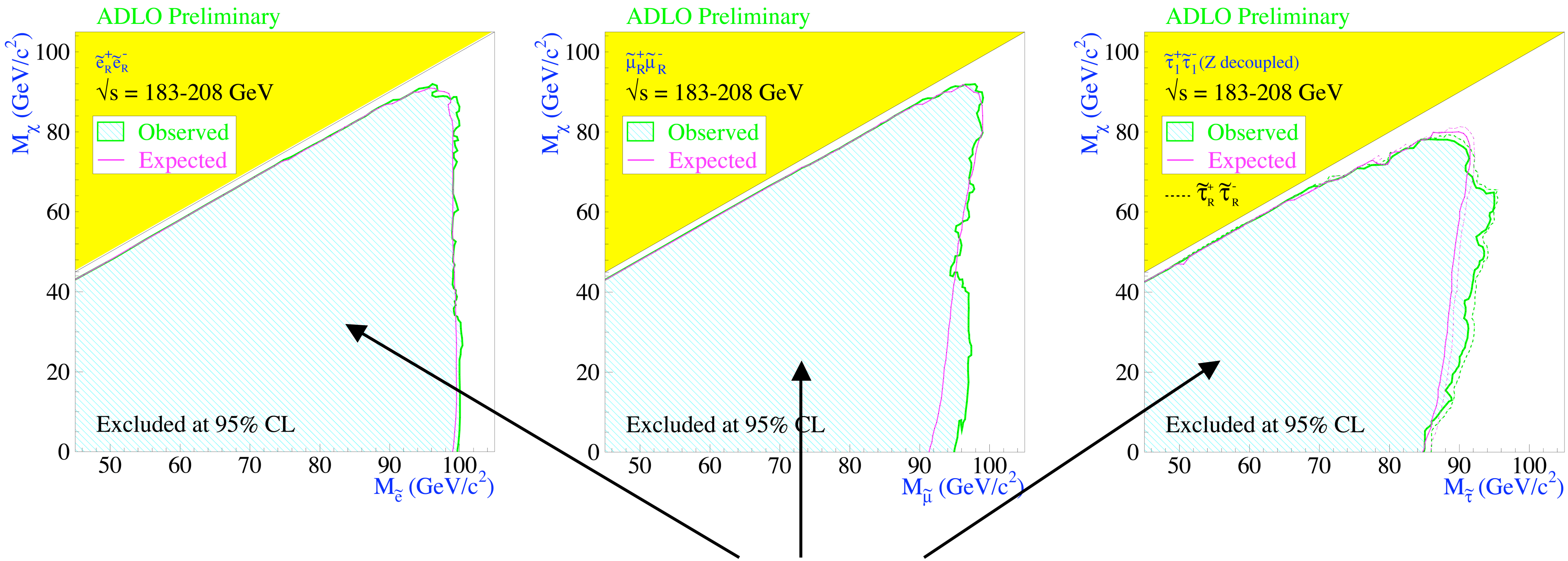
In Supersymmetric models each "normal" particle has a SUSY partner whose spin differs by 1/2.

Particles, $R = +1$			Sparticles, $R = -1$			
Particle	Spin	Charge	Sparticle	Spin	S-name	Mass eigenstates
e	1/2	- 1	$\tilde{e}_L, \tilde{e}_R$	0	selectron	
μ	1/2	- 1	$\tilde{\mu}_L, \tilde{\mu}_R$	0	smu	
τ	1/2	- 1	$\tilde{\tau}_L, \tilde{\tau}_R$	0	stau	
$\nu = \nu_e, \nu_\mu, \nu_\tau$	1/2	0	$\tilde{\nu}$	0	sneutrino	
q = u,d,s,c,b,t	1/2	2/3, -1/3	$\tilde{q}_L, \tilde{q}_R$	0	squark	
g	1	0	$\tilde{g}$	1/2	gluino	
γ	1	0	$\tilde{\gamma}$	1/2	photino	
Z^0	1	0	$\tilde{Z}^0$	1/2	zino	neutralinos
H_1^0, H_2^0	0	0	$\tilde{H}_1^0, \tilde{H}_2^0$	1/2	neutral Higgsinos	($\tilde{\chi}_1^0$ - $\tilde{\chi}_4^0$)
$H^\pm$	0	± 1	$\tilde{H}^\pm$	1/2	charged Higgsino	charginos
$W^\pm$	1	± 1	$\tilde{W}^\pm$	1/2	wino	($\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$)
G	2	0	$\tilde{G}$	3/2	gravitino	

	Spin		
	0	1/2	1
Particles and Sparticles	$\tilde{l}$ $\tilde{q}$ H_1^0, H_2^0 $H^\pm$	l q $\tilde{\chi}_1^0$ - $\tilde{\chi}_4^0$ $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$	γ, Z^0 $W^\pm$

Sleptons

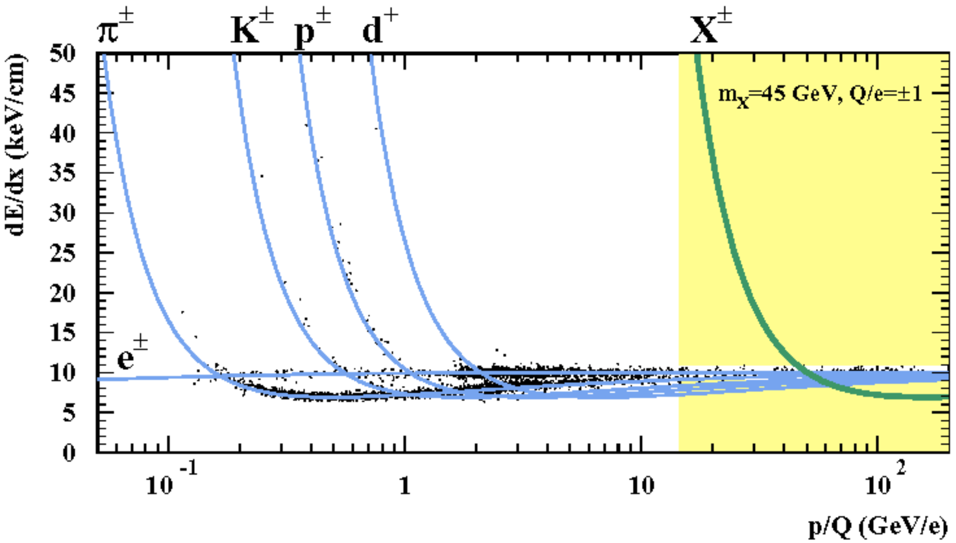
$$e^+e^- \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow l^+\tilde{\chi}^0_1\ l^-\tilde{\chi}^0_1$$

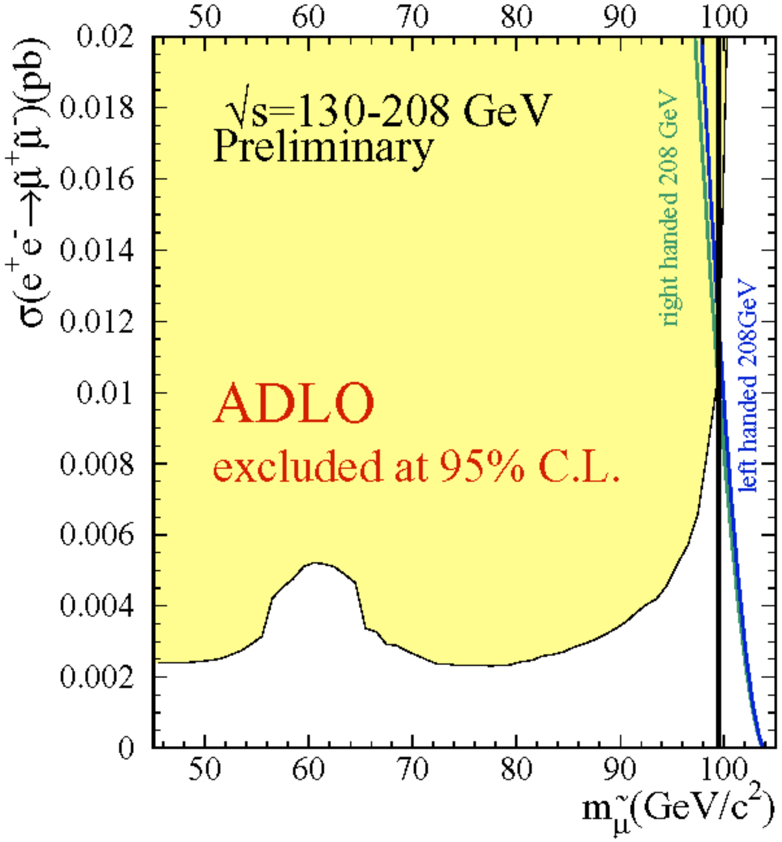


Regions in the plane ($m_{\tilde{l}}$, $m_{\tilde{\chi}_0}$) excluded at 95% CL

Stable charged particles

- Pair produced heavy stable charged particles.
  - ◇ Main tool: search for particles with anomalously high or low ionisation energy loss (dE/dx) in the tracking chambers:





⇒ for right (left) handed $\tilde{\tau}$, $\tilde{\mu}$:

$$m_{\tilde{\tau},\,\tilde{\mu}} > 99.4\ (99.6)\ \text{GeV/c}^2$$

⇒ for stable charginos with $m_{\tilde{\nu}} > 41.\ (500.)$ GeV/c^2:

$$m_{\tilde{\chi}_1^{\pm}} > 101.5\ (102.5)\ \text{GeV/c}^2$$

Historical and sociological aspects

Changing size of experimental teams

<1970 Small single groups
>1970 Collaborations of few groups
LEP Tens of groups → also for non accelerator experiments
LHC Hundreds of groups

>1980 Preliminary workshops

Many activities and involvement of many people

Start construction of LEP and of 4 experiments

Very active phase: contruction, tests, MonteCarlos
Many felt the lack of physics results

1989 Start data taking

The beginning of an exciting phase

Start improvements [Luminometers, microvertex detectors, ...)

New organizational structure

"Government" (spokesman+executive committee,...)+project leaders

Historical and sociological aspects/2

1989 LEP1 → 1995 → LEP2 2000

"Paperosity"

Collaboration	Number of authors	Papers/Authors
LEP	330 – 550	0.5 – 1
CDF-D0	400 - 500	0.3 – 0.5
H1-ZEUS	"	0.23
UA1-UA2	65 – 150	0.33

"Visibility"

Presentations in working groups, collaboration meetings, conferences

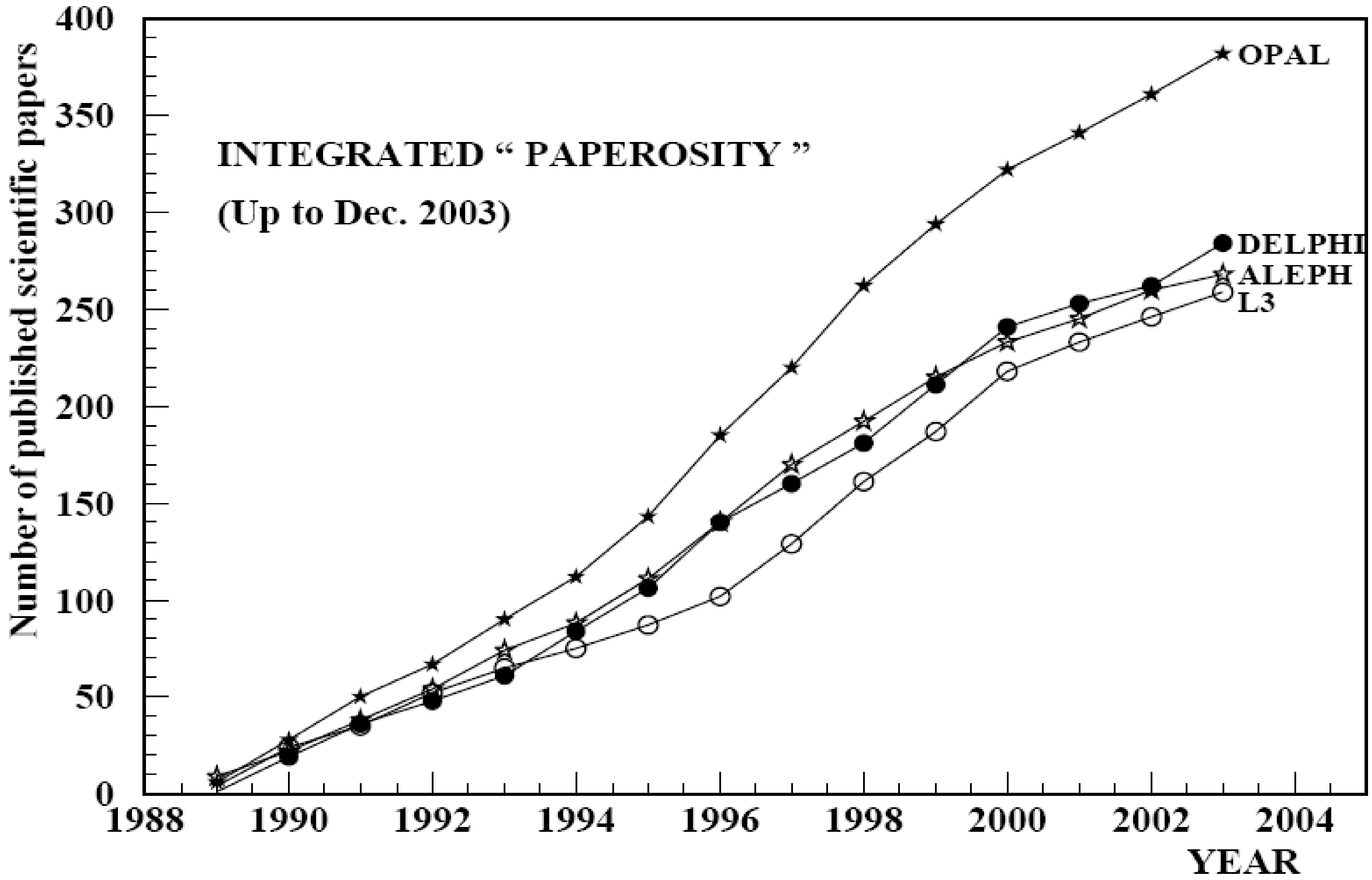
Internal notes with/without referees

Computing

1983: 2 units/experiment (1 unit = 1 IBM 370/168)

2000: >1000 units/experiment; distributed computing

Computer memories: from MB to GB



In total the 4 LEP experiments have published more than 1100 publications on refereed scientific journals

Historical and sociological aspects/3

CERN most important invention: WWW

LEPC committee

Very good cooperation between experimentalists and theoreticians

Competition and cooperation between the 4 experiments

The experiment secretariats

Sport (CERN races; soccer) Great enthusiasm and team spirit

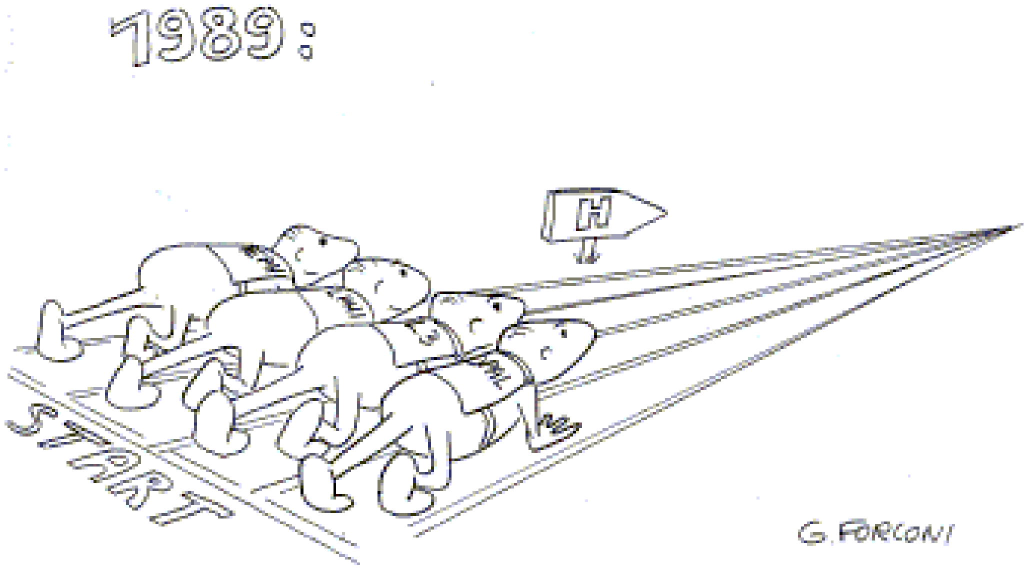
Participants happy even when they won a "random prize"

"Love affairs" They followed the changing life pattern: encounters, new encounters, new experiences, course changing, few marriages, few babies, ... After year 2000 may be more marriages and more babies ...

In conclusion: most physicists considered the LEP experience positive and exciting; Colleagues from DC started working in HEP, as groups

One shouldnot forget the large number of Diploma and PhD theses

Searches for the Higgs Boson by the 4 experiments at LEP



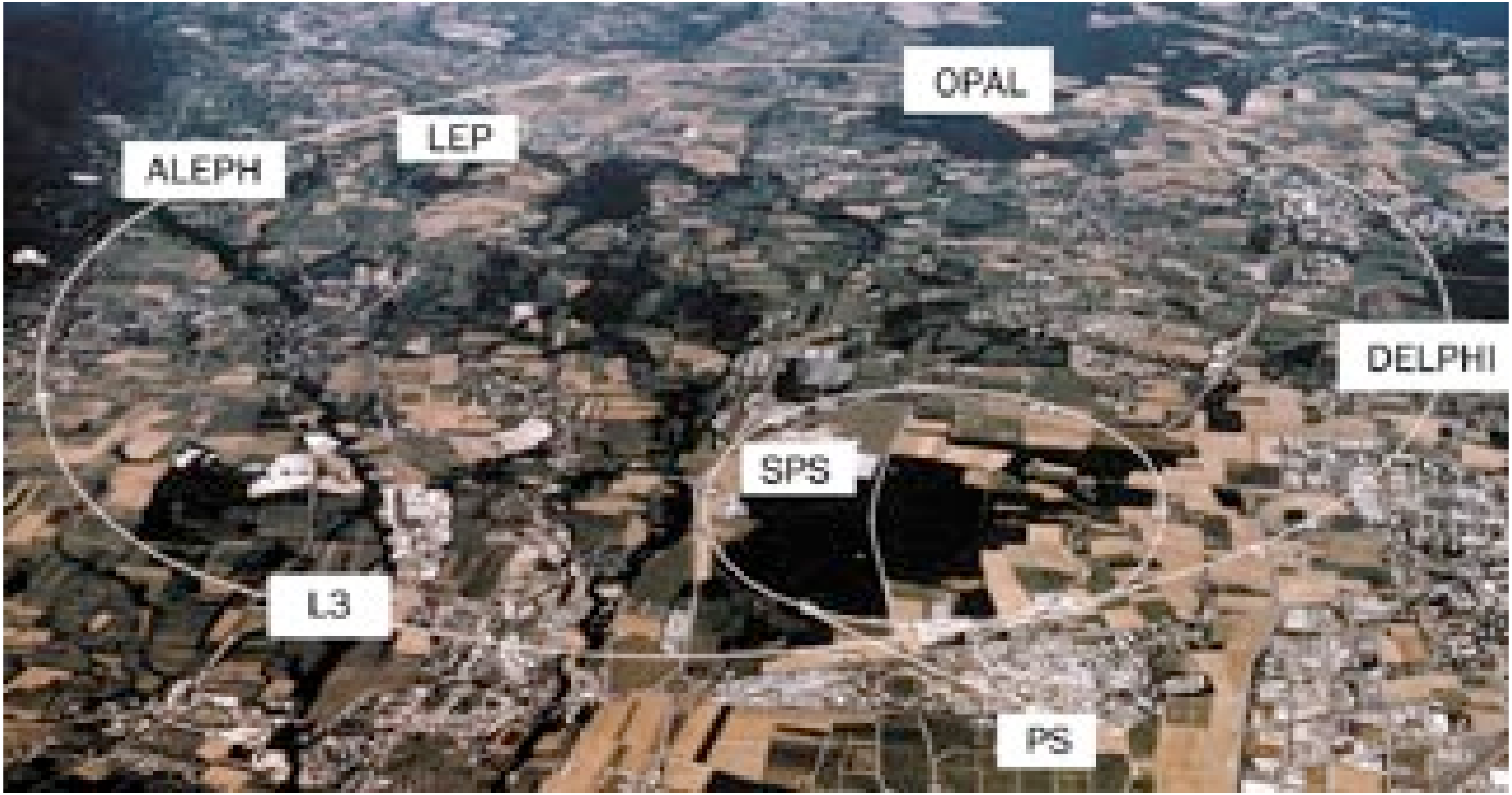
Conclusions

LEP operated very reliably from 1989 to 2000

The most important LEP results :

i) Determination of the number of neutrino families (3)
ii) Very precise measurements of all the EW parameters
iii) Precise tests of QCD. Determination of α_S running
iv) The first determination of m_{top} below threshold
v) Measurements of the B mesons and tau short lifetimes
vi) Measurement of m_W, Γ_W, triple bosonic vertex, ...
vii) Higgs boson: lighter than ~200 GeV (m_H = 116 GeV?)
iii) Stringent limits on new particles

The Particle Data Book is full of results from LEP


OPAL
LEP
ALEPH
DELPHI
SPS
L3
PS