LEP加速器と検出器

田中礼三郎（岡山大学）

Contents

References:

- “**Accelerator Physics at LEP**”, D.Brandt et al,
  Pep. Prog. Phys. 63 (2000) 939-1000, (CERN-SL-2000-037 DI)
- **LEP Fest 2000, Science Symposium**, Oct.9-11, 2000, CERN
  http://cern.web.cern.ch/CERN/Announcements/2000/LEPFest/ScienceSymposium.html
- **The Legacy of LEP and SLC**, Oct.8-11, 2001, Siena, Italy
  http://www.bo.infn.it/sminiato/siena01.html

1. LEP Physics

LEP

- First conceived in 1976 after SPEAR's J/Ψ discovery in 1974.
  - "Very high-energy electron-positron colliding beams for the study of the weak interactions", B.Richter (NIM 136 (1976) 47).
- LEP Summer Study in 1978 (Les Houches, CERN 79-01)
  - Z Production and Decay
  - WW Production (gauge cancellation)
  - Higgs Search
  - Search for New Leptons and Quarks
  - QCD

  Note: W and Z not discovered until 1983.

The study correctly foresaw LEP Physics !

except:

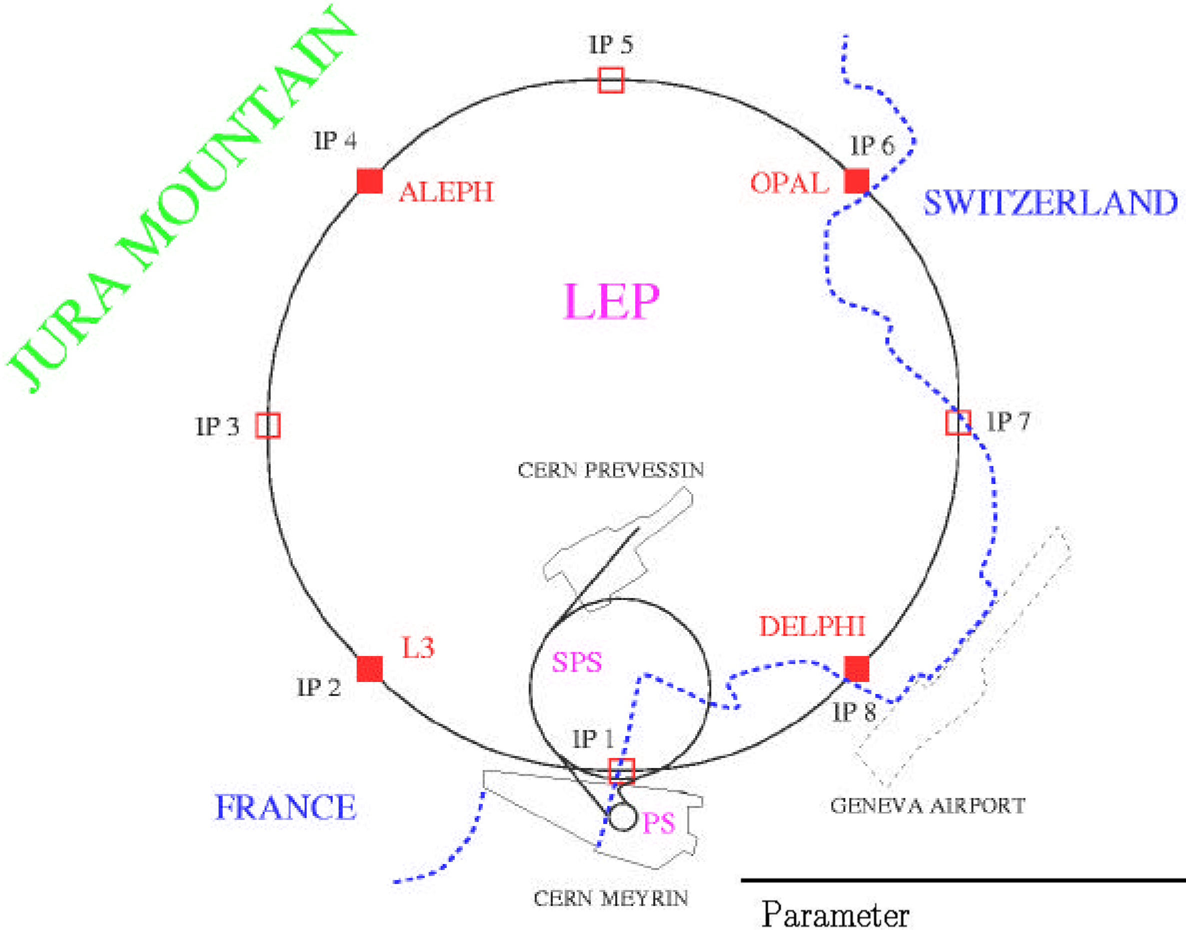
- Missing energy measurement with hermetic detector (ex. SUSY)
- B physics (micro-vertex detectors)

- Physics benchmarks
  - Z^0 decay, $Z \rightarrow bb$ tag via e/μ, $A_{FB}(bb)$
  - B lifetime
  - Neutrino counting via Z-width and $\nu\nu\gamma$
  - Toponium $\zeta' \rightarrow \gamma + {}^3P(tt) \rightarrow \zeta + \gamma + \gamma$ (ζ ® $l^+ l^-$), $\zeta' \rightarrow \gamma + {}^3P(tt) \rightarrow \gamma$+hadrons
  - Search for Higgs via $e^+e^- \rightarrow Z+H$, charged Higgs $e^+e^- \rightarrow H^+ + H^-$
  - Search for free quarks of Q=1/3 and 2/3 (no LEP publication yet!)

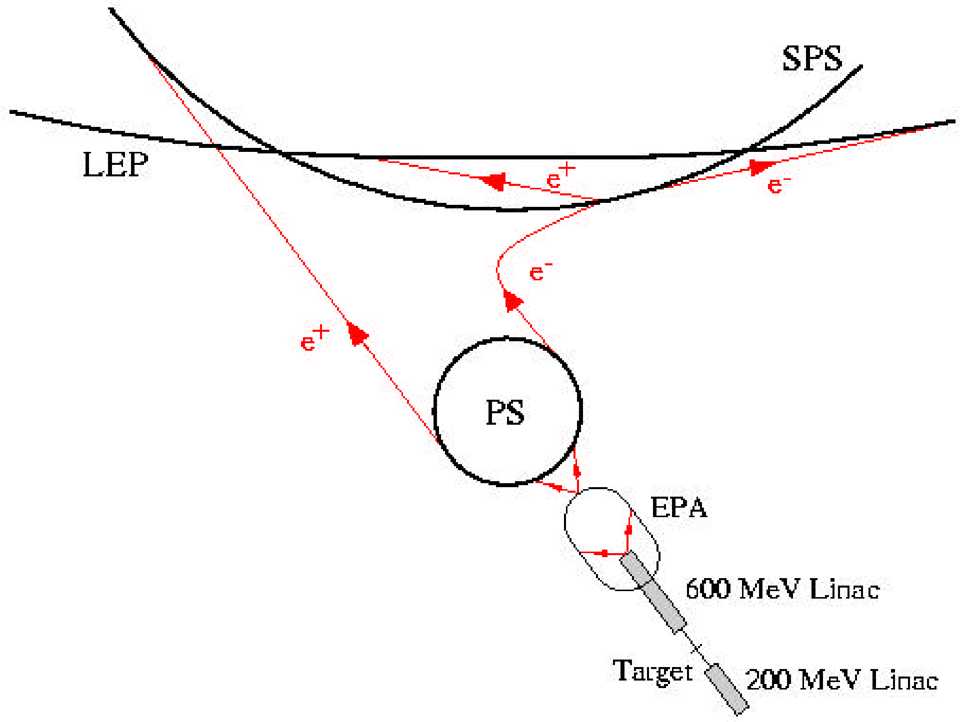
- Nov. 1982 … 6 LoI discussed

Approved	**ALEPH**	**(Jack Steinberger)**
	DELPHI	**(Ugo Amaldi)**
	L3	**(Sam Ting)**
	OPAL	**(ALDO Michelini)**
Disapproved	ELECTRA	
	LOGIC	

2. LEP Accelerator



Parameter	Symbol	Value
Effective bending radius	ρ	3026.42 m
Revolution frequency	$f_{\rm rev}$	11245.5 Hz
Length of circumference, $L = c/f_{\rm rev}$	L	26658.9 m
Geometric radius $(L/2\pi)$	R	4242.9 m
Radio frequency harmonic number	h	31320
Radio frequency of the RF-system, $f_{\rm RF} = h\, f_{\rm rev}$	$f_{\rm RF}$	352 209 188 Hz



Accelerator	L (km)	L/L_{EPA}	Energy (GeV)	
			Injection	Top
Linacs	≈ 0.1	–	0	0.6
EPA	0.126	1	0.6	0.6
PS	0.628	5	0.6	3.5
SPS	6.912	5×11	3.5	20-22
LEP	26.66	$5 \times 11 \times 27/7$	20-22	101

Why is LEP so Big? Why SC RF?

$$U_0 \propto \frac{E_b^4}{E_0^4}\frac{1}{\rho} = V_{RF}\sin\varphi_s$$

Losses due to Synchrotron Radiation

E0 = .511MeV for electrons and 938.256 for protons

$$P_{Cu} \propto \frac{V_{RF}^2}{lr_{sh}} \propto \frac{E_b^8}{E_0^8}\frac{1}{\rho^2}\frac{1}{lr_{sh}}$$

Power Dissipated in the walls of the Cu cavities

$$P_{sc} \propto I_{tot}U_0 \propto \frac{E_b^4}{E_0^4}\frac{I_{tot}}{\rho}$$

Power to Beam from the SC cavities.....

So to minimise power you need ρ to be as large as possible **i.e. large radius.** The radius for LEP1 was optimised for around 80GeV with Cu cavities.

For sc cavities the power needed is "only" proportional to the 4th power of energy. NOTE to operate LEP at 103 GeV with copper cavities would have needed 1280 cavities and 160MW of RF power!! Impossible for many reasons.

LHC For protons since E_0 is a factor of 1836 higher, the RF power is not an issue and the bending radius can be made as low as is technically possible. i.e. High fields.

Le 14 juillet 1989 - la joie éclate dans la salle de contrôle : le premier faisceau circule dans le LEP

Summary of LEP Performance

Year	$\int \mathcal{L} dt$ (pb^{-1})	E_b ($\mathrm{GeV/c^2}$)	k_b	$2k_b I_b$ (mA)	$\mathcal{L}$ ($10^{30}\ \mathrm{cm^{-2}\ s^{-1}}$)	ξ_y
1989	1.74	45.6	4	2.6	4.3	0.017
1990	8.6	45.6	4	3.6	7	0.020
1991	18.9	45.6	4	3.7	10	0.27
1992	28.6	45.6	4/8	5.0	11.5	0.027
1993	40.0	45.6	8	5.5	19	0.040
1994	64.5	45.6	8	5.5	23.1	0.047
1995	46.1	45.6	8/12	8.4	34.1	0.030
1996	24.7	80.5 to 86	4	4.2	35.6	0.040
1997	73.4	90 to 92	4	5.2	47.0	0.055
1998	199.7	94.5	4	6.1	100	0.075
1999	253	98 to 101	4	6.2	100	0.083

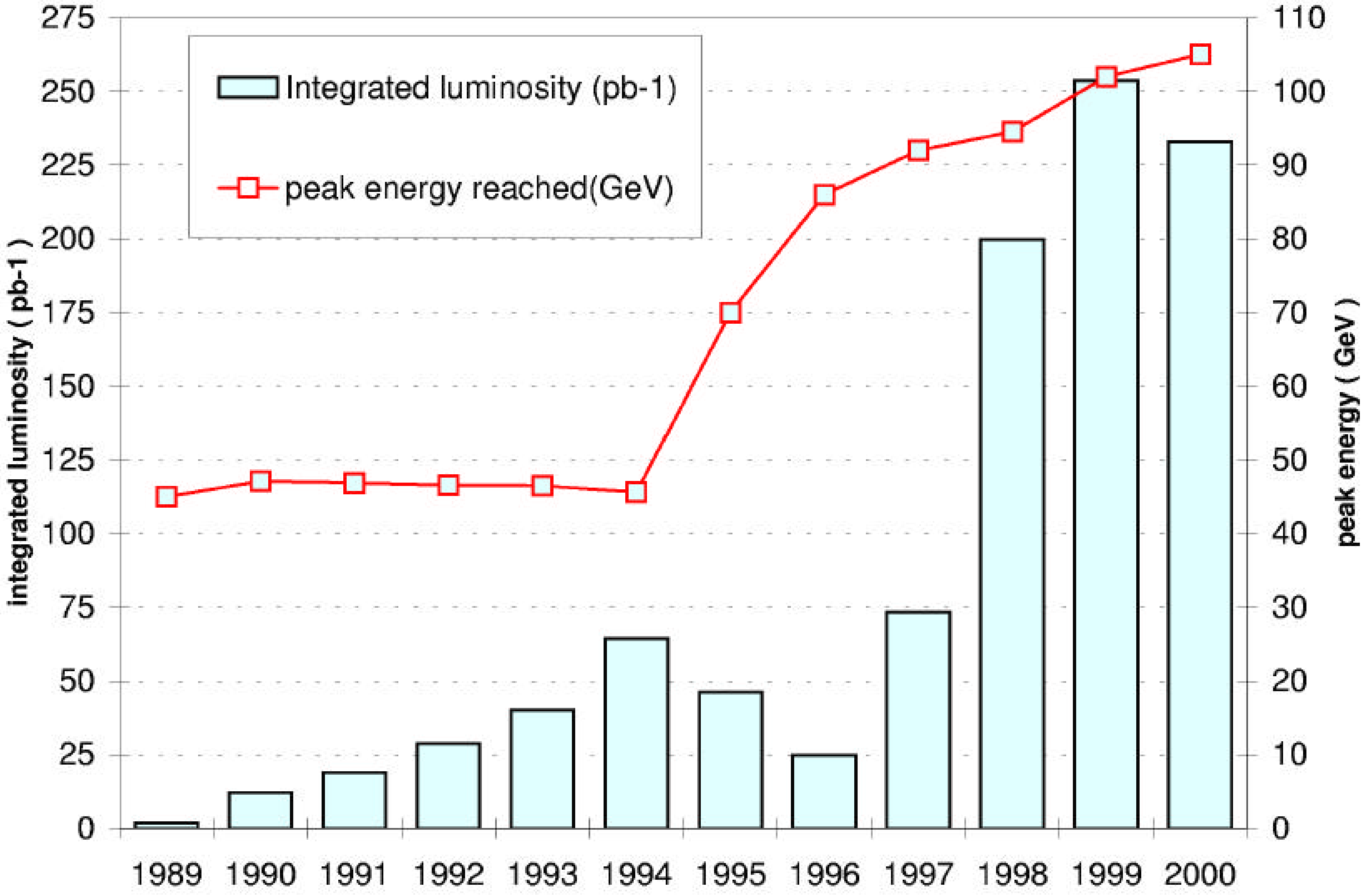
Record

LEP Modes of Operation

Bunch schemes and optics used at LEP.

Year	Optics	Comment	Bunch scheme
1989	$60^\circ/60^\circ$	LEP commissioned	4 on 4
1990	$60^\circ/60^\circ$		4 on 4
1991	$60^\circ/60^\circ$	$90^\circ/90^\circ$ optics tested	4 on 4
1992	$90^\circ/90^\circ$	Pretzel commissioned	4 on 4 / Pretzel
1993	$90^\circ/60^\circ$		Pretzel
1994	$90^\circ/60^\circ$		Pretzel
1995	$90^\circ/60^\circ$	tests at 65-68 GeV	Bunch trains
1996	$90^\circ/60^\circ$	$108^\circ/90^\circ$ tested	4 on 4
1997	$90^\circ/60^\circ$	$108^\circ/60^\circ$ and $102^\circ/90^\circ$ tested	4 on 4
1998	$102^\circ/90^\circ$		4 on 4
1999	$102^\circ/90^\circ$		4 on 4

Performances evolution from 1989 to 2000



Luminosity Limitation

LEP1

- Limited by beam-beam interaction

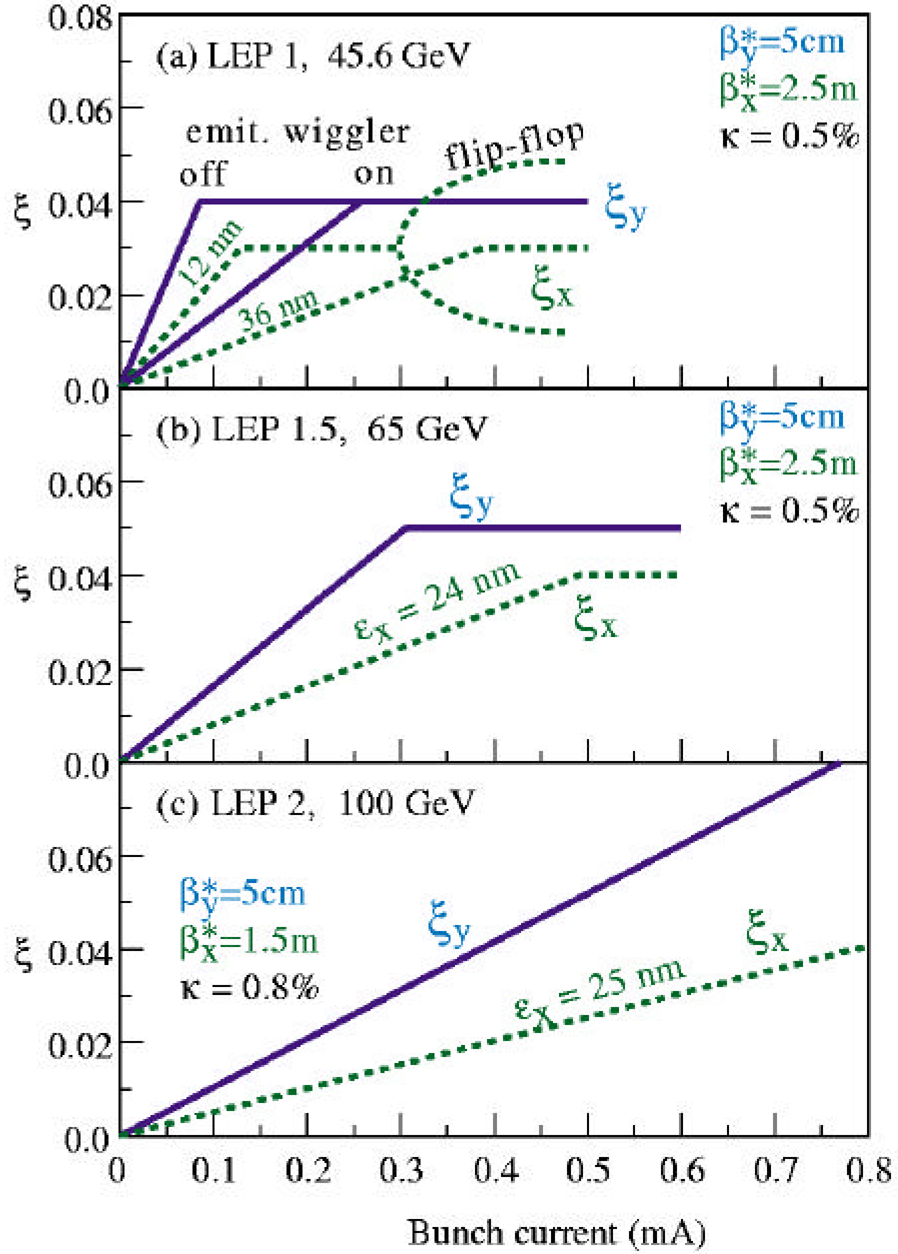
⇒ needs more bunches,

Pretzel scheme, **Bunch train**.

LEP2

⇒ more SC RF cavities installed.

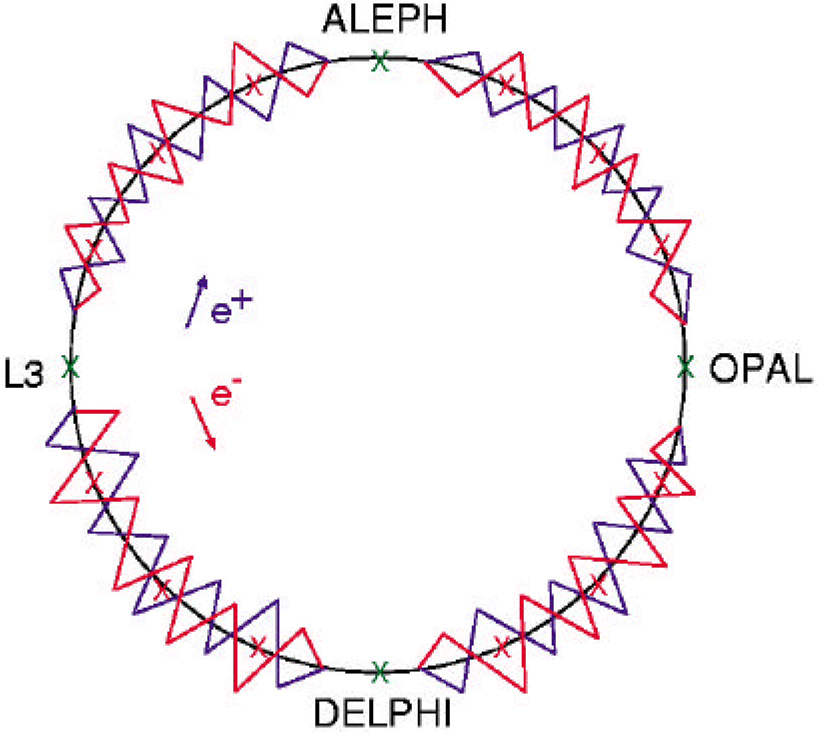
- Cryogenic limit
- Injection current limit
- RF stability limit



ξ: beam-beam tune shift
Luminosity μ ξ

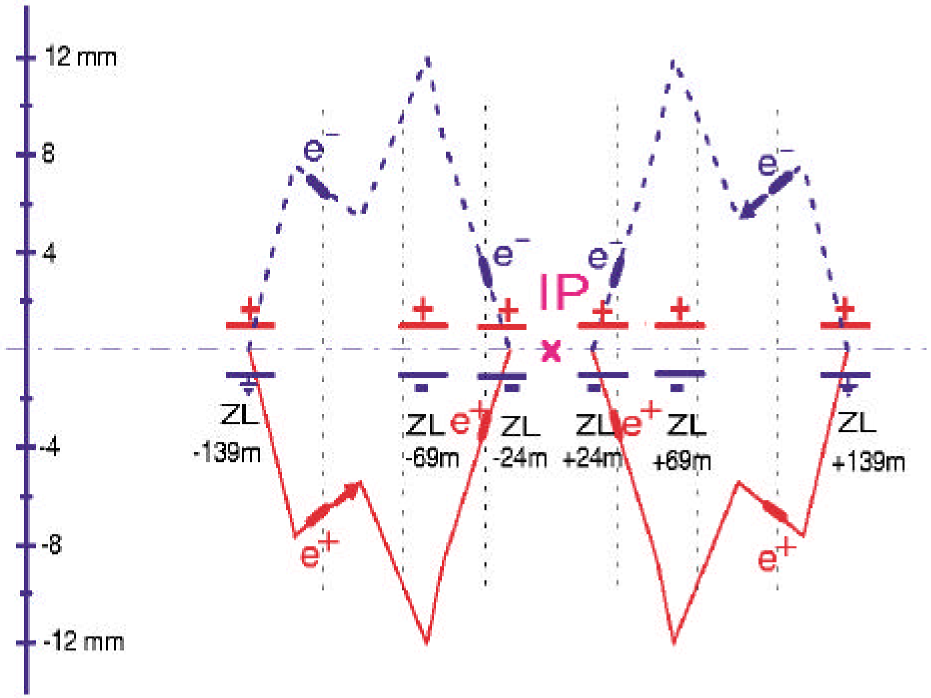
Pretzel Scheme

- e^+ and e^- travel on orbits which are distorted in opposite directions by horizontal electrostatic fields.
- Potential for large # of bunches/beam, 8 equidistant bunches per beam.



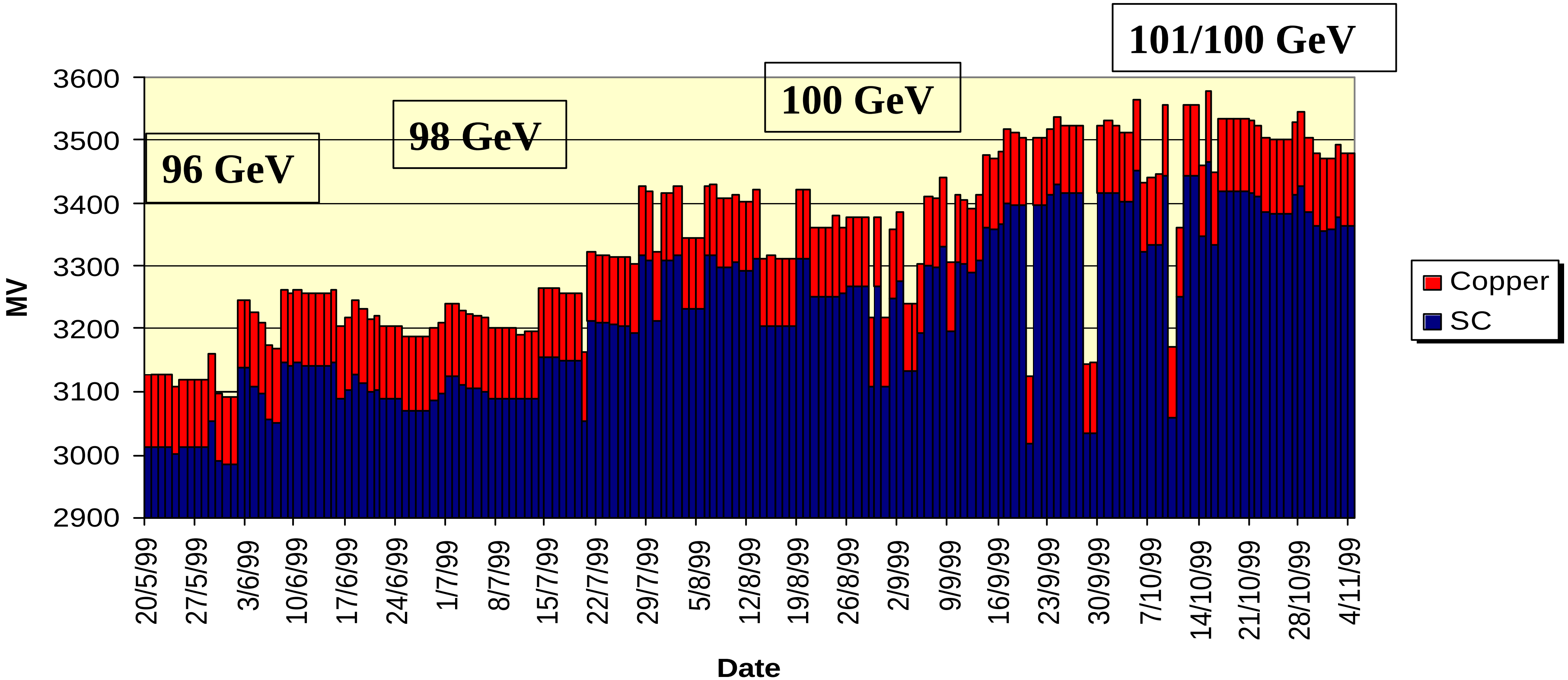
Bunch Train

- String together individual bunches in trains, 2-3bunches/train, 4trains/beam.
- Electrostatic separators(ZL) to build the vertical separation bump.



RF-Cavity

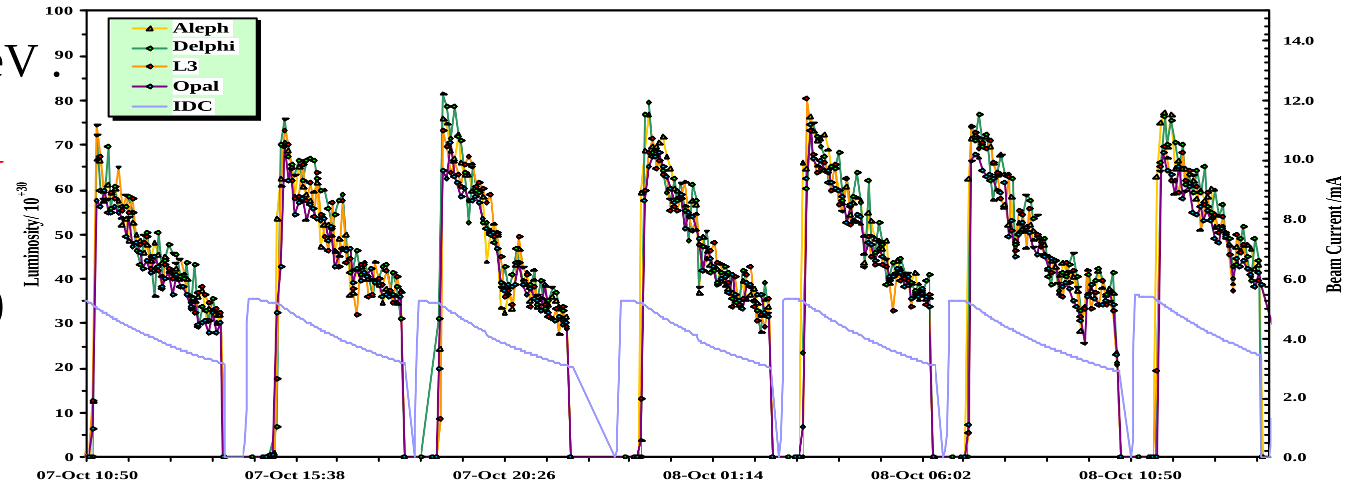
- 56 Cu-Cavity, 288 SC-Cavity(16Nb, 272Cu/Nb), 44 Klystron
- Cavity Gradient=7.5MV/m after conditioning (design 6.1MV/m)



Huge effort for maintaining RF

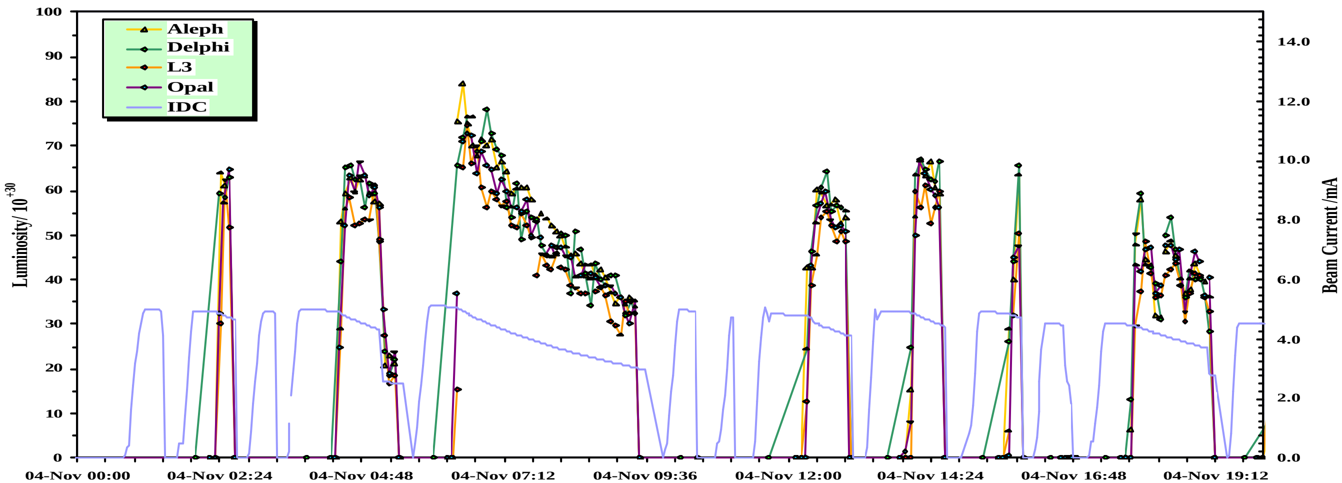
- After 2 days at 101GeV :
  - available RF voltage 3510 MV
  - margin 210 MV

  (2 klystrons can trip)



- Still at 101GeV…
  - but available RF voltage down to 3440 MV
  - margin 140 MV

  (1 klystron can trip)



Beam Energy Calibration

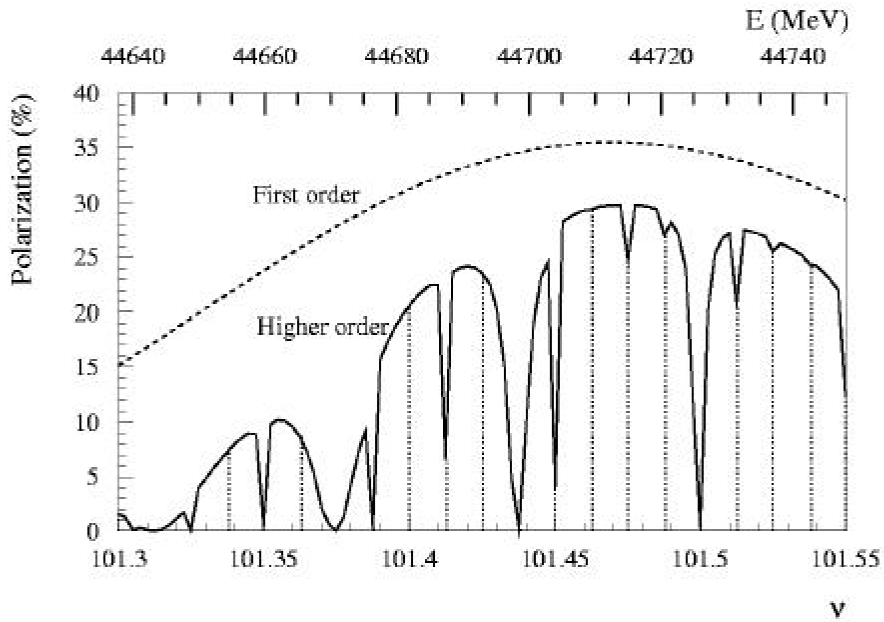
LEP1

- Proton velocity
- Resonant depolarization

but no beam polarization at LEP2!

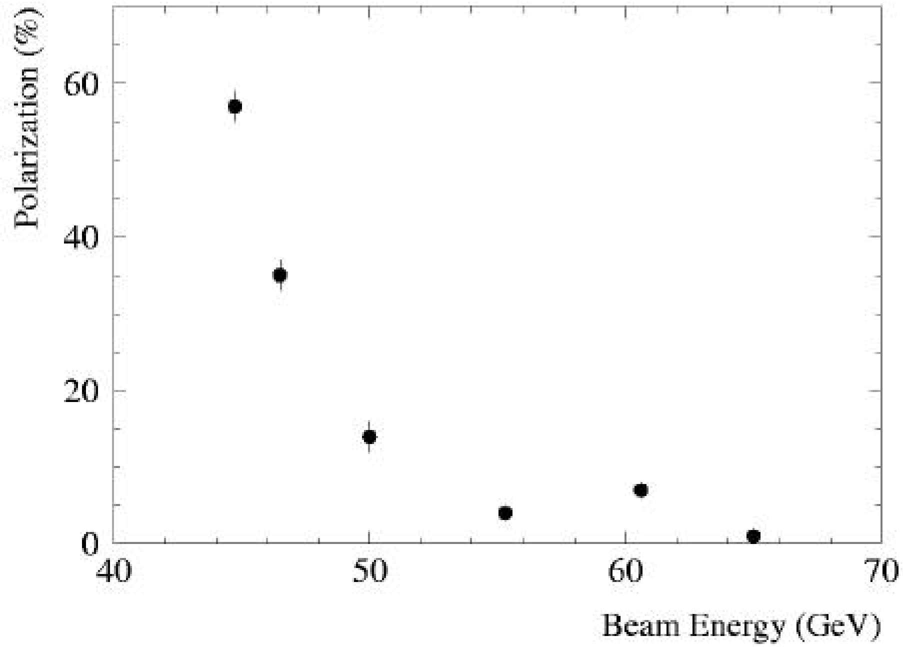
⇐ Large beam energy spread

Strong synchrotron spin resonance



LEP2

- NMR – Extrapolation from 41-60GeV
- Spectrometer – dipole magnet
- Synchrotron tune $Q_s \propto$ Acc. voltage



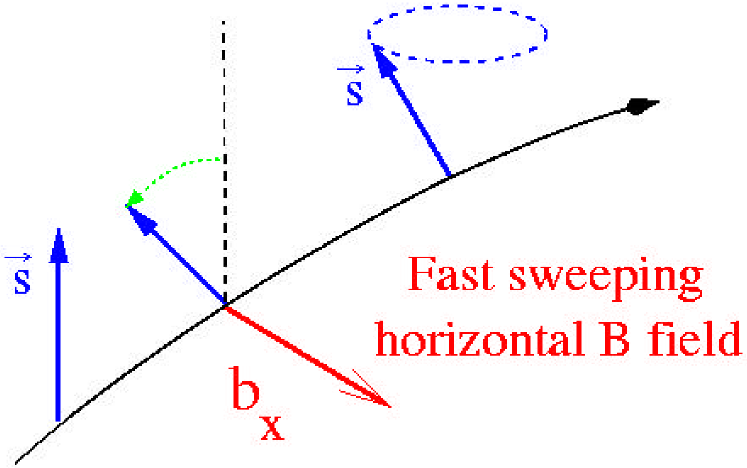
Resonant Depolarization

The interest of P_T: magnetic moments precess in B-fields.

The number of precessions/turn ν is proportional to the energy :

$$\nu = \frac{g_e - 2}{2}\frac{E}{mc^2} = \frac{E[\mathrm{MeV}]}{440.6486(1)[\mathrm{MeV}]}$$

To determine the energy → **Measure ν !**



Principle :

- Get a fast magnet ("kicker").
- Sweep the B-field and observe P_T.
- If kicker frequency and ν match, P_T is rotated away from the vertical axis.

Resonant depolarization

Earth Tides

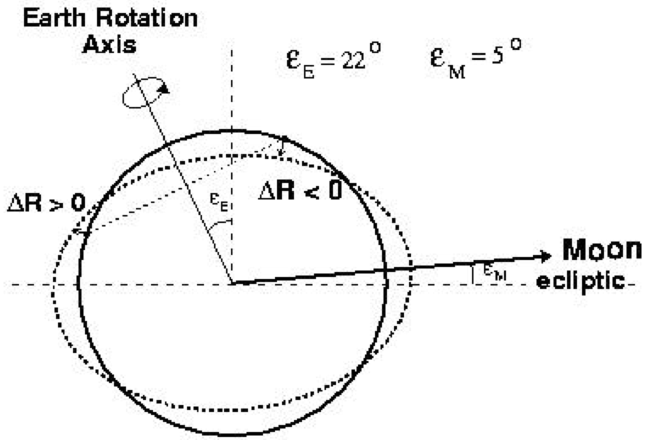
Tide bulge of a celestial body
of mass M at a distance d :

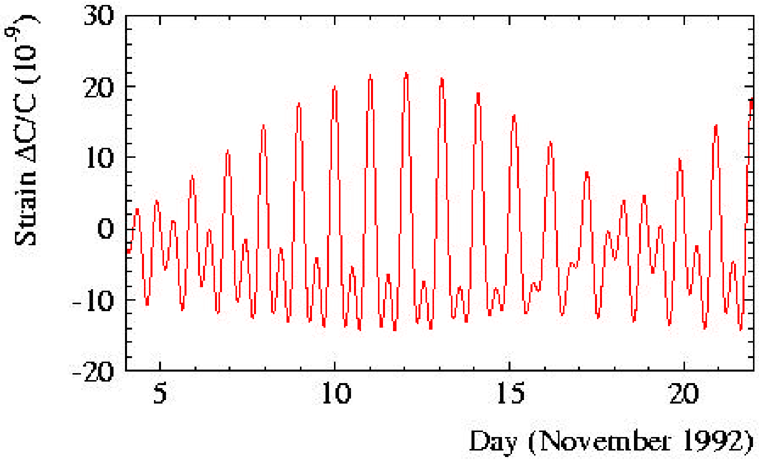
$$\Delta R \sim \frac{M}{2d^3}(3cos^2\theta - 1)$$

θ = angle(vertical,the celestial body)

Earth tides :

- The Moon contributes 2/3, the Sun 1/3.
- NO 12 hour symmetry (direction of Earth rotation axis).
- Not resonance-driven (unlike Sea tides !).
- Accurate predictions.





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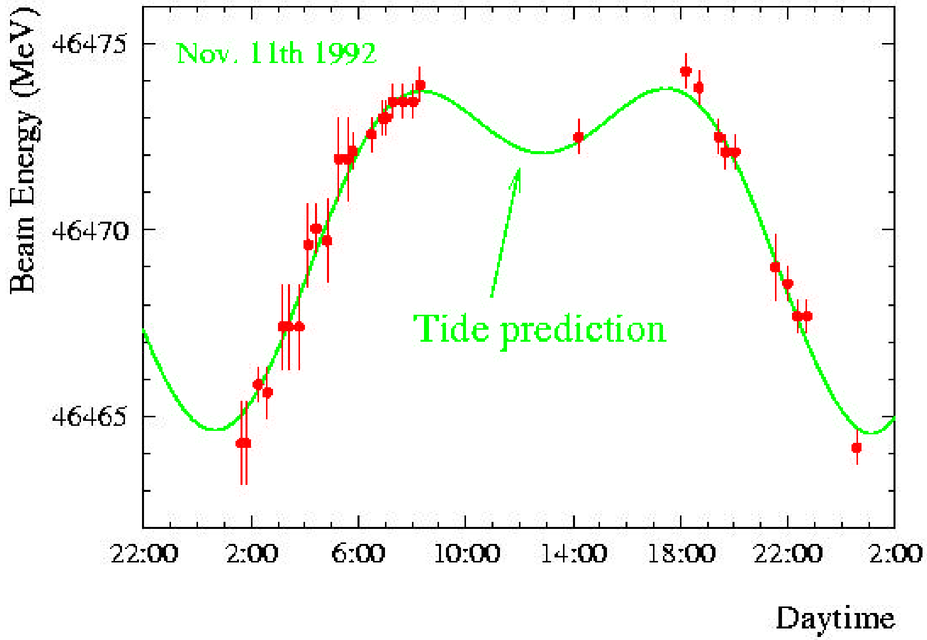
Moonrise over LEP

Fall of 1992 : The historic tide experiment !



The total strain is 4 x 10^{-8} (ΔC = 1 mm)

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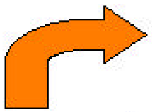
Underground Water

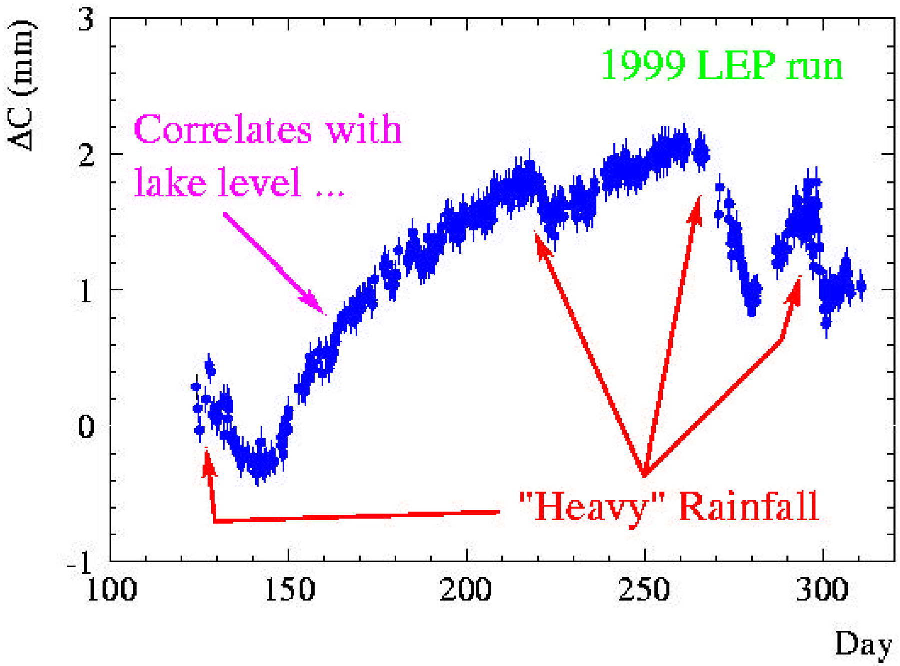
1993 : Unexpected energy "drifts" over a few weeks were traced to cyclic circumference changes of ~ 2 mm/year.

Driving "forces" :

- Underground water
  → Rainfall
- Lake levels
- Other ?



Circumference change measured with the radial beam position.



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The Field Ghost

Summer 1995 : the first field measurements inside ring dipoles.

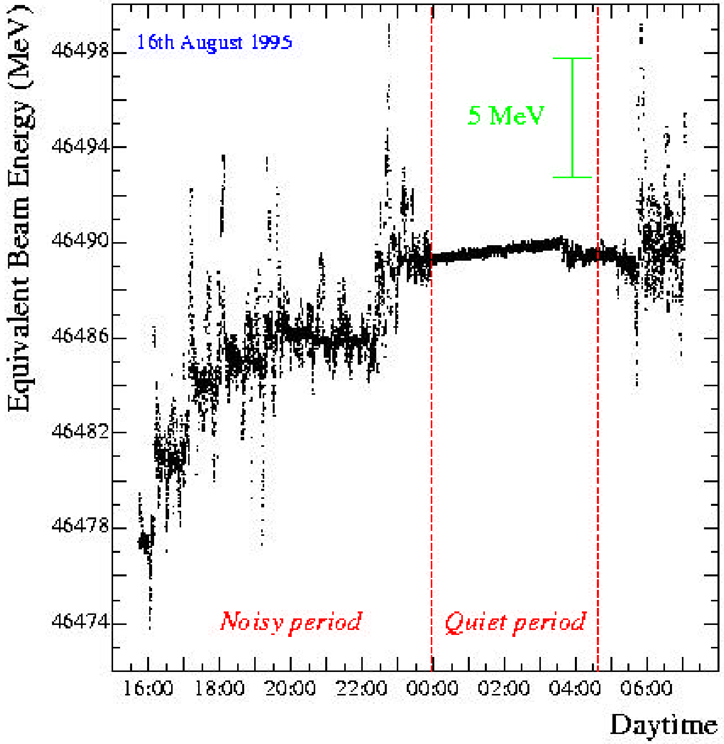
The data showed (unexpected) :

- Short term fluctuations
- Long term increase (hysteresis)
- ⇨ Energy increase of ~ 5 MeV over a LEP fill !
- Quiet periods in the night !

⇩

Human activity !

But which one ??



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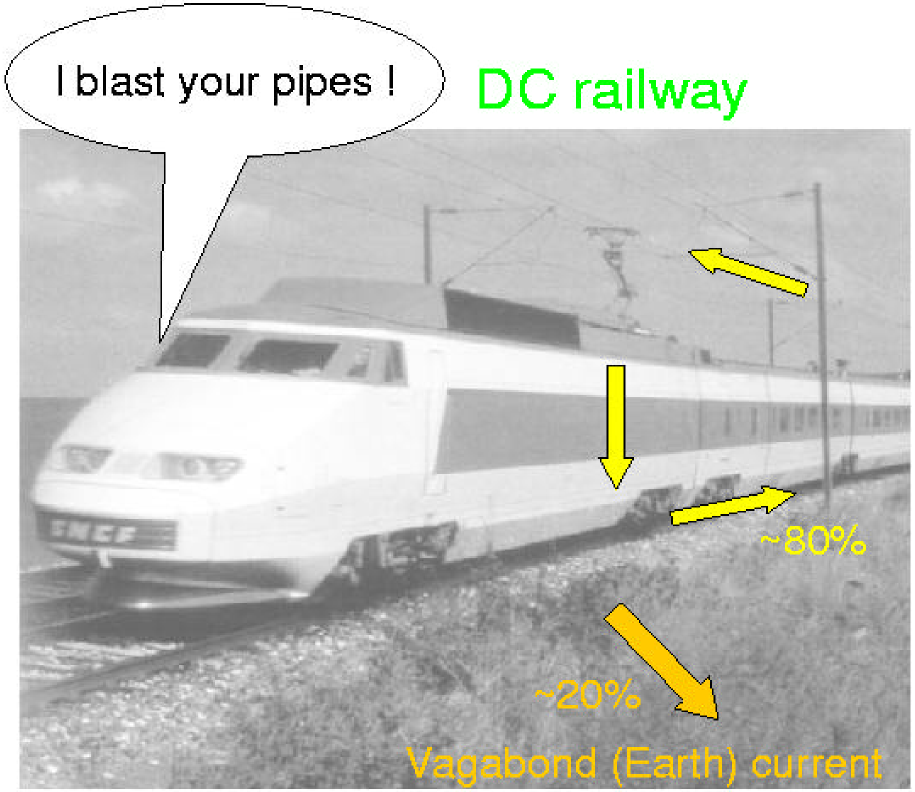
Pipebusters

The explanation was given by the Swiss electricity company EOS...

Vagabond currents from trains and subways

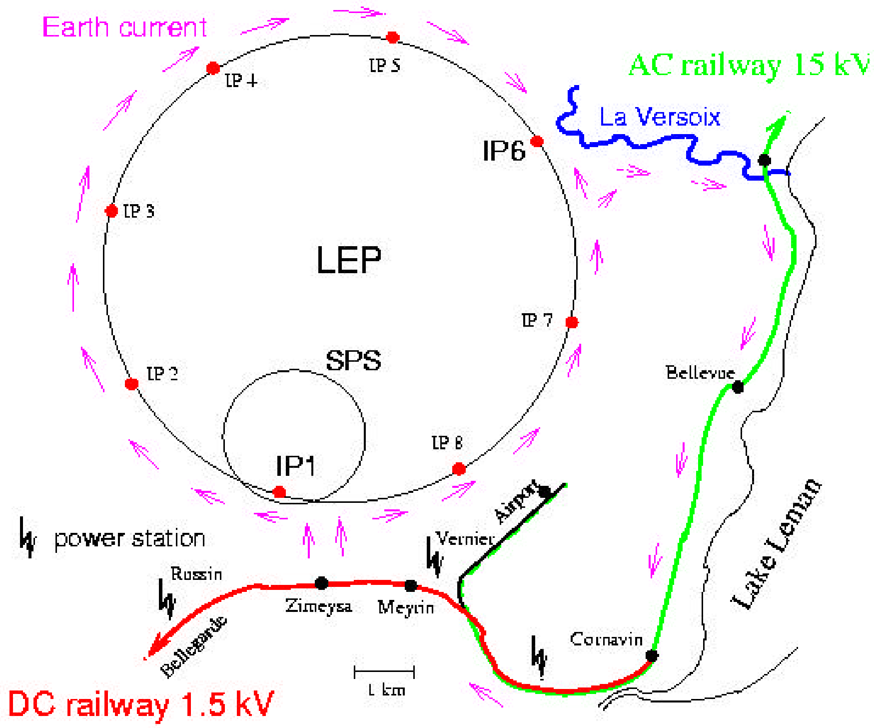
Source of electrical noise and corrosion (first discussed in ...1898 !)



Vagabonding Currents

LEP is affected by the French DC railway line Geneva-Bellegarde

➡ A DC current of 1 A is flowing on the LEP vacuum chamber.



Entrance/exit points :

- Injection lines (Point 1)
- Point 6 (Versoix river)

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TGV for Paris

November 1995 : Measurements of

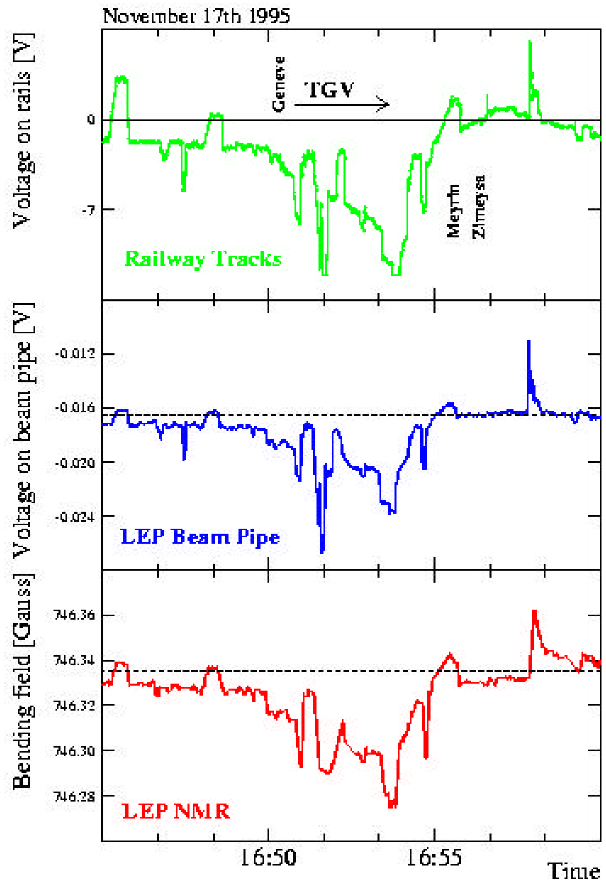
- The current on the railway tracks
- The current on the vacuum chamber
- The dipole field in a magnet

correlate perfectly !

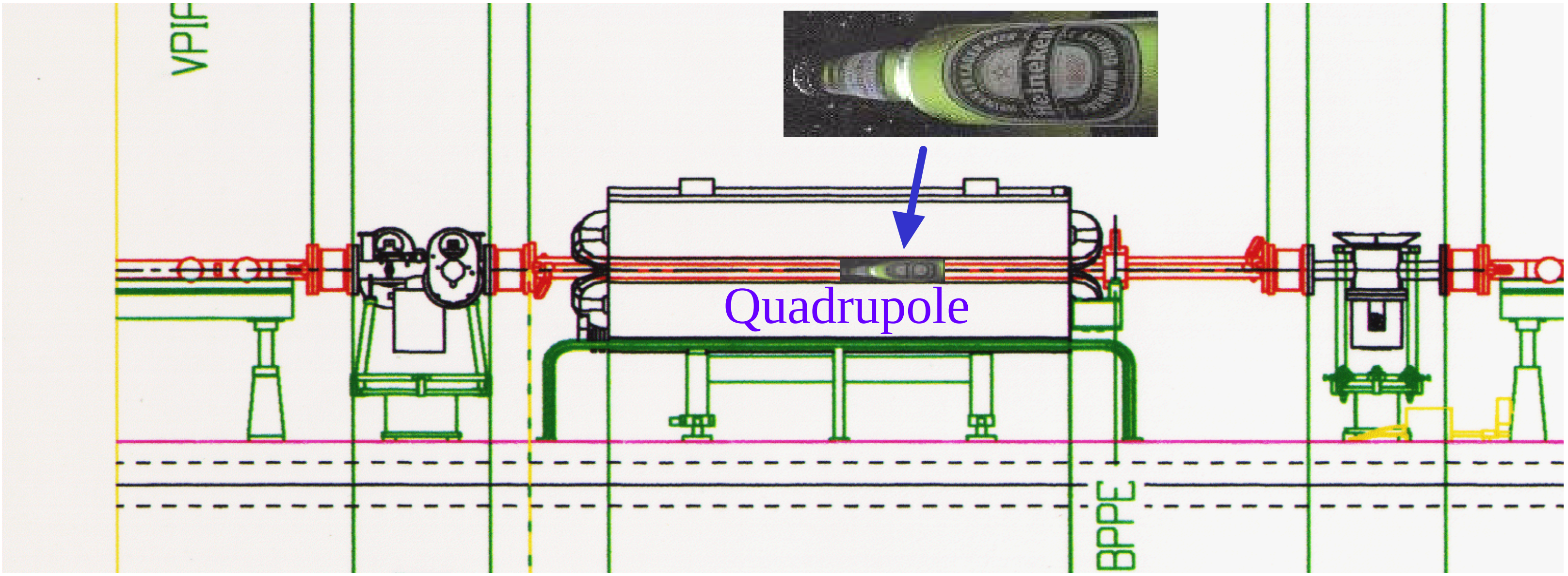
Because energy calibrations were usually performed :

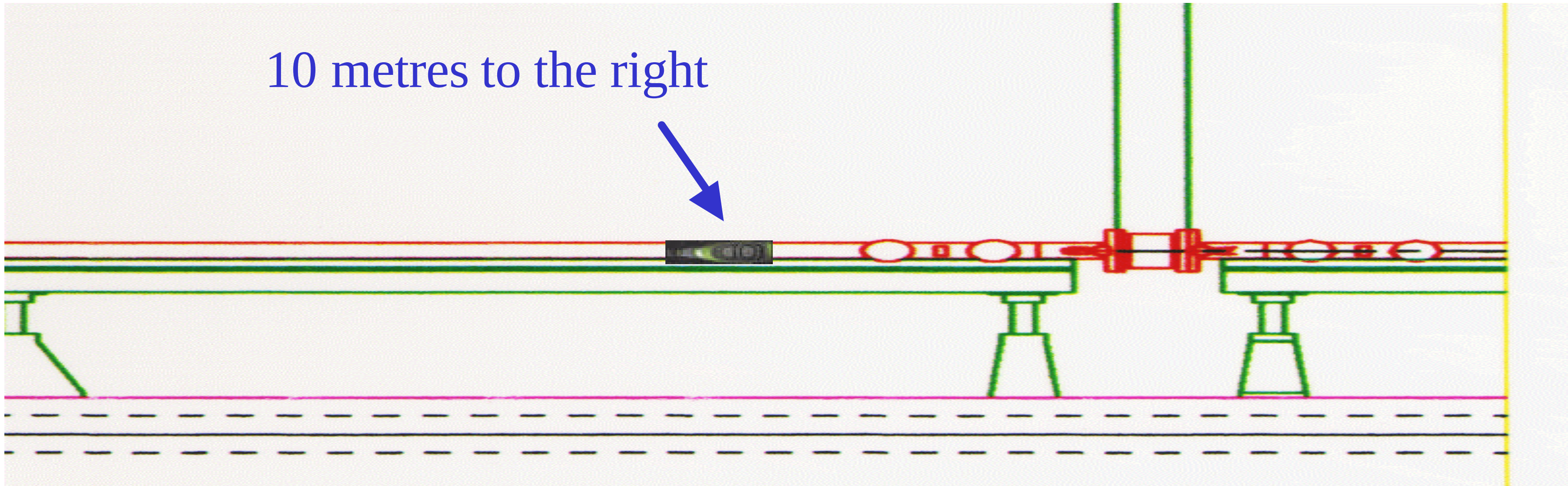
- At the end of fills (saturation)
- During nights (no trains !)

we "missed" the trains for many years !

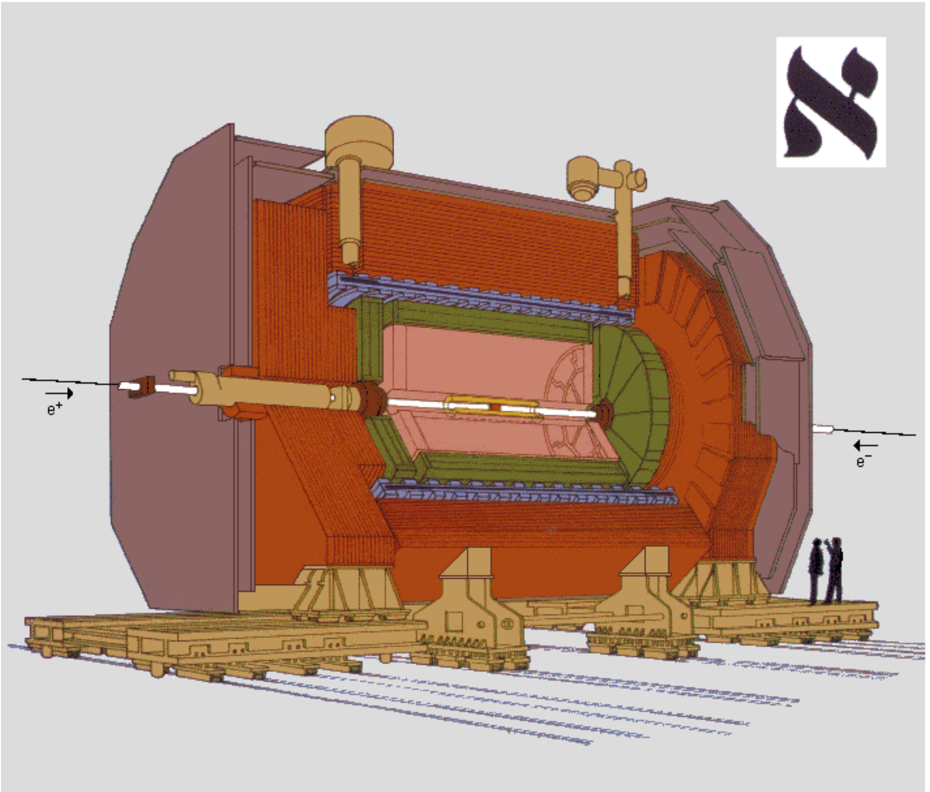


Heineken Beam Stopper June 20, 1996





3. LEP Detectors



Vertex Detector

Inner Tracking Chamber

Time Projection Chamber

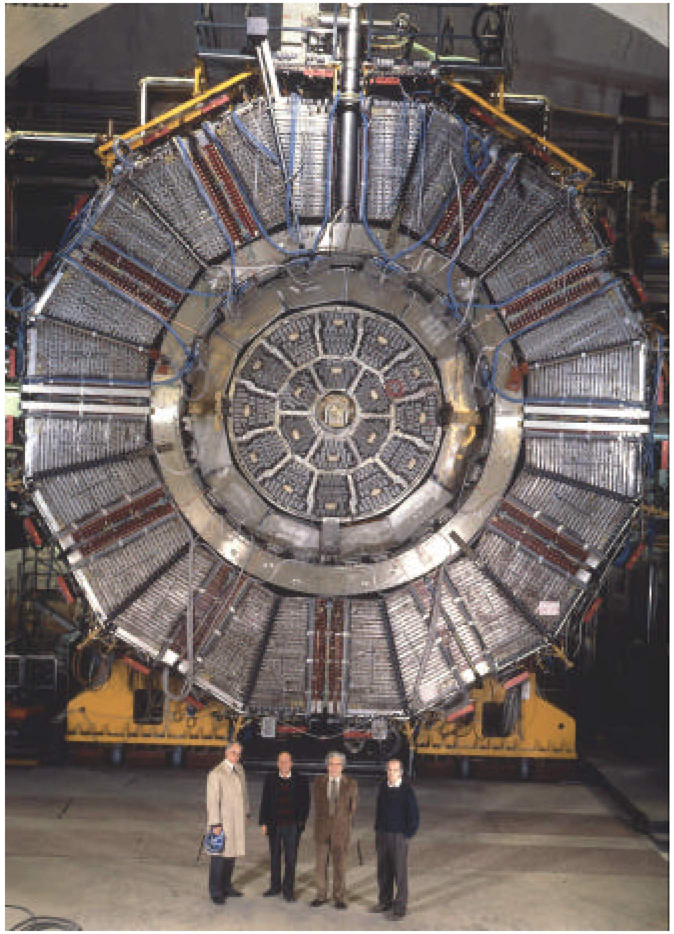
Electromagnetic Calorimeter

Superconducting Magnet Coil

Hadron Calorimeter

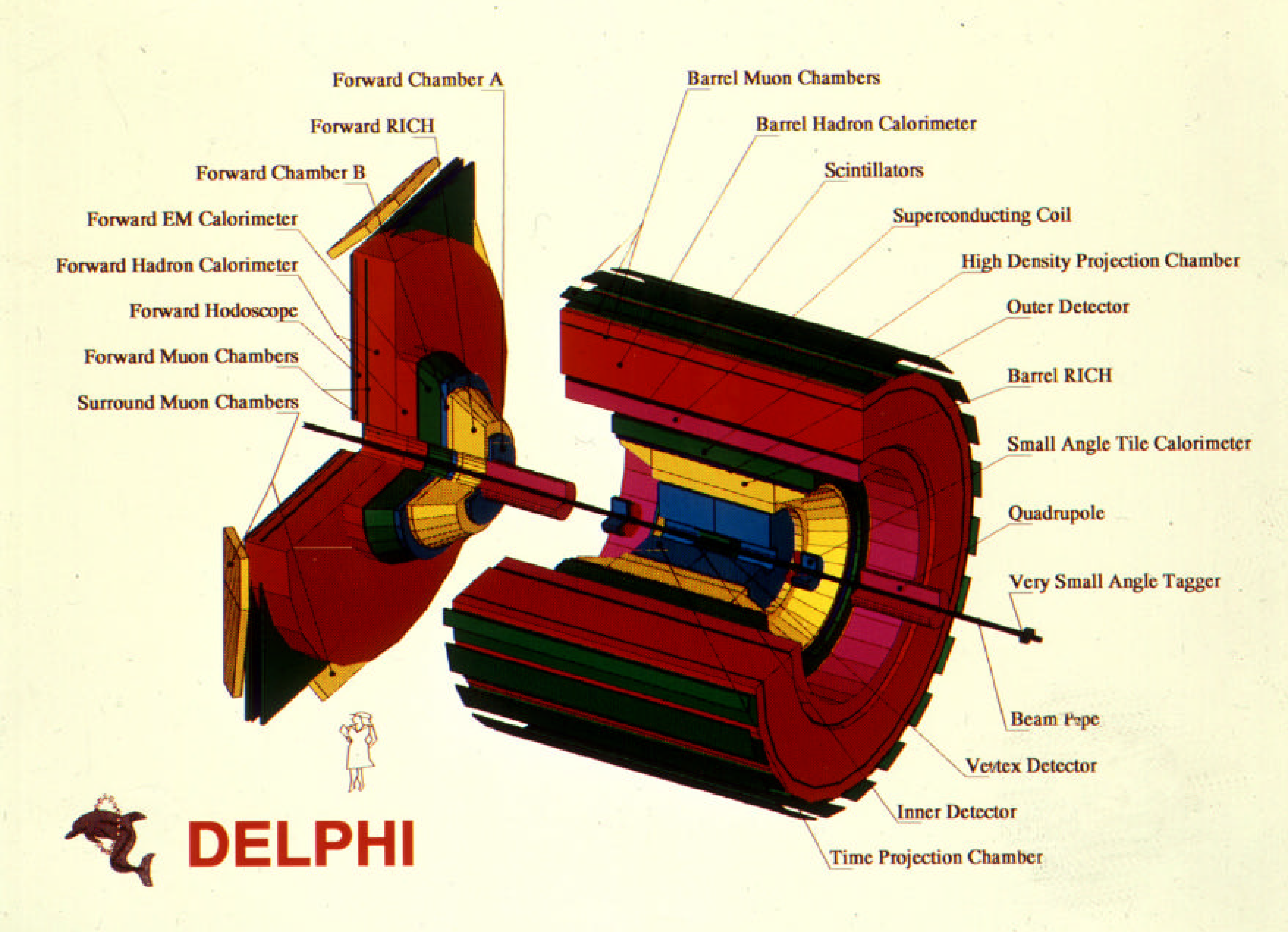
Muon Chambers

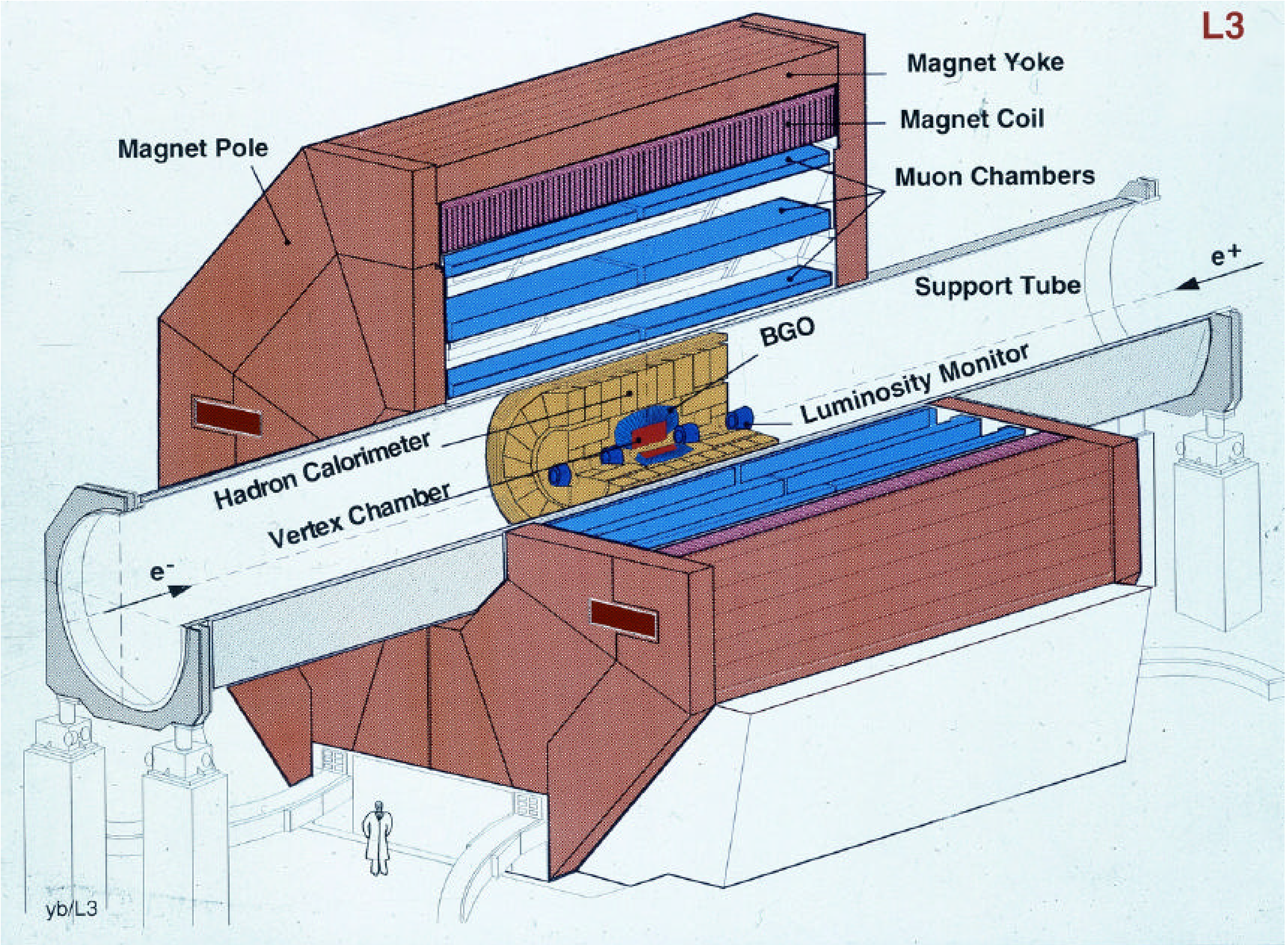
Luminosity Monitors



The ALEPH Detector


mühlebach

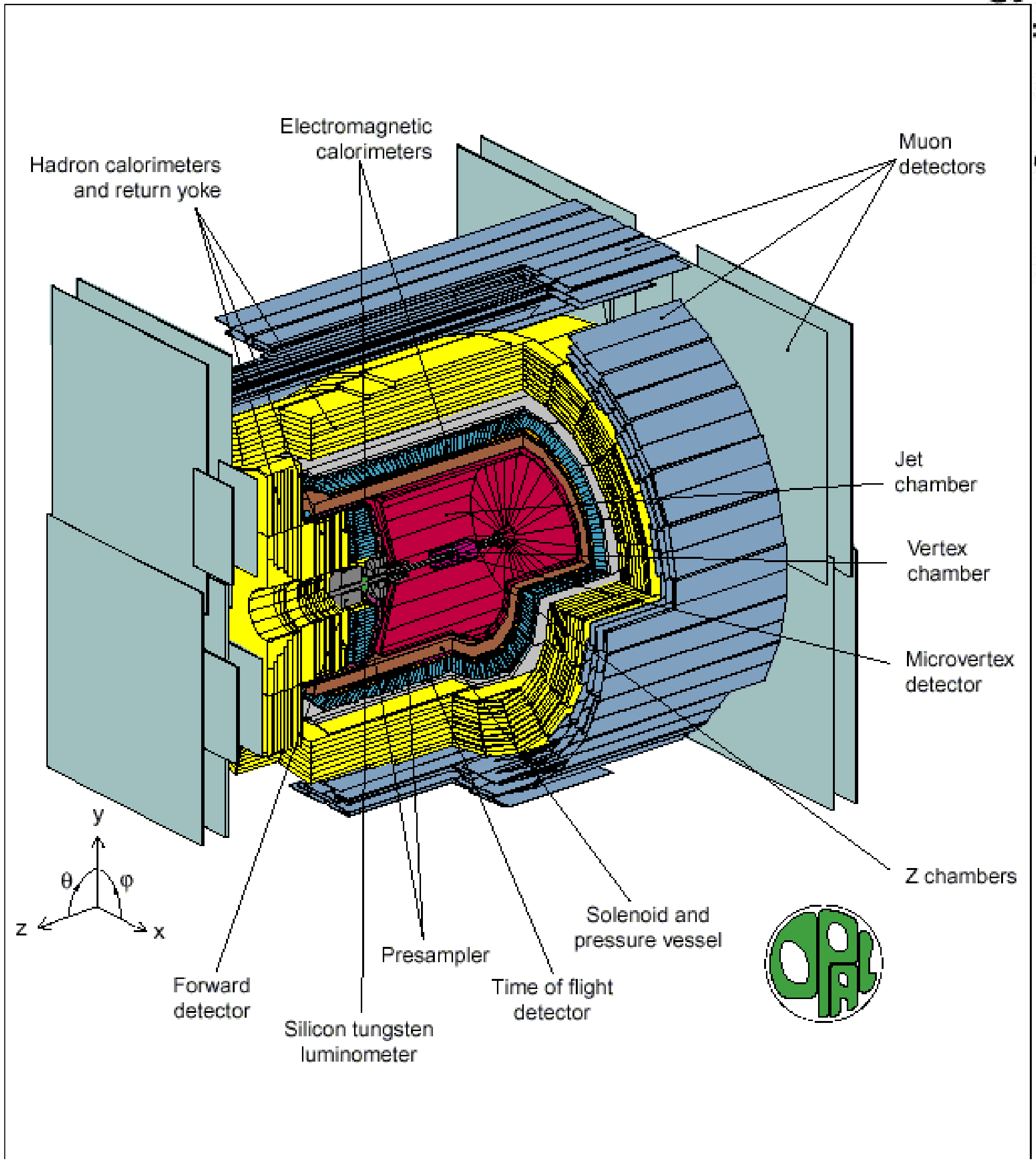

Forward Chamber A
Forward RICH
Forward Chamber B
Forward EM Calorimeter
Forward Hadron Calorimeter
Forward Hodoscope
Forward Muon Chambers
Surround Muon Chambers
Barrel Muon Chambers
Barrel Hadron Calorimeter
Scintillators
Superconducting Coil
High Density Projection Chamber
Outer Detector
Barrel RICH
Small Angle Tile Calorimeter
Quadrupole
Very Small Angle Tagger
Beam Pipe
Vertex Detector
Inner Detector
Time Projection Chamber
DELPHI


L3
Magnet Yoke
Magnet Coil
Magnet Pole
Muon Chambers
e+
Support Tube
BGO
Luminosity Monitor
Hadron Calorimeter
Vertex Chamber
e-
yb/L3

「New Detectors for High Energy Physics」KEK (1982)

OPAL DETECTOR AT LEP, S. Orito

Department of Physics, University of Tokyo, Japan

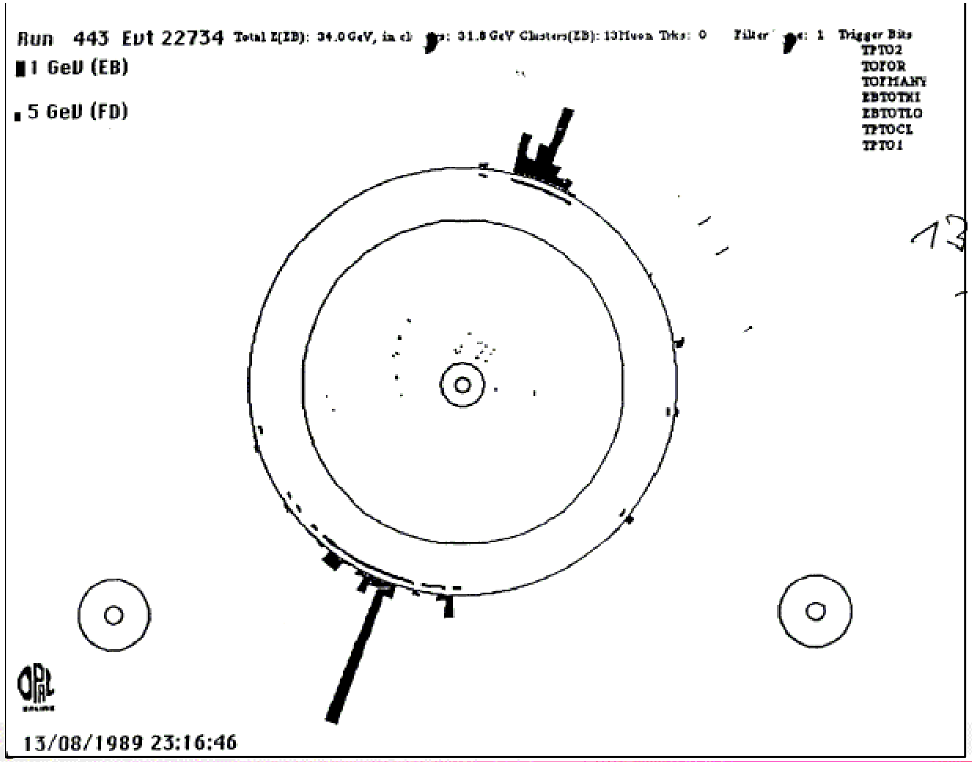


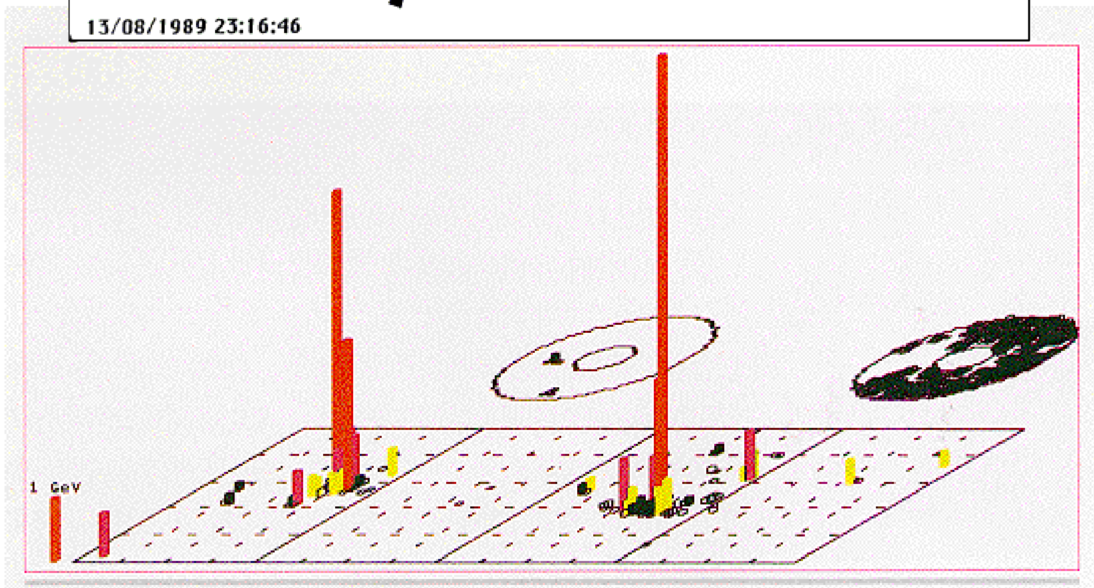
Concept :

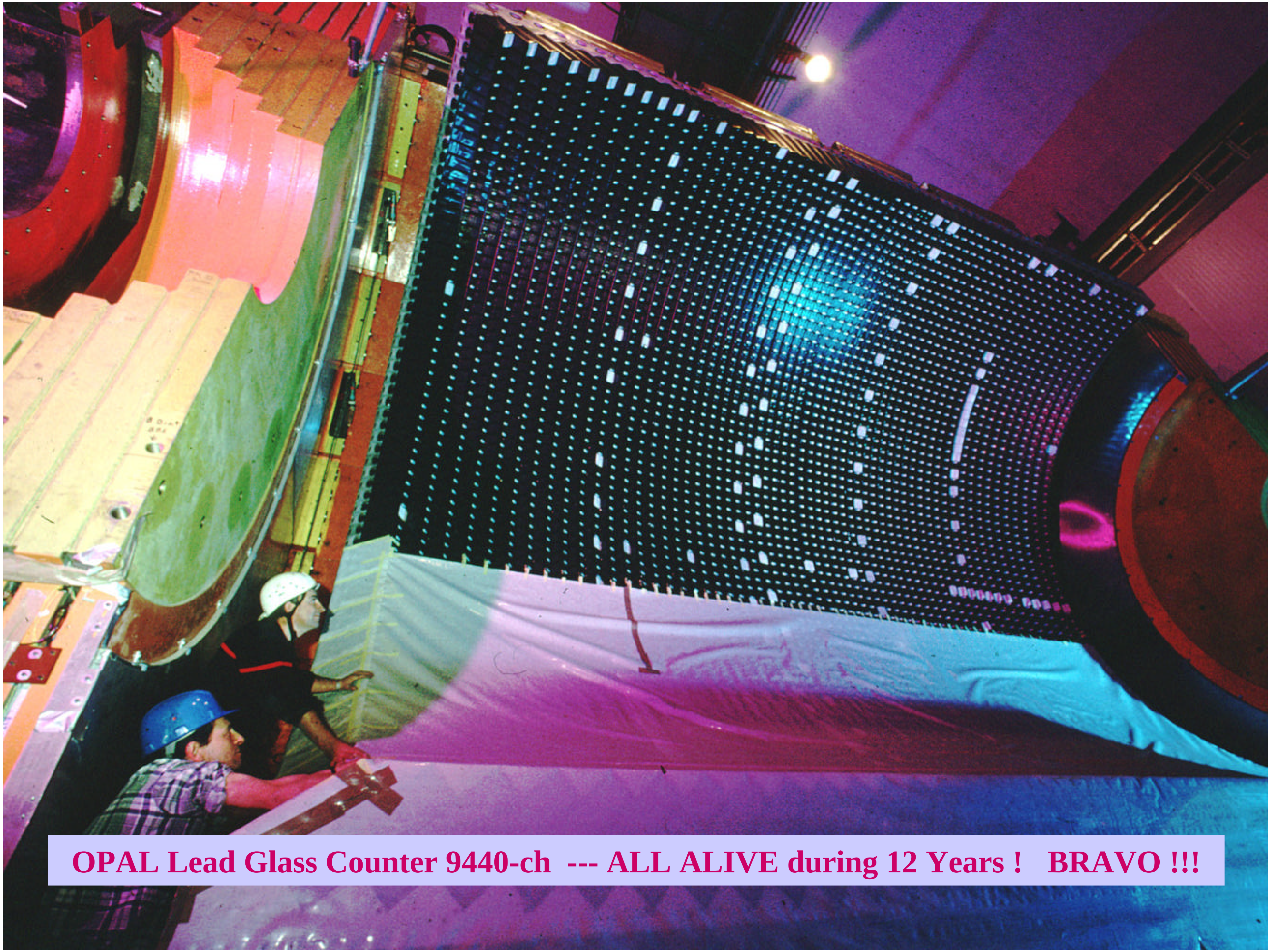
1. 4π, Uniform, Hole less
2. good e and μ ident.
3. Excellent shower energy resolution at High Energy
   $t\bar{t} \to \gamma H$
   ZH ↳ e^+e^-
4. good δp/p
   2×120GeV
   ZH ↳ $\mu^+\mu^-$, Asymmetry to 10^{-3}
5. Hadron Calorimeter
   K_L, n ↔ missing P_T, new particle
   $e^+e^- \to W^+W^- \to$ (had)(had)
   ZZ
   ZH
6. Quick start up, Reliable, stable
   JADE. June 29.1979 Start data taking
   Aug.23,1979 Full results at FNAL Lepton Sympo
7. Profit from JADE experiences

First Z event at LEP observed by OPAL

13 August 1989 at 23:17



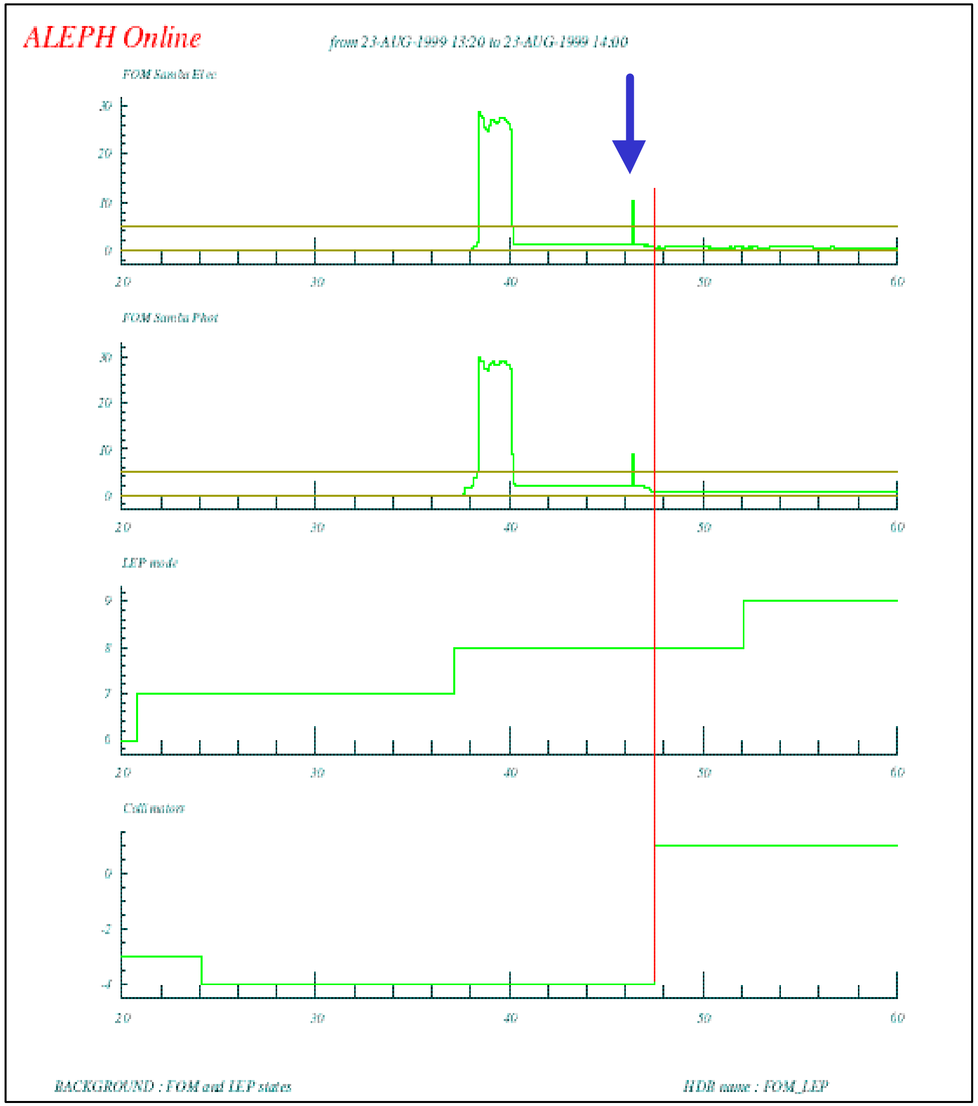




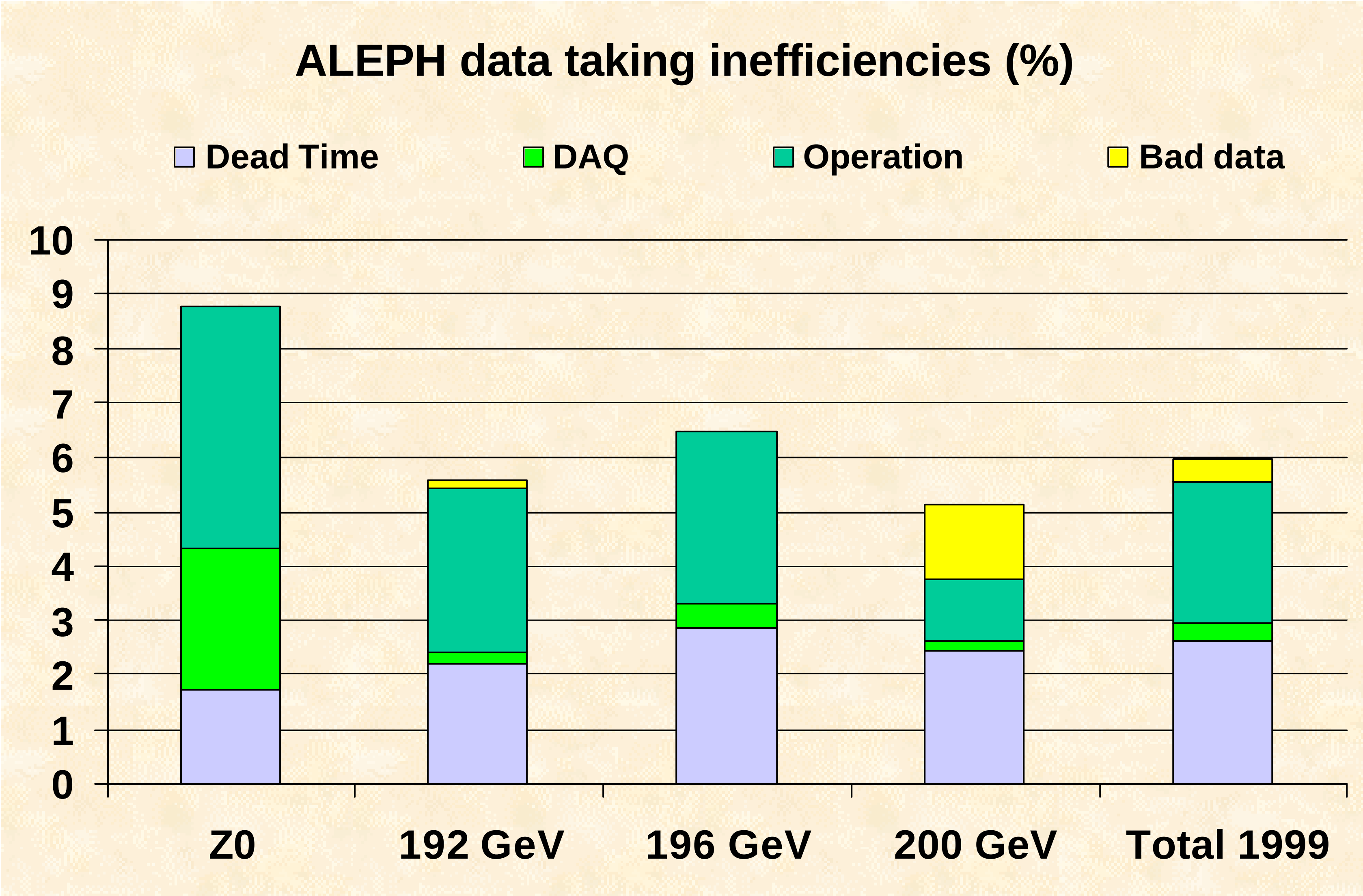
OPAL Lead Glass Counter 9440-ch --- ALL ALIVE during 12 Years ! BRAVO !!!

Data Acquisition in ALEPH   example in 1999

- Turn ON after the "Tune Jump", detected by a background spike.
- HV is ON when the collimators are moved IN, and start data taking BEFORE the Stable Beam indicator by LEP.
- About 1% extra luminosity on tape, very low Operation inefficiency !



ALEPH performance: excellent efficiency ~ 95% in 1999.



Central Tracker

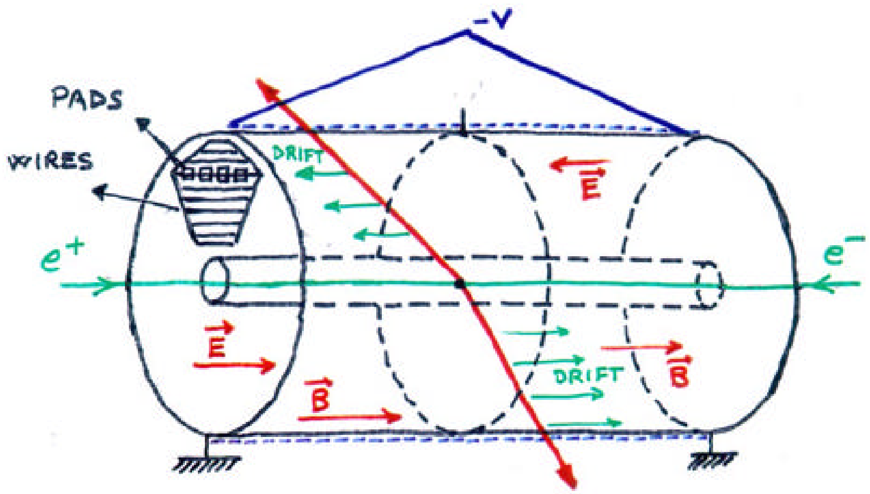
	Wire Chamber	TPC
Small or Medium Size	**L3 – TEC** B=0.5T 2 Atm.	**DELPHI - TPC** B=1.2T 1 Atm.
Large Size	**OPAL – JET** B=0.43T 4 Atm.	**ALEPH - TPC** B=1.5T 1 Atm.

TPC - Original idea by G.Charpak (1970)

Pioneering work by D.Nygren('70s)

ALEPH – TPC + ITC(trigger)

DELPHI – TPC + RICH(for π/K/p id.)



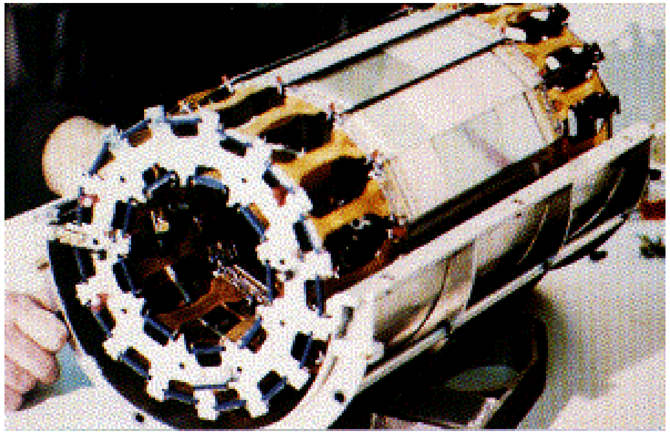
Vertex Detector

- 1960's – silicon detectors for Nuclear Physics
- Fixed target experiment for study on charm quark.
- First design for Collider Physics (ALEPH,CDF) in 1981.

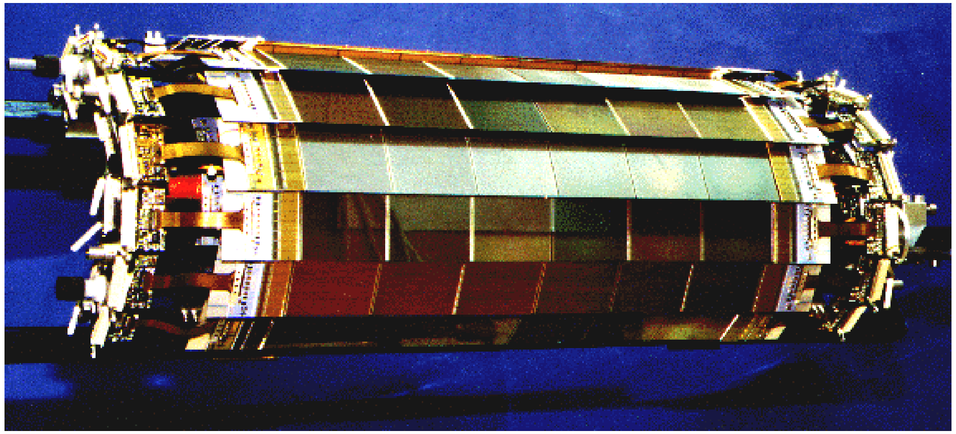
⇒ Opened the door to the heavy flavour ((t),b,c,τ) physics.

Upgraded at LEP2 for Search for Higgs via $e^+e^- \rightarrow ZH(H \rightarrow bb)$.

ALEPH@LEP1



ALEPH@LEP2



LEP2 Vertex Detectors

Experiment	ALEPH	DELPHI	L3	OPAL
Layers	2	3	2	2
Radii (cm)	6.3, 11.0	6.6, 9.2, 10.6	6.4, 7.9	6.1, 7.4
Modules/layer	9, 15	24, 20, 24	12	12, 15
Sensors/module	6	4, 8	4	5
Module length (cm)	40	28, 48	28	30
Max. $\lvert\cos\theta\rvert$	0.88, 0.95	0.91, 0.93	0.83, 0.93	0.89, 0.93
Overlaps (%)	5	12–15	0–12	0
Channels	95 000	150 000	73 000	65 000
Front-end chips	MX7-RH	MX6, TRIPLEX	SVX-H3	MX7, MX7-RH
AC coupling	Capacitor chip	Integrated	Capacitor chip	Integrated
Sensor type	Double-sided	Double + single	Double-sided	Single-sided
z coordinate readout	Polyimide fanout	Double-metal	Kapton rerouting	Glass print
Readout pitch (μm)	$\phi: 50,\ z: 100$	$\phi: 50,\ z: 44-176$	$\phi: 50,\ z: 150,200$	$\phi: 50,\ z: 100$
Material[a] (% of χ_0)	1.5	3.1	1.2	1.5
Support structure	Hollow carbon fibre	Carbon honeycomb	Carbon honeycomb	Beryllium
Cooling	Water + air	Water	Water	Water + nitrogen
Stability monitor	Laser spots + particles	Particles	Laser spots + particles	Particles
Sensitive area (m^2)	0.96	1.37 + 0.41(VFT)	0.52	0.53

[a] At normal incidence. To obtain the material seen by a particle coming from the interaction point, 0.4% of radiation lengths has to be added due to the beryllium beam pipe.

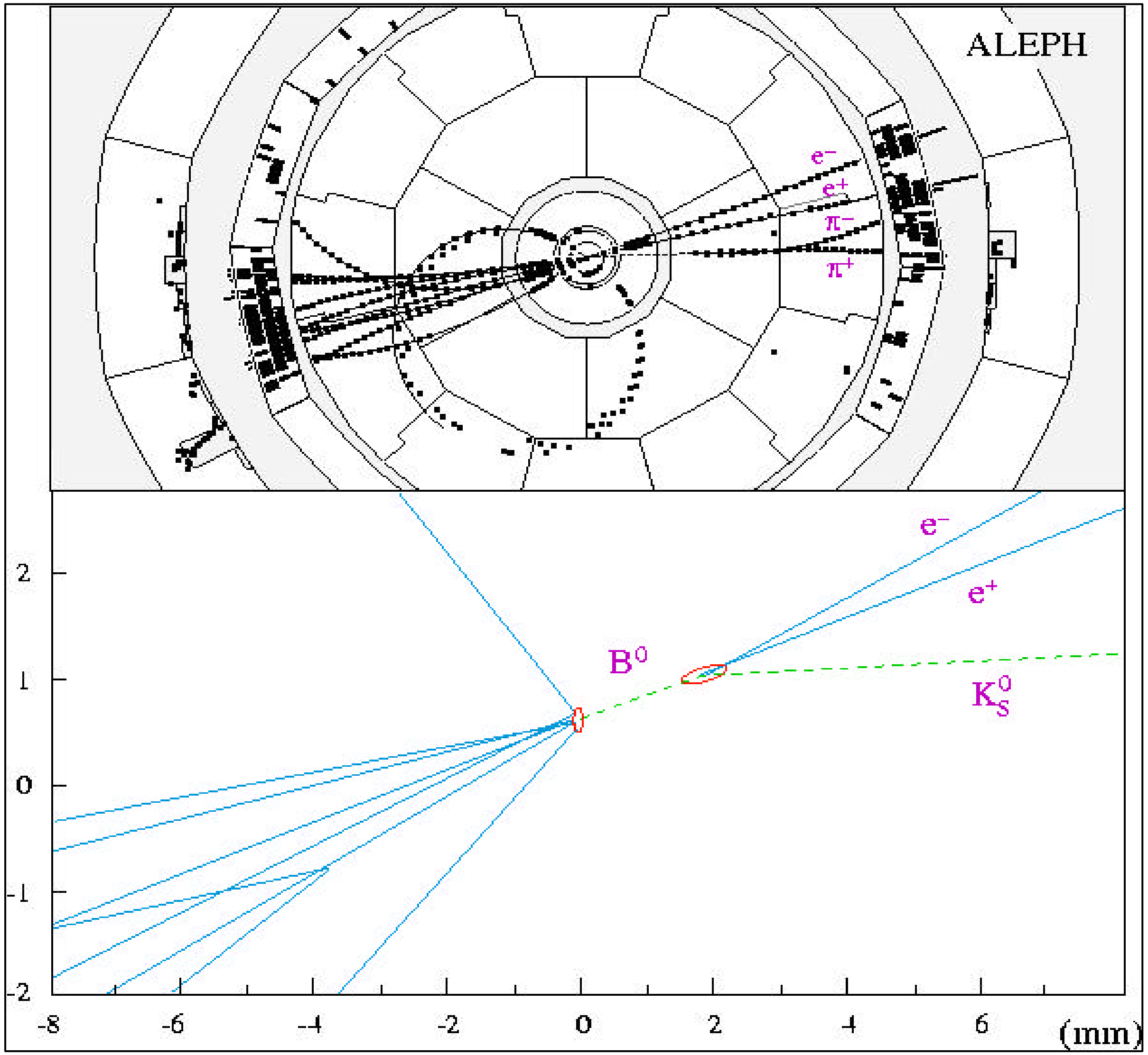
Vertex Detector Performance at LEP2

Experiment	ALEPH	DELPHI	L3	OPAL
Signal-to-noise ratio ($R\phi$)	31	10–28	18	24/29
Signal-to-noise ratio (z)	18	10–28	18	20/24
Impact param. resol. ($R\phi$) (μm)	34[b]	25	30	18
Impact param. resol. (z) (μm)	34[b]	34	130	24
Multiple scatt. term[a] (μm GeV/c)	70	70	80	100
Point resolution ($R\phi$) (μm)	10	8	8	8–10
Point resolution (z) (at 90°) (μm)	15	11	20	10–12

[a] Estimated from fits with one constant term and one proportional to $1/(P \sin^{3/2}\theta)$, where P is the momentum and θ the polar angle.

[b] ALEPH quotes the resolution for a three dimensional impact parameter.

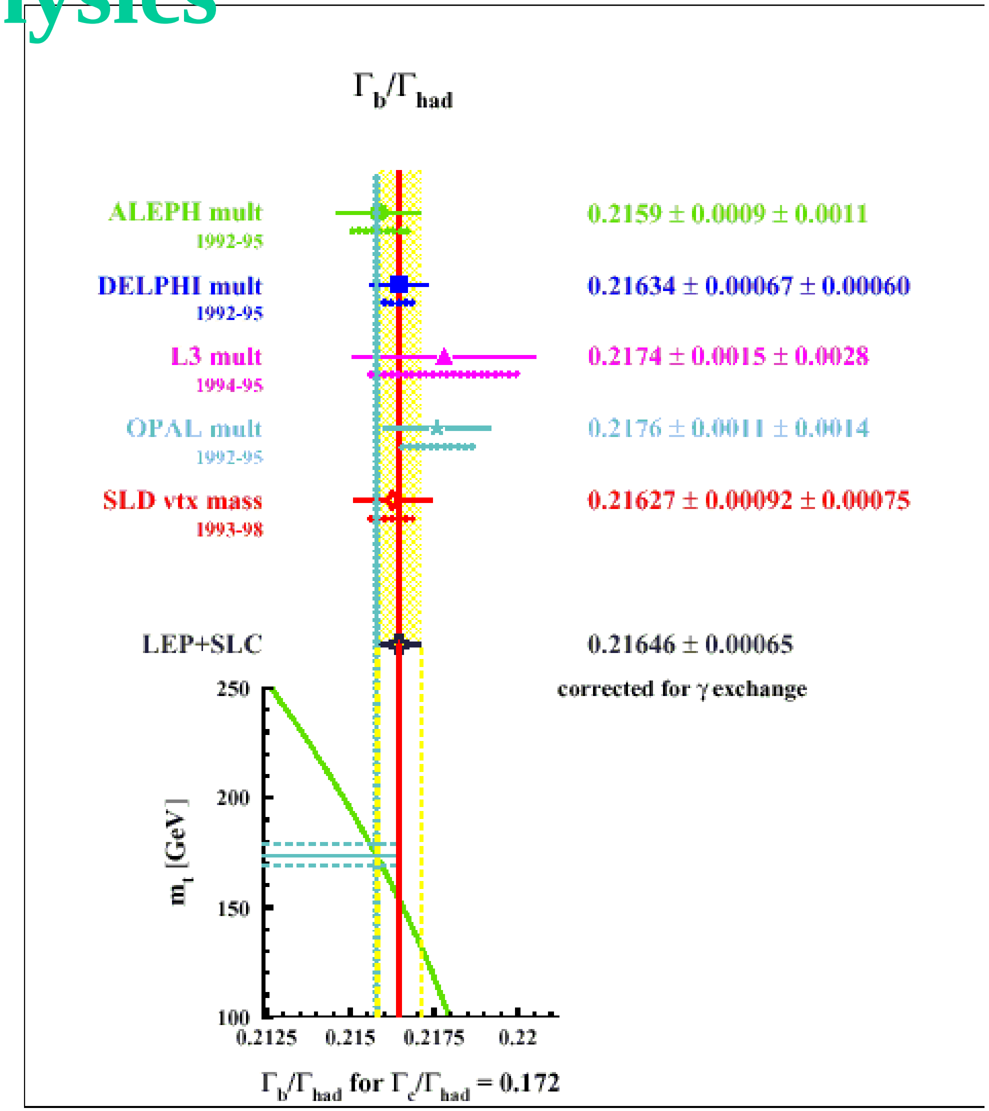
CP violation in $B^0 \rightarrow J/\Psi\ K^0_s$ event



B Physics

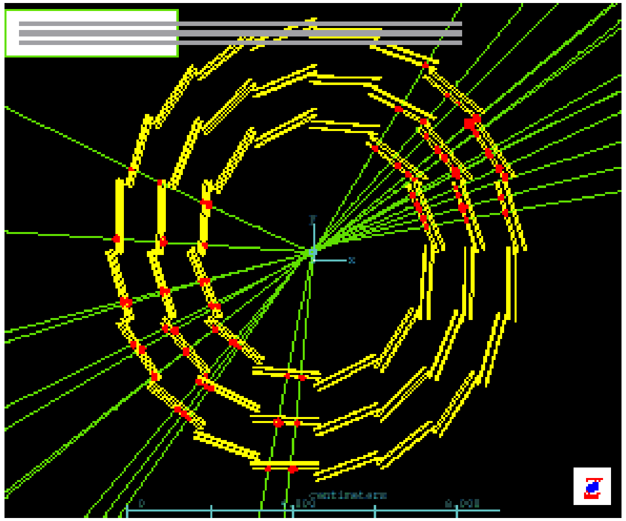
- DELPHI – 3 layers
- SLD – CCD at r=2.7cm

  beam spot size



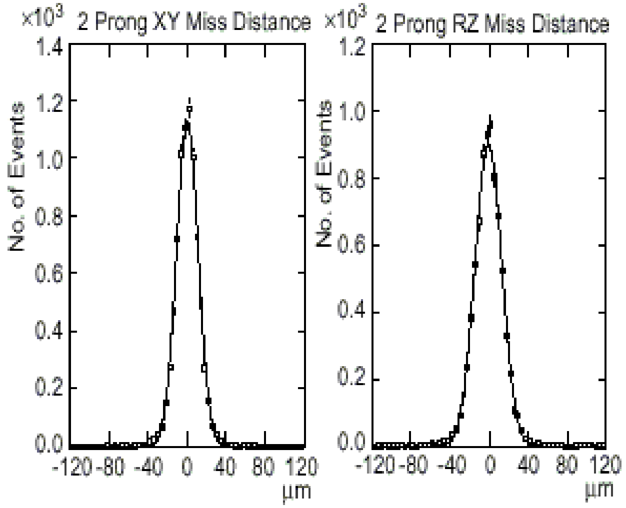
Heavy Flavour Tagging I

Vertex Detector



* inner radius = 2.7 cm
* max $\cos\theta = 0.90$
* SLC beam spot resolution :
$1.5 \times 0.8 \times 700\mu m$ (x, y, z)
* PV: $4 \times 4 \times 11\mu m$

* local hit resolution (triplets):
$3.6(r\phi) \times 3.9(z)\mu m$
* trk IP resolution: $7.7 \times 9.6\mu m(r\phi, z)$
* VXD3 stand-alone tracking ($\geq$3 hits)



Calorimeter (EM)

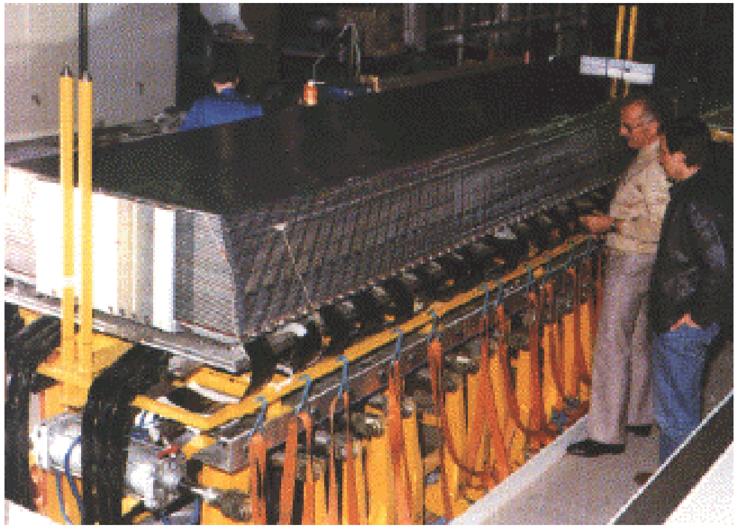
- Crystal: BGO(L3), Lead Glass(OPAL)
- Sampling: Pb-Gas Chamber(ALEPH), HPC(DELPHI)

ALEPH – fine granular EM calorimeter

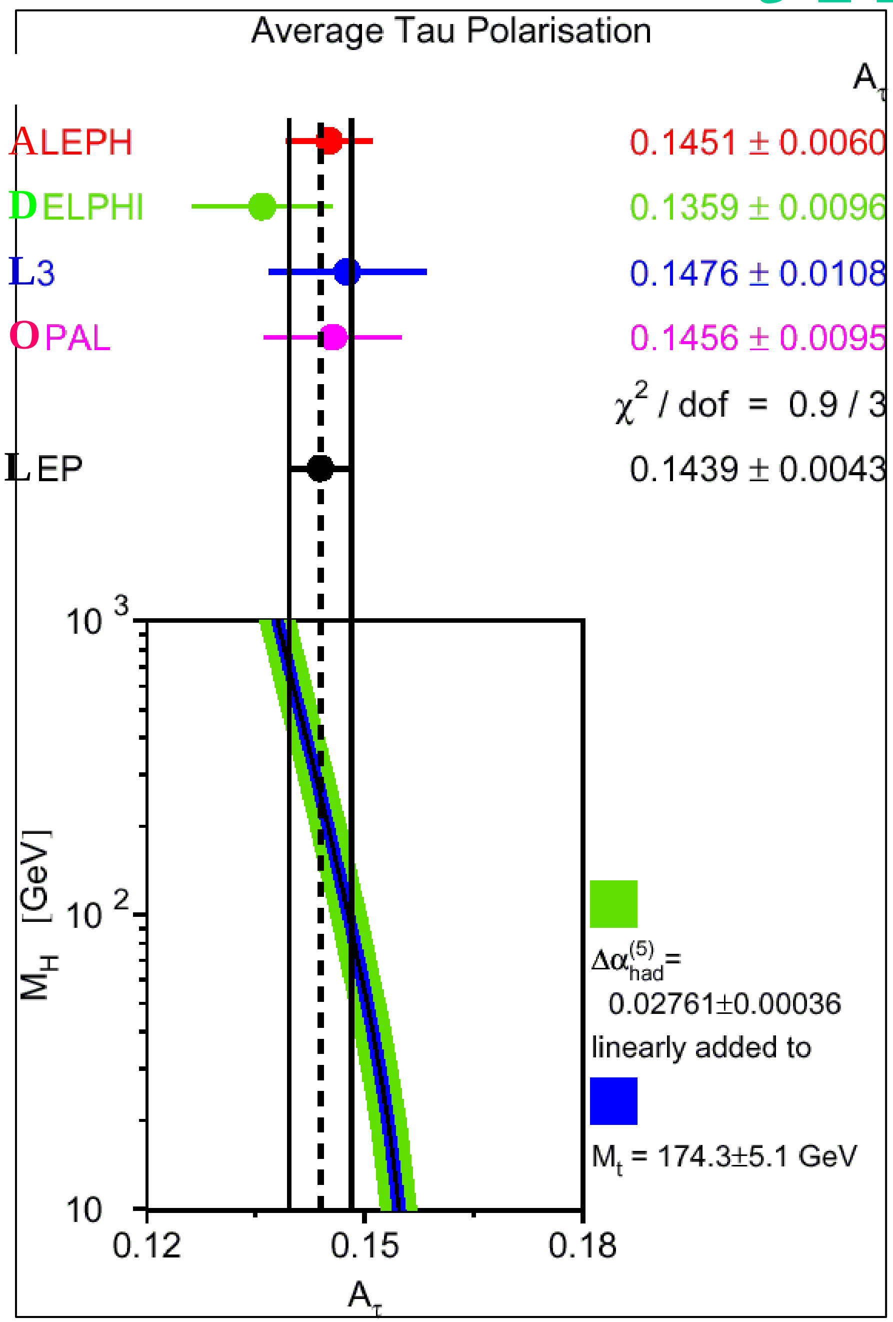
- 3D 3cm×3cm cathode pad (3×73,000 readout cells)
- 3 longitudinal segmentation

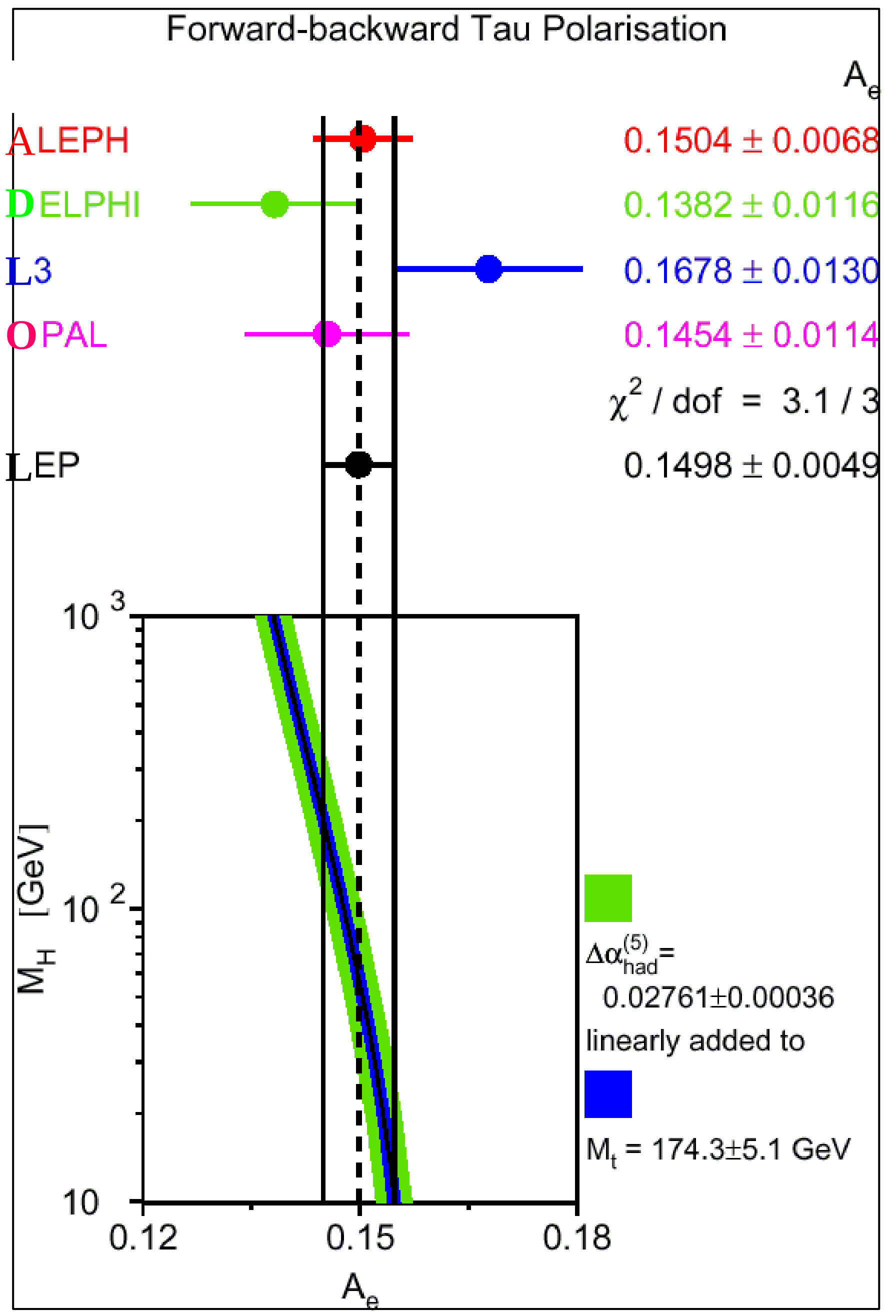
"Position resolution is more important than energy resolution"
(Jacques Lefrançois, Orsay)

⇒ Strong impact on physics,
ex. τ and B-physics



τ Physics


Average Tau Polarisation
A_τ
ALEPH 0.1451 ± 0.0060
DELPHI 0.1359 ± 0.0096
L3 0.1476 ± 0.0108
OPAL 0.1456 ± 0.0095
χ^2 / dof = 0.9 / 3
LEP 0.1439 ± 0.0043
10^3
10^2
10
M_H [GeV]
0.12
0.15
0.18
A_τ
$\Delta\alpha^{(5)}_{had}$=
0.02761±0.00036
linearly added to
M_t = 174.3±5.1 GeV


Forward-backward Tau Polarisation
A_e
ALEPH 0.1504 ± 0.0068
DELPHI 0.1382 ± 0.0116
L3 0.1678 ± 0.0130
OPAL 0.1454 ± 0.0114
χ^2 / dof = 3.1 / 3
LEP 0.1498 ± 0.0049
10^3
10^2
10
M_H [GeV]
0.12
0.15
0.18
A_e
$\Delta\alpha^{(5)}_{had}$=
0.02761±0.00036
linearly added to
M_t = 174.3±5.1 GeV

Energy Flow

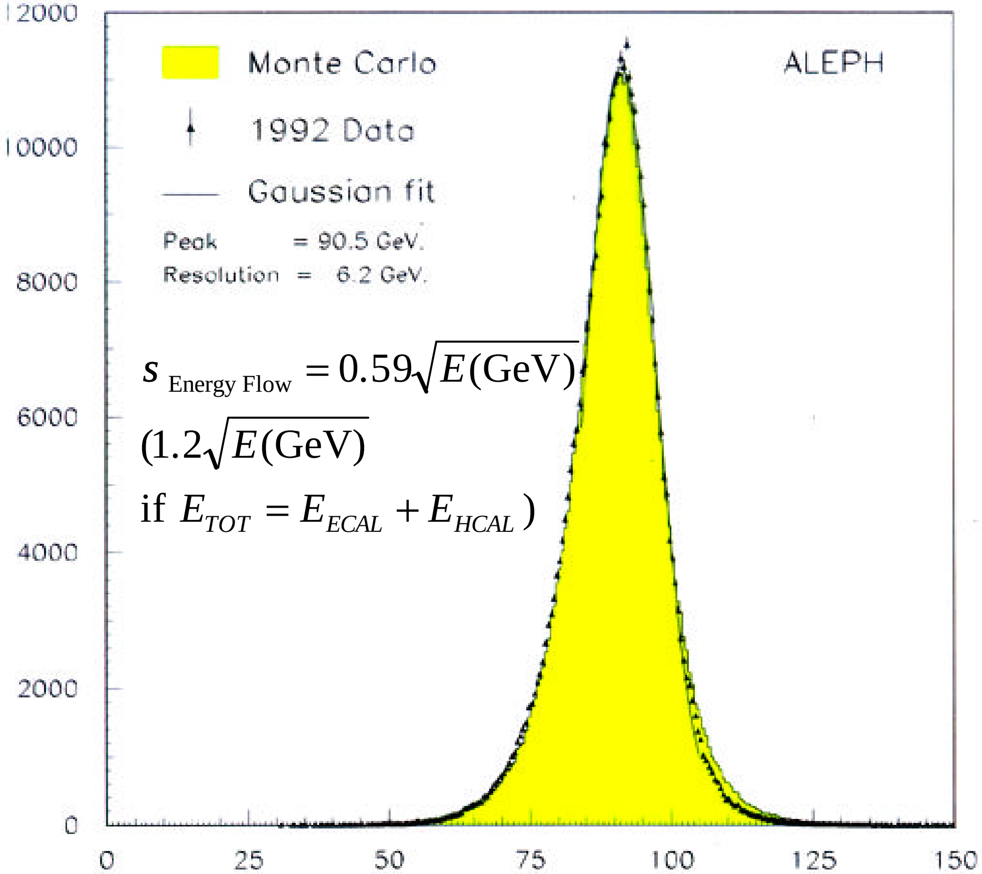
Total energy in the Jets

$E_{TOT} = p_e + p_m + p_{charged\ hadron} + E_g + E_{neutral\ hadron}$

[tracks only] [calorimeter only]

- to improve the energy flow resolution, the neutral particle id such as $\gamma(\pi^0)$, neutron, $K^0{}_L$ is most important,
- this is achieved with fine granular and hermetic calorimeter design.
- e/π ratio can be corrected to unity with software correction

(*i.e.* don't need to construct Scinti:Pb=1:4 calorimetre for hardware compensation).



4. Summary

- **Physics**
  - ✓ LEP experiment with 20 year-long physics vision.
- **Accelerator**
  - ✓ LEP had never been the same accelerator each year.
  - ✓ 6 optics in operation , 2 on 2 ~ 16 on 16 bunches, wide beam energy range of 45 ~ 104.5 GeV/beam.
  - ✓ About 4,000 physics fills $\Rightarrow \int L dt = 1\ fb^{-1}$/experiment.
- **Detector**
  - ✓ Tracking: Gas-chamber $\rightarrow$ Silicon, 3D-tracking(TPC).
  - ✓ Calorimetry: importance of fine granular calorimeter.
  - ✓ Energy-flow: jet physics, heavy flavour(b,τ) as tool.