ALEPH Plan

1. Early History -> Driving ideas on detector conception
2. Main detector parts description with more details on the ECAL (electromagnetic calorimeter)
3. The Physics at ALEPH at LEP I : some selected topics among the many subjects… About 300 papers were published by ALEPH!

Because of commitments on administrative duties or committees, my role in ALEPH decreased considerably after 1996 ☹ so I did not participate in LEPII physics and therefore signed LEPII papers…. However analysis of LEPI data continued for quite some time after

Early History (I)

ALEPH (Apparatus for LEP Physics) was one of the four large LEP experiments. Its started at a meeting organised in Jack Steinberger's office July 9th 1980 => 17 physicist representing 7 institutions (of these 17 only 11 would continue until the first collisions but of course all institutions continued until the end) I was there with Michel Davier as the 2 Physicists from LAL Orsay .

It was the start of the work to define what a LEP experiment we wanted to build.

We grew gradually to 19 institutions at the time of submission of the Letter of Intent in March 1982 (and 30 institutions in 1989).

Under the guidance of Jack, the discussions were very open, this was in my opinion extremely important , even if a physicist main work was in tracking, he could in many instances write a note on his opinion and arguments about calorimetry or the opposite.

Also the discussion were very free. I think, probably to push us to not censure very unusual ideas, Jack himself proposed and studied a magnet in form of a sphere (!!!)

Early History (II)

The brain storming on the best choice for detector elements continued for a sizeable time: Even at the time of letter of intent in March 1982 we had for most main elements of the detector a preferred choice and a back up solution, ex:

The main tracking was a TPC but there was a backup as a cylindrical drift chamber (axial wires)

The main ECAL solution was a MWPC-Lead sandwich with a liquid Argon-Lead backup

An extremely important driving idea of Jack was to limit as much as possible the number of different techniques: This was not easy since naturally a physics group prefers to implement an “independent and different concept” on each small element he builds! But, for example, Jack insisted that muon chambers could be like the layers inside HCAL; and the End Cap ECAL and Luminosity Calorimeter (LCAL) built with the same technique and electronics as the Barrel ECAL etc… Since Photomultipliers where not used for a major role then none should be used even as a trigger layer etc… I think globally we all agreed that his idea was the right one but it took Jack’s charisma and authority to have it implemented.

This 1.5 Year of brainstorming together, was also important to unite the collaboration, a common team spirit was built which turned out to be essential in future times of difficulty.

Early History: general concepts

We were aware that we were embarking in a task longer and more difficult than any of our previous apparatus construction (1980-1989) I remember Jack telling me: "clearly we will need a bigger collaboration than before, but we have to be careful, I cannot see how a collaboration bigger than 100 physicist can work(!!!)" well by sept-1989 for our first paper we were 374! with Jack spokesman.

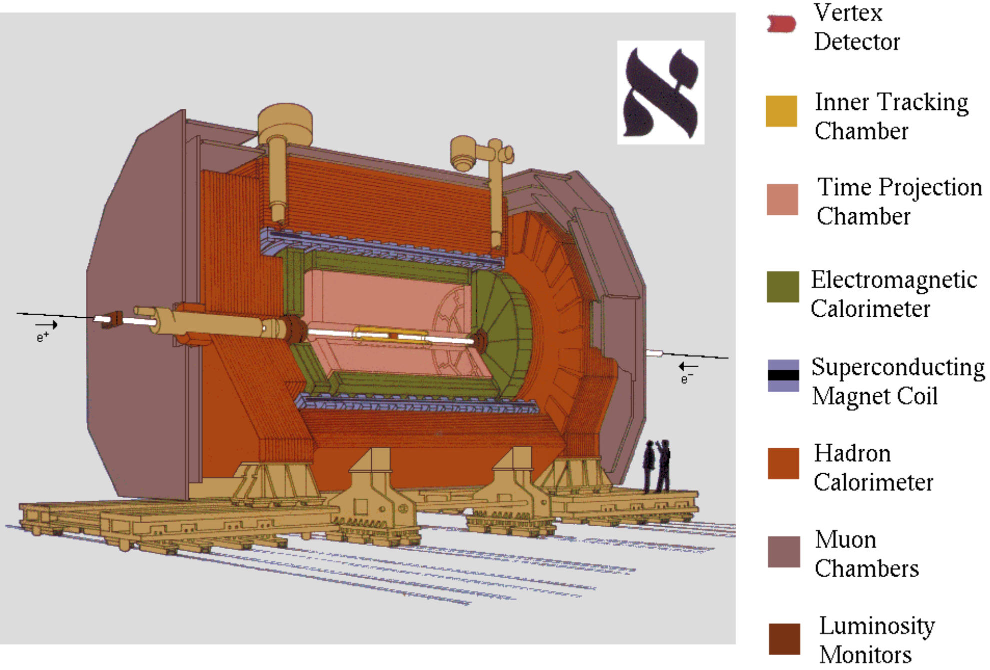
A key point was that most physics would be in the form of high energy jets and therefore a small granularity of the detector was essential. Because of the high density of particles we also emphasized that particle reconstruction would be very difficult with combination of 2D information. True 3D detectors were much better: this was the case for tracking with a TPC (Time Projection Chamber) and for ECAL with small cells.

Also we emphasized that there should be redundancy in the detector information: this would ease calibration and increase reliability for example the TPC had 2 modules of chambers with pad readout along a track trajectory (see next), and ECAL and HCAL had pad readout and wire readout.

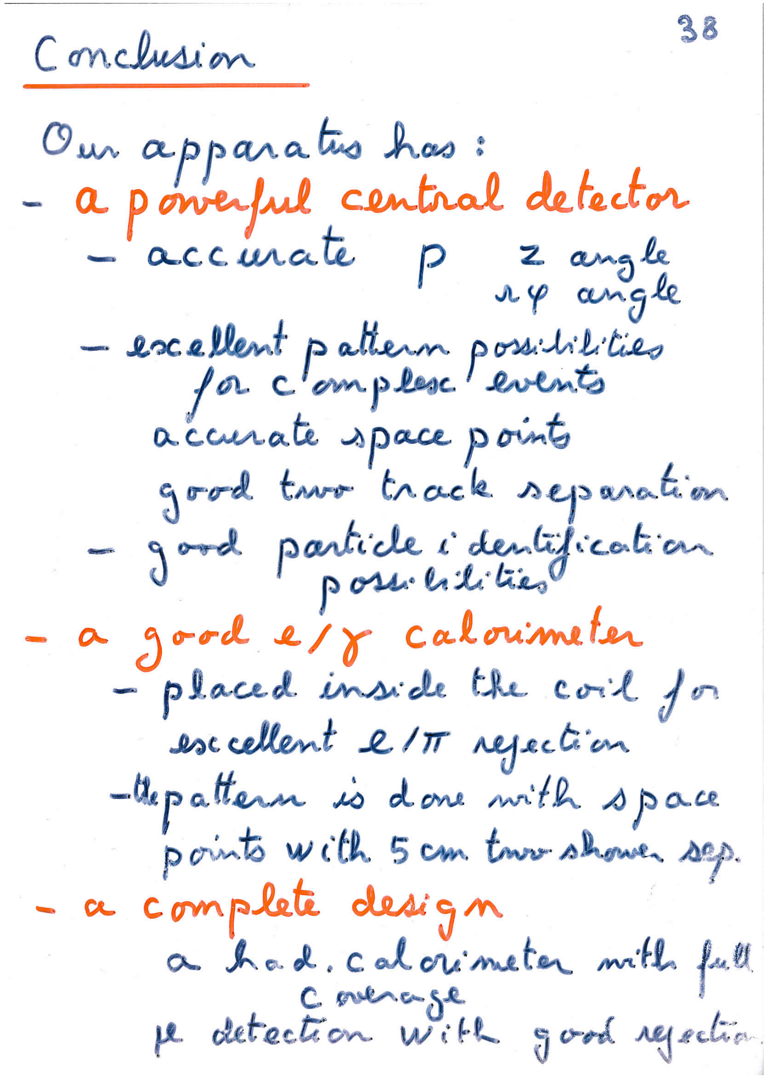
We handed in, our Letter of Intent March 82 and Jack asked me to present it at the LEP committee => one old style slide (out of 38!) is shown next. I will described then some of the detectors and their performance.

Approval

After discussions and questions, the LEPC recommended us for approval Nov 82 and final approval in June 83 after we produced a technical report. After Nov 82 we were joined by many institutes from ELECTRA which was not approved. We started a steering committee (collaboration board) I was asked by Jack to be chairman.



The ALEPH Detector



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Conclusion

Our apparatus has:
- a powerful central detector
  - accurate p   z angle
    $r\varphi$ angle
  - excellent pattern possibilities
    for complex events
    accurate space points
    good two track separation
  - good particle identification
    possibilities
- a good e/γ calorimeter
  - placed inside the coil for
    excellent e/π rejection
  - the pattern is done with space
    points with 5 cm two shower sep.
- a complete design
  a had. calorimeter with full
  coverage
  μ detection with good rejection

The TPC(I)

It was one of the key piece of the ALEPH apparatus. Our choice was to make it large 4.4m long and 3.6m outer diameter 0.6m inner.

It was our preferred choice in Oct 81 already, even if no good TPC existed at the time!!!

What is a TPC: Large volume of gas (Ar CH4), the track ionisation are drifted to the end plate by the electric field of 27KV/2.2m it takes 44 µs. Then the ionisation electrons are amplified by MWPC and the rφ position is read by the pulse-height on pads with 100MHz flash ADC. The time of arrival of the ionisation with respect to the particle time gives the drift time => Z coordinate

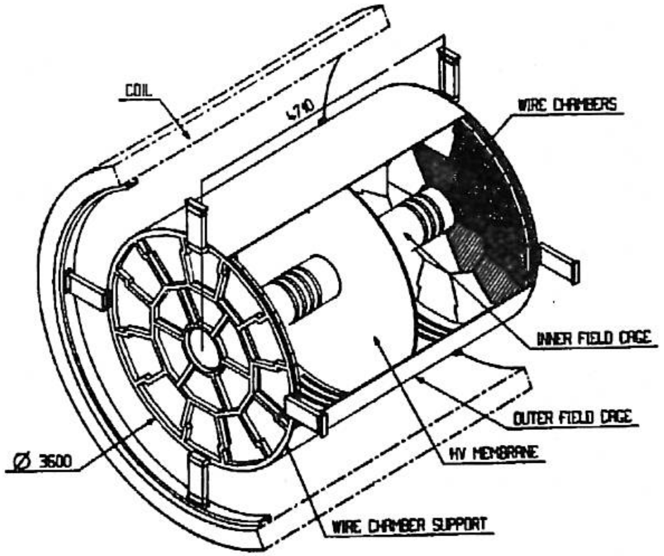
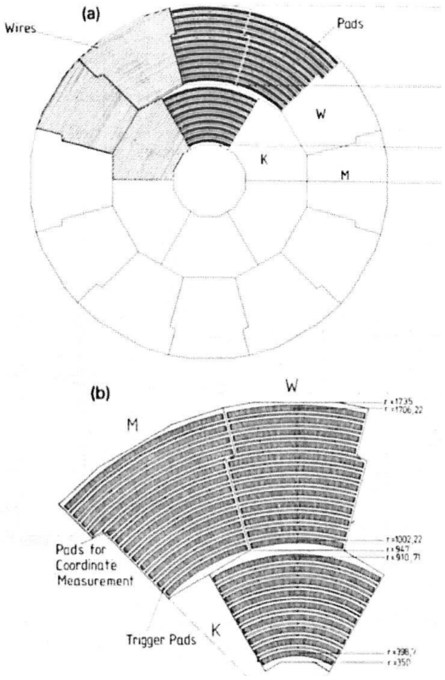


Fig. 10. TPC overall view.



Pads:6.2X30 mm

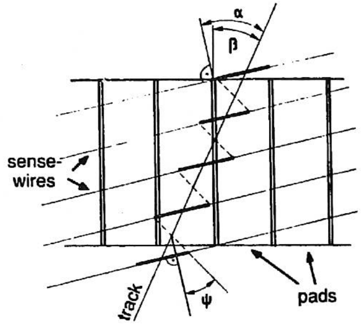


Fig. 22. Definition of angles between track, wire and pad.

The device is accurate because the strong B field 1.5T // to the electric field, prevents the ionisation electrons to spread, they stay grouped. There are 21 pad rows along the trajectory and therefore 21 space points measured… close to a visual device!

Tracking and the TPC (II)

Another advantage of a TPC is that, once inside, it has very little material along the tracks (1.5 m of Argon CH4 gas) Δp/p OK for low momentum

The 21 space points on tracks were measured with a precision of 173µm in rφ and 740µm in Z. There were 41000pads to be read by Flash 100 MHz 8-bits ADC: this was a very daring program at the time!

The tracking was completed by a drift chamber (the ITC) between r= 12cm and 28cm which was also used in the trigger since the information is present rapidly while the only drawback of the TPC is that it is slow (up to 44µs drift). This was not very important at LEP where (at least initially) the beam crossing were every 25µs. However at LHC it would have been a big problem (except for ALICE)

There was (after a lot of difficulties) a silicon vertex detector installed with r between 6.5cm and 11.3cm measuring accurately r and φ

With the TPC alone the ΔP/P accuracy for high momentum track was $1.2*10^{-3}$ and $0.6*10^{-3}$ using all 3 position detectors. This was I think the most accurate of all 4 LEP detectors and was due to the large diameter and the strong solenoid field of 1.5T

Particle Identification with the TPC

The other big advantage of the TPC is that, in the end cap, where the ionisation is collected one can also read the ionisation of a track on the 340 wires of the MWPC. If you look at the PDG pages on ionisation you will see that at high ß the DE/DX increases (it also increases at low ß as $1/ß^2$) as shown below left. The DE/DX is measured by doing a truncated mean (removing 40% highest and 10% lowest) of the ≈ 340 wire measurements: e/π are well separated but also π/K which played a big role in the physics program.

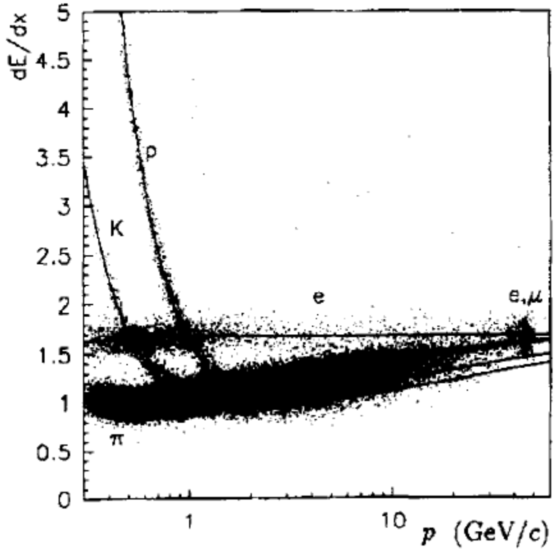


Fig. 8. The measured dE/dx versus particle momentum for a sample of about 40000 tracks. Each track was required to have at least 150 dE/dx measurements. The fitted parametrization is superimposed for electrons, muons, pions, kaons, and protons.

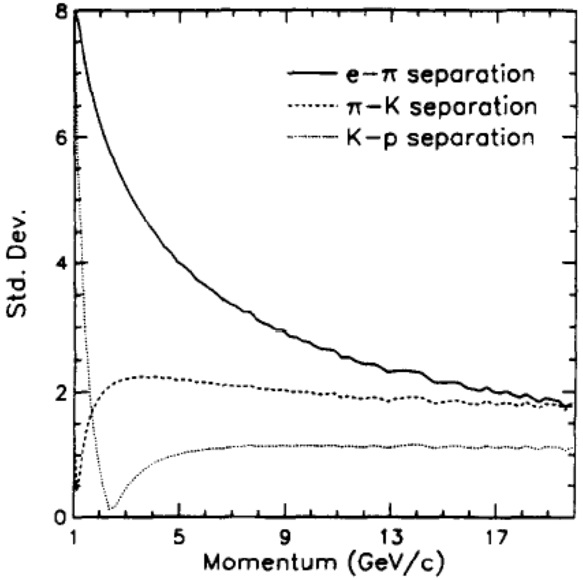


Fig. 9. The average dE/dx separation in standard deviations between particle types, computed using all tracks in hadronic Z decays which have at least 50 dE/dx measurements.

ECAL(I)

Ecole Polytechnique, Saclay, and LAL Orsay, were very involved from the start in the thinking on the type of ECAL we wanted. H Videau brought back from US the idea of a MWPC+lead sandwich with cathode pad readout; after my experience in NA3 it was clear to me that reconstruction of gamma position from an X-Y U-V detector would be very hard in jets. We initially thought of bigger cells with 12-bits ADC, and with a cheap readout after 4X0 to get the X-Y position. The breakthrough came from an excellent electronic engineer from LAL Bob Chase who convinced us he could built cheap and accurate electronics by multiplexing 32 channels and reading them in series with precise 12- bits ADC in the 25 μs between beam crossing.

So we could build an ECAL with small 3X3cm cells (size of showers) and 3 reading in depth 4X0, 9X0, 9X0 this meant a total of 222,000 readout channels!!! Very daring!

However the drawback of the MWPC ECAL was that its accuracy in energy was about 18%/sqrt(E) as we measured with a prototype.

D. Fournier from LAL who had built a liquid Argon ECAL for CELLO at Desy and would built the Liquid Argon ECAL for ATLAS in the future, preferred liquid Argon, with an energy accuracy of about 10%/sqrt(E) but there was no possibility at that time to obtain a high granularity for a liquid argon detector => cells of about 10cmX10cm at least.

Important decision=>decide to build ECAL inside coil to not have 1X0 in front of ECAL.

ECAL(II)

So we had to choose between the higher granularity option (which I supported) and the higher accuracy option. One argument for the high granularity was electron identification in b or c jets, but more generally it was adapted to the expected very busy environment. So the MWPC ECAL was chosen by the collaboration end of 1982.

This turned out to be a very good decision, as Michel Davier (tau expert from LAL) pointed out later, the high granularity was also a key element for the excellent tau physics of ALEPH. It was also a key element which allowed ALEPH to develop the "particle flow techniques" that I will discuss later.

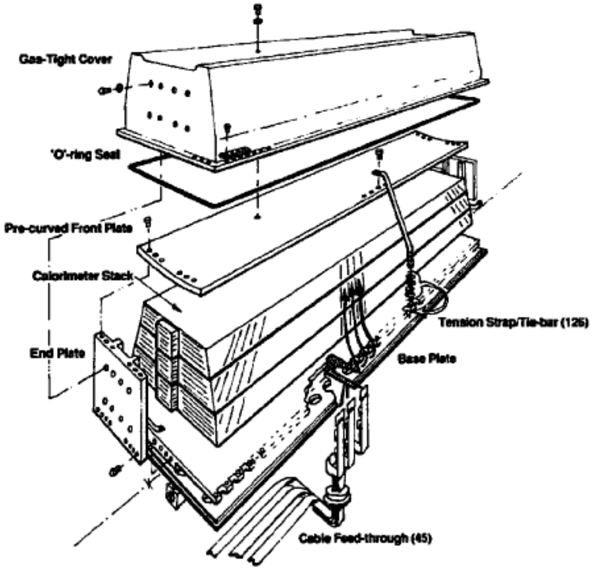


Fig. 29. Barrel module of ECAL; the length of the module is 4.7 m.

Left:One of the 12 barrel modules.
Right detail of one layer.
About 2*10^6 pads to connect for Barrel !!!

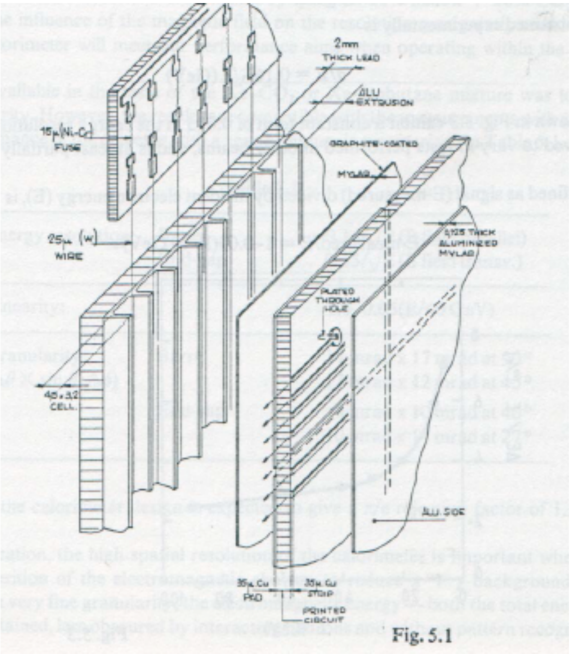


Fig. 5.1

ECAL(III)

We organised the construction: All French labs of ALEPH (Clermont, Ecole Polytechnique , Marseille, LAL-Orsay, Saclay) collaborated on the 12 Barrel modules. U.K. labs took the responsibility of the 24 (smaller) End-Cap modules built with the same technique. The luminosity monitor (LCAL) were built with the same technique in Denmark.

The program was the occasion of a few very nice ideas ☺

- There was an individual HV connection for each MWPC plane (45 layers X 12 modules) but to protect us against loosing a plane if a wire broke each wire was in series with a fuse: if a wire breaks => disconnect HV+ connect LV high current + blow the fuse =>HV back => small local correction to photon energy (about <1% but known) (in Year 2000 about 30 dead wires/150000)
- We read also the pulses from the wire planes => limited number of readout 36 modules X 45 = 1620 => no multiplexing needed => ideal fast readout for trigger.. The information was also used to do a sum per module of pads and wire and check by redundancy the coherency. These wire planes could also be pulsed individually => by induction it gave a pulse on the pads => easy access to the (rare) disconnected pads.
- After some search, I invented a radioactive gas source Kr^{83m} of 2 hours lifetime which was produced by a radioactive Rb^{83} source (83days) , it was used to test and intercalibrate all modules in early 89. This technique has been used by many other experiment since.

Other detectors

The HCAL was built by Italian groups with streamer tubes. They were 2 readings : pads with about 3.7X3.7 degree (about 4X4 ECAL) consistent with the larger hadronic shower size, but also reading of all the wires (about 350000 !) giving redundancy since one has two readout and an excellent granularity in one direction. The typical accuracy is .84/sqrt(E)

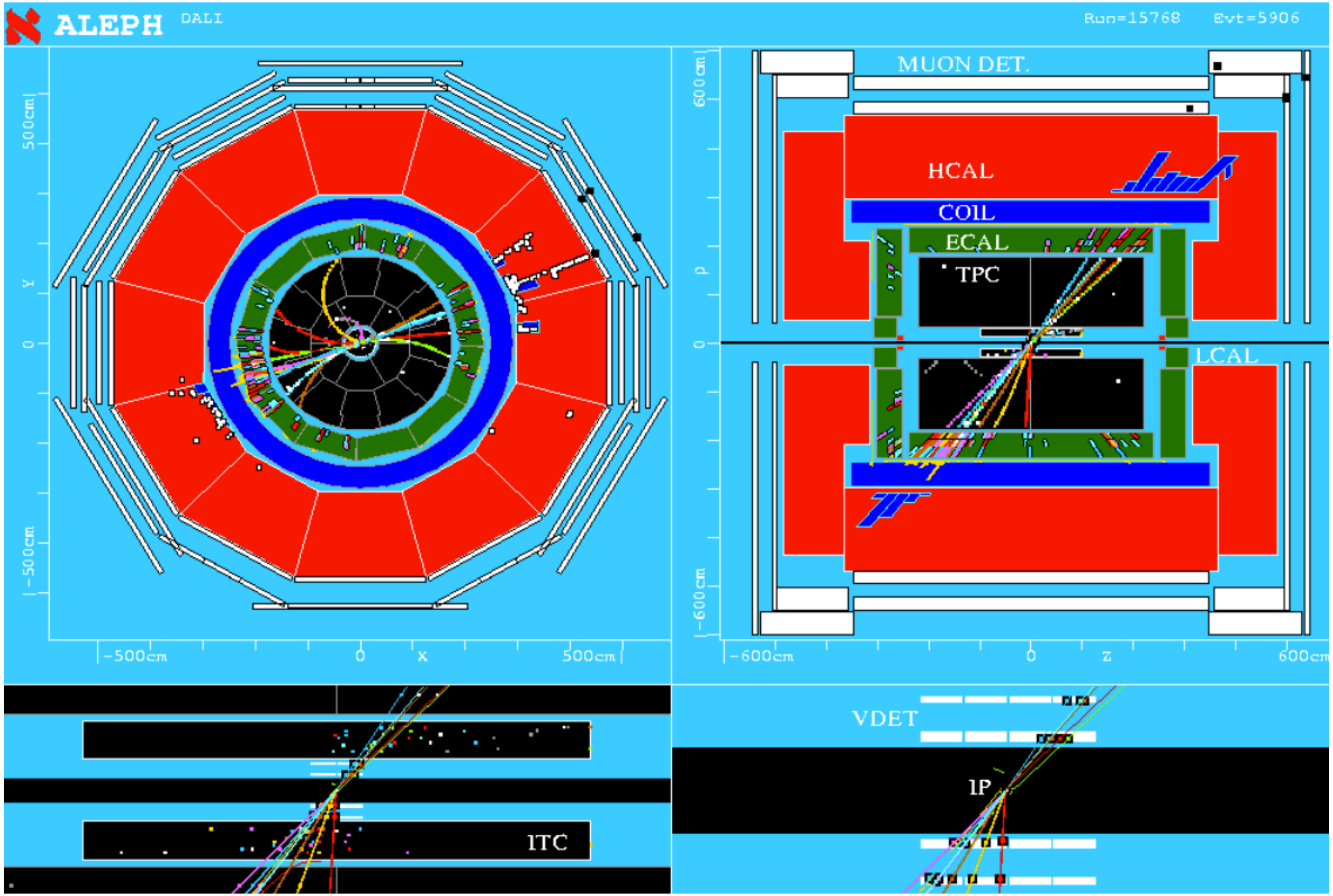
Muon chambers: They were built with streamer tubes giving two orthogonal readout. The first layer was built by Italy and the second by China.

Inside the TPC here was an ITC (Inner Tracking Chamber) about 2m long, built by Imperial College UK. It had 960 sense wire and was giving along tracks 8 points with a precision of about 100µ in rφ and about 3cm in Z (measured from time difference on signal arrival at both ends , not bad!!!!)

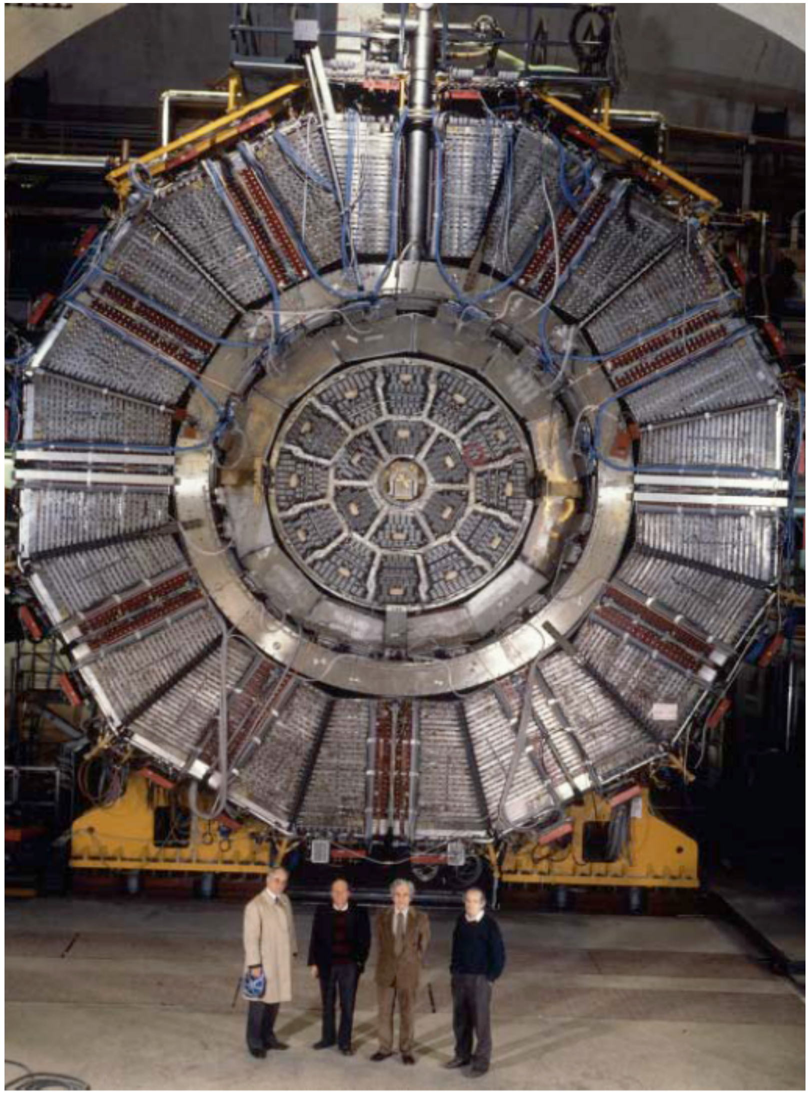
A silicon strip Silicon detector with two-side readout was gradually installed and operational in 1991 . It was build by Munich and Pisa. It played a key role in the B and Charm physics.

Finally there were luminosity monitor initially LCAL and chambers and later a sandwich of Tungsten and Silicon detector, that allowed an accuracy of 0.1%!

ALEPH 2-Jet Event (Apparatus in operation!)



A nice memory!



One day, before the final cabling started, Jack Steinberger took to the pit P. Lazeyras our technical coordinator Lorenzo Foa (HCAL coordinator) and J.L. (ECAL)
For a nice picture!
(Lorenzo and I were also the next spokesmen, did Jack know in advance!)
If you want more details on ALEPH apparatus, you can read
NIM A294 p 121-178 (1990)
NIM A360 p 481-506 (1995)
One important detail the budget was respected the cost was about 80 MCHF with the ECAL about 15%
Actually in 1989 we saw we had saved money and we invested 500KCHF for 25 Gigabytes of Disk for our data at the CERN computer center!

A Few Specific Performance (I) Trigger

The noise from the machine was not very high, so this allowed us to have a few simple triggers in // This ensured an excellent redundancy . These were for example an energy >6 GeV in an ECAL module or 2 tracks in the ITC pointing at an ECAL module with > 200 MeV. Or track in the ITC with hits in a corresponding HCAL module.

Since most event have two opposite particles or jets one can get the efficiency for each side from the data looking at the events with 2 sides triggered or 1 side triggered. Then with both side the inefficiency = (single side inefficiency)^2

The numbers achieved were astonishing: efficiency typically >99.98%!!!

The trigger rate was typically 4-5Hz ½ from luminosity and ½ from the main detectors.

A Few Specific Performance (II) PID

I have shown the π,K,p separation from the DE/DX in the TPC

Very important for τ and b,c quark physics was e and μ identification. In both case there was redundancy: μ could be separated from hadrons by the characteristic aligned hits in the HCAL or from the muon chambers : in hadronic jets typically the identification efficiency was 86% with an efficiency for hadrons due to decay to μ or punch trough of 0.8%

For electrons one can use the energy in 2X2 cells this is 85% of p for electrons => Rt=(measured vs predicted)/ sigma
Rl is measured vs predicted for the longitudinal behaviour: => in fig 14 one sees the nice signature.
Then in fig 16 one sees the (DE/DX in the TPC minus the predicted value) /sigma
In total, the efficiency is ≈66% while, the efficiency for hadrons is < 0.1%

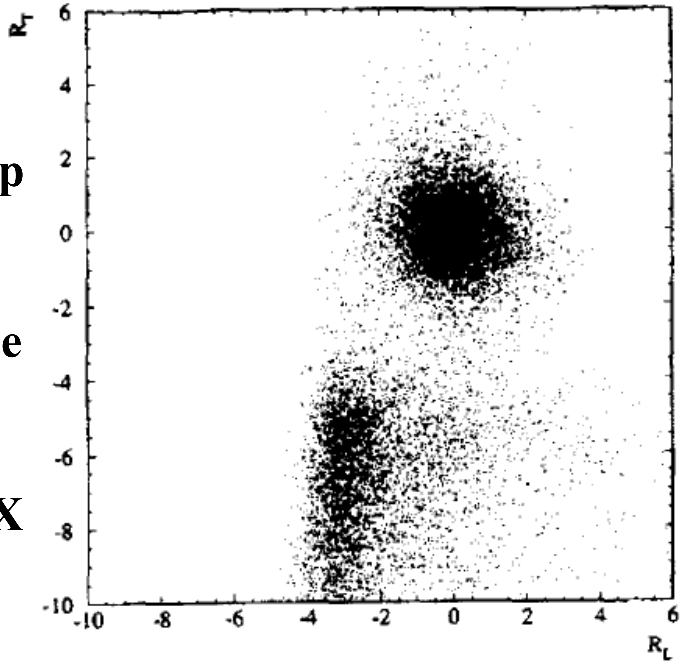


Fig. 14. Electron estimators from the electromagnetic calorimeter for a sample of tracks enriched in photon conversion electrons.

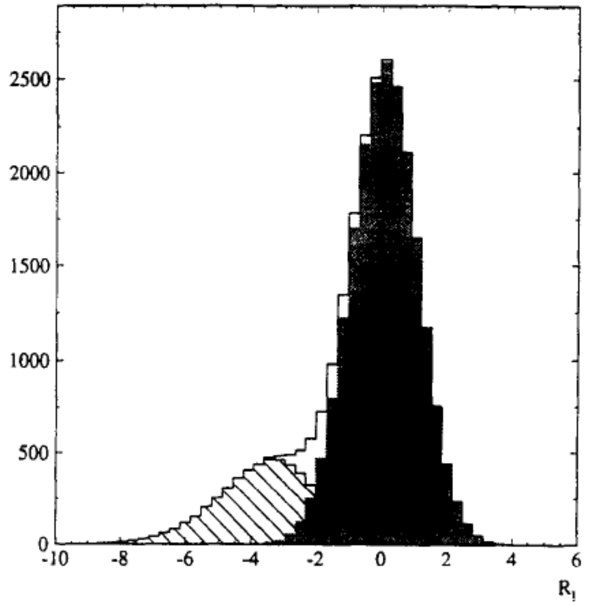


Fig. 16. R_I distribution for electron candidates which have been selected using calorimetric information. The hatched part represents the hadronic contamination, and the shaded part electrons.

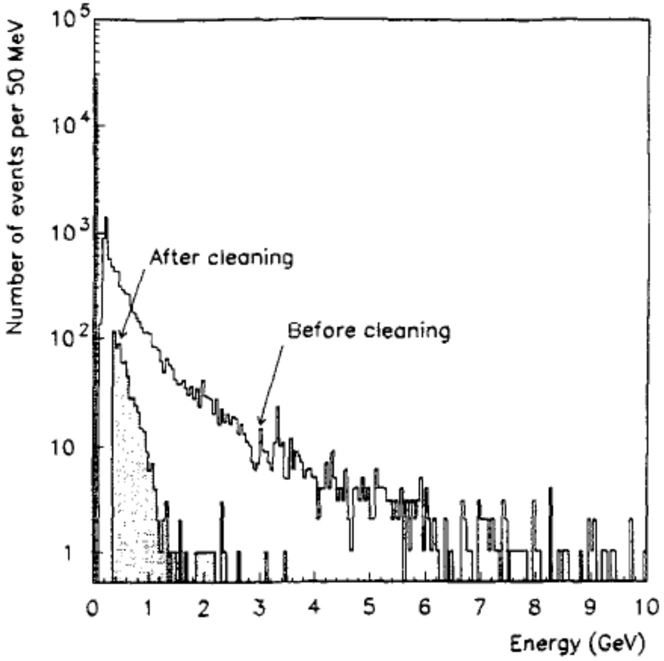
A Few Specific Performance (III) “Energy Flow”

From the design of ALEPH we thought of the possibility of measuring jet energy by measuring charged particles in the TPC, π^0,γ in the ECAL and K^0_L or neutrons in HCAL , this is what was called “energy flow” measurement

Previous experiments (UA1,UA2 Fermilab etc…) had summed the ECAL+HCAL energy in our case this would have given a $\Delta E/E = 1.2/\mathrm{sqrt}(E)$ and because of the effect of the strong B field the jet direction would be very badly measured so energy flow was better in principle but not trivial.

The problem was finally solved around mid 1990 by a small group of LAL physicist with Patrick Janot as a key person.

An initial problem was to clean the output of the ECAL and HCAL as shown on right plot. This was possible because of the redundancy of ECAL and HCAL readout.
Note the peak at zero noise energy.
Before cleaning 30% of events have about 1GeV of noise.
After cleaning 98% have 0 noise 2% on average 500 MeV



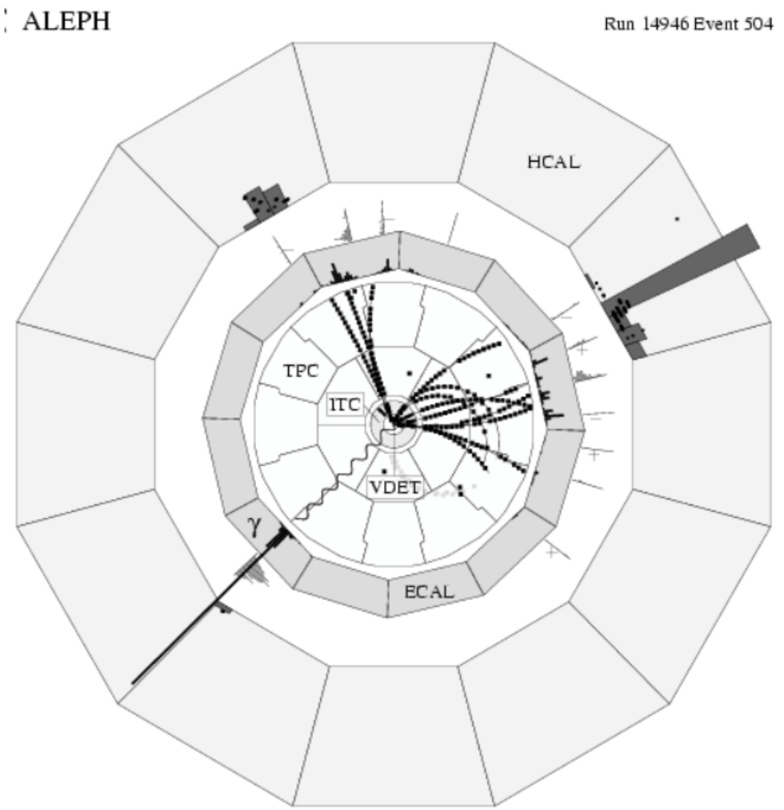
A Few Specific Performance (IV) “Energy Flow”

But the key problem is to avoid double counting: if you measure a track with the TPC you should not then add its energy from HCAL (the method is now call particle flow, you have to follow each particle and separate ECAL, HCAL energy caused by neutral from energy caused by charged particle). This was perfectly adapted to ALEPH its excellent track finding from the TPC and the calo’s small granularity.

The resolution obtained was ΔE/E = 0.6/sqrt(E) The jet angular resolution was also excellent (18mrad for a 45 GeV jet vs about 100 mrad if using only calo information. The calibration and resolution of jets vs energy were calibrated with Z=>qqbar γ event (an example on the right) By measuring the γ energy you know the true qqbar mass which you can compare with the result of the particle flow.

The particle flow was an essential tool of ALEPH, for B-jet physics, for Higgs search in Z=> ννbar+Higgs (Higgs=>b+bbar) etc… Used in CMS… =>ILC?

If interested read P.Janot account in http://indico.cern.ch/event/96989/other-view?view=standard



Back to ALEPH History

Before switching to a few selected nice physics result obtained by ALEPH , let me finish the History part =>

By end of 1989 after the first 3 months of physics and the measurement of the number of ν families Jack Steinberger finished his mandate and I was chosen by the collaboration to be the next spokesman starting February 1990 for 3 years.

We had still to adapt completely to being a large collaboration ☺ I remember that as soon as I started the spokesmanship I organised an Editorial Board: This had a bigger role than now : A large part of the referees and the Board role was to check also the physics which had only been checked before in oral presentations (with written notes of course).

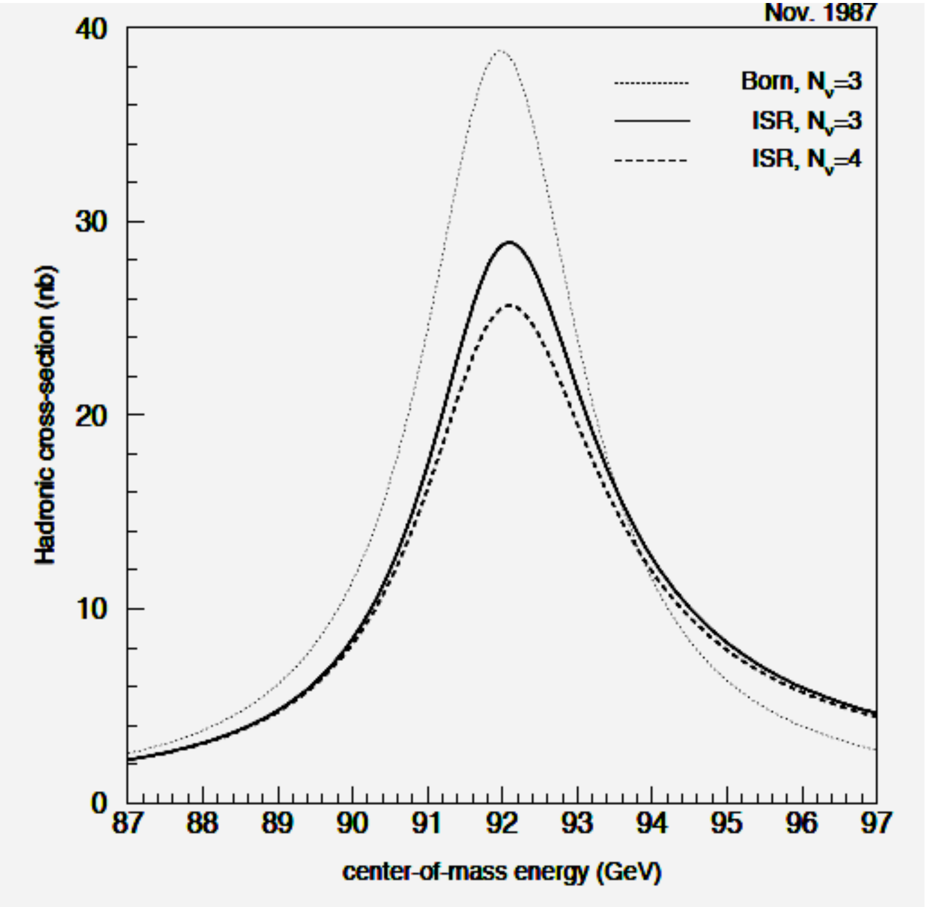
So after I finished my 3 year mandate, I was asked by the next spokesman to continue as E. B. chairman for a few years!!!

Meanwhile Jack continued to be active in some nice analyses, and also he was at the origin of meetings of the 4 LEP spokesmen, from this came the groups to average the results of the 4 LEP experiments (we thought we knew better than PDG or theorist how to do this!). This group was also useful to prepare a common position on LEP Schedule for discussion with CERN Management.

Selected Physics: Number of ν families (I)

- LEP had a few days of operation in August 1989 and started again on September 20th and after 3 weeks each expt had collected 3000 Z=>qqbar =>N_ν measurement
- To get Nν the number of neutrino families one could think of measuring the Z total width Γ_Z and subtract the hadronic Γ_h and leptonic Γ_l contribution from theory, then $N\nu = \Gamma_{invisible} / \Gamma_\nu$

But G. Feldman from SLAC had pointed out that it is more accurate to measure the peak cross-section rather than Γ_Z since σ_{peak} is $\propto 1/\Gamma_Z^2$ This is seen clearly in the fig right => What is also seen is that there is ≈ 30% radiative correction on the peak x-section. This is not different to the correction at ACO when measuring the φ meson (lecture 1) . It is because the colliding electrons behave as a spectrum of degraded electron energies accompanied by photons. In 1989 this was calculated at first order (+exp) to 0.5% accuracy, later at 2nd order the accuracy reached 0.05%

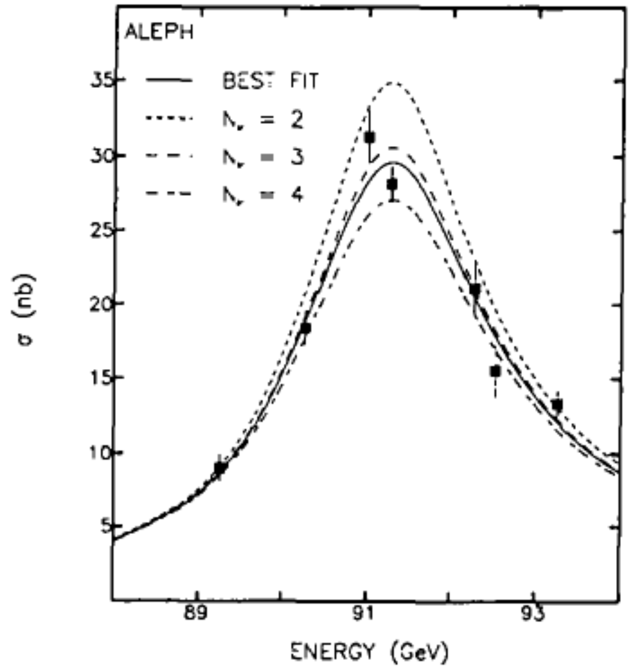


Selected Physics: Number of ν families (II)

As we showed it is more accurate to use the peak x-section $\sigma_f^0 = \frac{12\pi(\hbar c)^2}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}$:

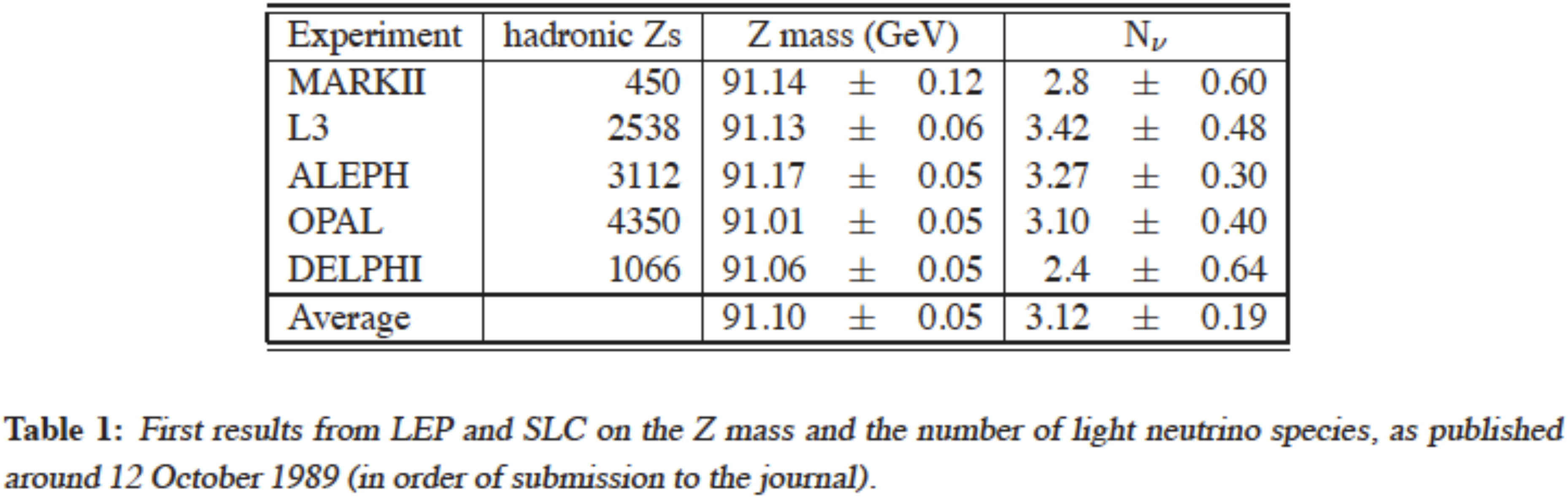
The formula above can be transformed to $N_\nu = \frac{\Gamma_\ell}{\Gamma_\nu}\cdot\left(\sqrt{\frac{12\pi R_\ell}{M_Z^2\sigma_{\mathrm{had}}^{\mathrm{peak},0}}} - R_\ell - 3\right)$

R_l = the ratio Γ_h/Γ_l was taken initially from E-W theory and corrected by the QCD correction
The first data gave $N_\nu = 3.27\pm0.24_{stat}\pm0.16_{sys}\pm .05_{th}$
An important point was to measure accurately the luminosity using small angle Bhabha : our Copenhagen colleagues building the LCAL had done a good metrology: the limit is when half the shower is inside the fiducial region of pads half outside => the total systematical error was ≈ 2% including a theory error of 1%
With the full 1989 data we reached
$N_\nu = 3.01\pm0.15_{exp}\pm .05_{th}$
At then end of LEP the Lumi theory error was .06% and $N_\nu = 2.984\pm0.0082$ from the 4 LEP expts



ig. 5. The cross-section for $e^+e^-\rightarrow$hadrons as a function of entre-of-mass energy and result of the three parameter fit.

N_ν October 1989



Experiment	hadronic Zs	Z mass (GeV)	N_ν
MARKII	450	91.14 ± 0.12	2.8 ± 0.60
L3	2538	91.13 ± 0.06	3.42 ± 0.48
ALEPH	3112	91.17 ± 0.05	3.27 ± 0.30
OPAL	4350	91.01 ± 0.05	3.10 ± 0.40
DELPHI	1066	91.06 ± 0.05	2.4 ± 0.64
Average		91.10 ± 0.05	3.12 ± 0.19

Table 1: *First results from LEP and SLC on the Z mass and the number of light neutrino species, as published around 12 October 1989 (in order of submission to the journal).*

Selected Physics: The E-W parameters

The E-W parameters are related at 0th order in the E-W theory by relations like

$\cos^2(\theta_w) = M_w^2/M_Z^2$, $(1-4*\sin^2(\theta_w)) = g_{ve}/g_{ae}$,

$\sin^2(\theta_w)*\cos^2(\theta_w) = \pi\alpha_e(Mz)/(G_F M_Z^2 * \mathrm{sqrt}(2))$

Figure 45 Top loop diagrams responsible for radiative corrections to W and Z° masses and couplings.

But because of loop diagrams as the one shown the relations are modified and become sensitive to the value of the top mass and of the Higgs mass.

The E-W corrections from the top contribute terms of the form $(1+a*(M_{top}/M_w)^2)$ and terms from the Higgs of the form $(1+b* \ln (M_H/M_Z))$. Obviously the E-W observable where more sensitive to M_{top}

If interested in more details you can consult hep-ex/0509008 280 pages!!! Year 2005 This gives in details all E-W results from the 4 LEP expts + SLD at SLAC

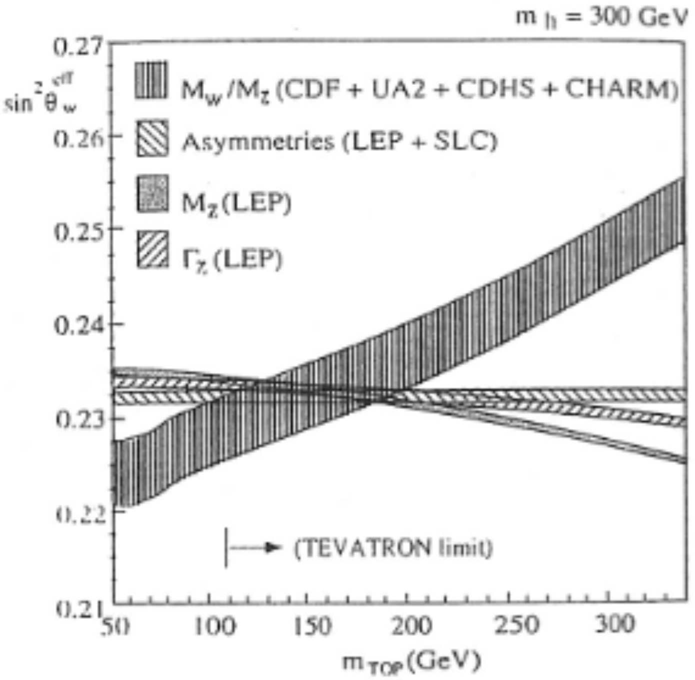
E-W precision measurements

Even with only the 1989, 1990 data ALEPH could publish (Zeit.Phys. C53 (1992)1. or CERN PPE 91-105 July 91) an EW precision measurement paper, giving the prediction from ALEPH data alone

M_{top} =170 GeV±45(expt)±20(Higgs 30GeV-1000GeV)

It was an intense pleasure, which I remember very well, to be able to predict a new particle mass. We are now all waiting either for new particles found directly or at least, as at that time, for a sign of new physics (but life is now more difficult.)

Different measurements contribute to the top mass prediction as shown on the plot right =>
By 1994 at the winter conference the prediction was M_{top} =173±12±19(M_H) By the summer 1994 the top was found at the Fermilab collider with Mtop=176±16GeV
I think the prediction was a fantastic achievement of LEP and generally of the S.M.
As is well known, similarly, using all E-W data the Higgs mass was predicted for example in ICHEP 2002 as M_H= 81 +52 -33 GeV



Scanning the Z(I)

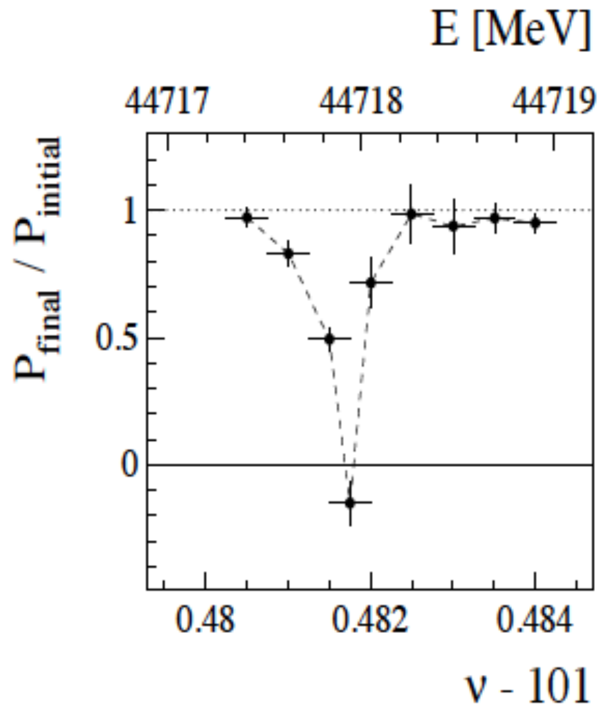
Two of the input for the E-W fit are the Z mass and width Γ .These were obtained by scanning the Z resonance. Because of the large statistics the accuracy reached could be fantastic (about 2 MeV was reached at the end!).

The accuracy is obtained mainly from the data taken at ± 2 GeV from the peak of the Z mass curve but it is then obvious that energy calibration is a major problem since the accuracy required is about 2* 10-5 !!! This accuracy is not trivial and uncommon for an accelerator. For example the range of energy inside a beam is about ±25 MeV

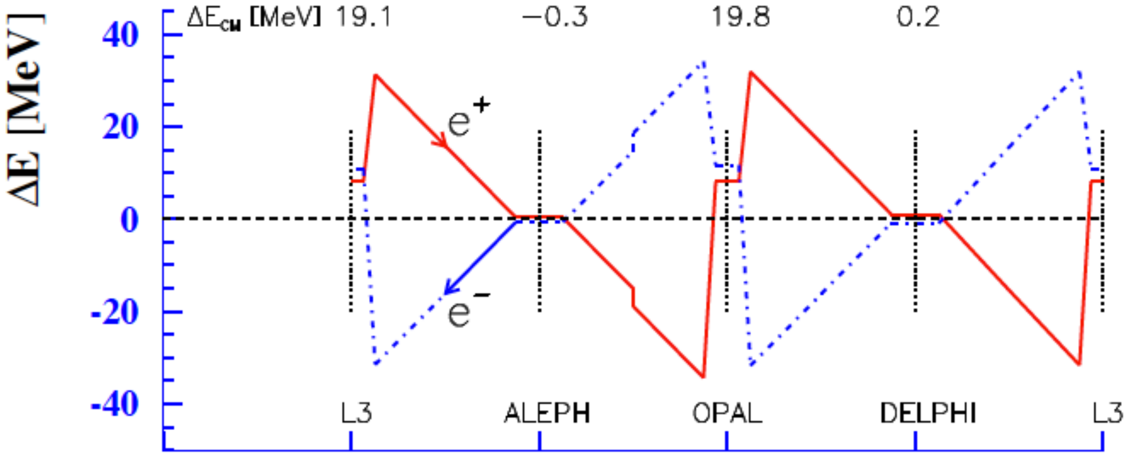
A crucial tool was the observation of depolarisation resonance of the beam: A group of Lep-physicist and accelerator physicists (with A. Blondel from ALEPH playing a key role) had been motivated to study beam polarisation with the hope of colliding longitudinaly polarised beam. This turned out not to be possible efficiently at LEP (it was used by SLD at SLAC) but the study of polarisation was useful. If careful with machine alignment polarisation builds up slowly in an e-e+ machine, then (if not vertical) the spin rotates by 2π*(E/m)*((g-2)/2) each turn. If you subject the beam to a small transverse field periodically you rotate a bit the spin; if you do it always at the same phase (i.e. at the spin frequency) the rotation effects add up and you depolarize the beam.

The polarisation is measured by collision with a laser P => asymmetry in photon angle

Scanning the Z(II)



You can see (top fig) how sharp the spin resonance is (≈ 10^{-6})! This integrates all effects and gives the energy averaged along the ring but because of synchrotron radiation losses compensated by RF the beam energy goes up and down and is not the same for all 4 expts (fig right down)



igure 2.8: Typical variations of the beam energy around the LEP ring during the 1993 run.

Scanning the Z(III)

There were also an NMR probe measuring the field of LEP bending magnet with high accuracy, it was found from the accurate polarisation measurement that the beam energy changed even when the B field was fixed!!!

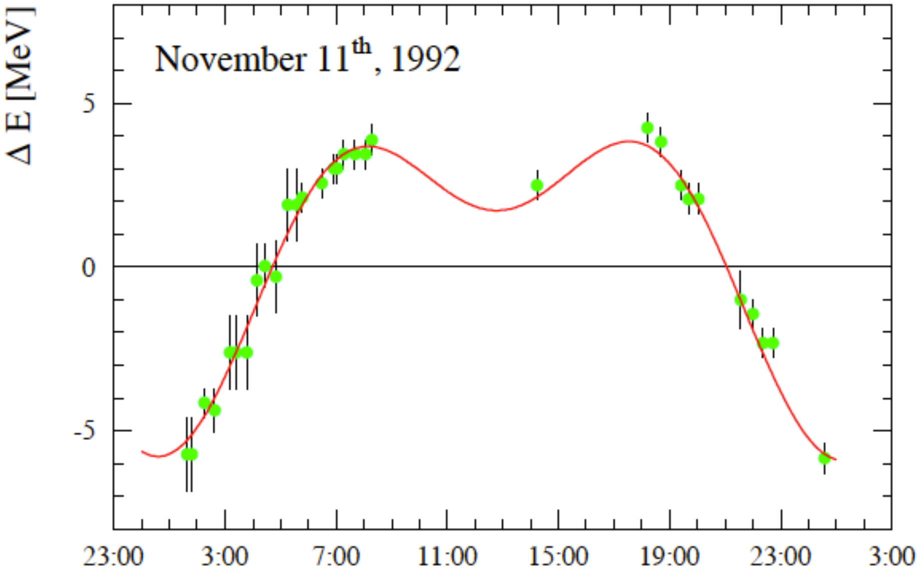
Albert Hoffman thought of the effect of the earth tide (sun, moon) changing the radius of the ring (0.15mm) : observations matched perfectly (fig below=> energy vs time of the day). Other subtle effects were also observed (DC earth current from railway system, pressure from the height of water in the Geneva lake modifying the ring size!) Finally an uncertainty of about 1 MeV was obtained.

At the end of Lep with the 4 expts

M_Z= 91.188±.002

Γ_Z = 2.495±.0023

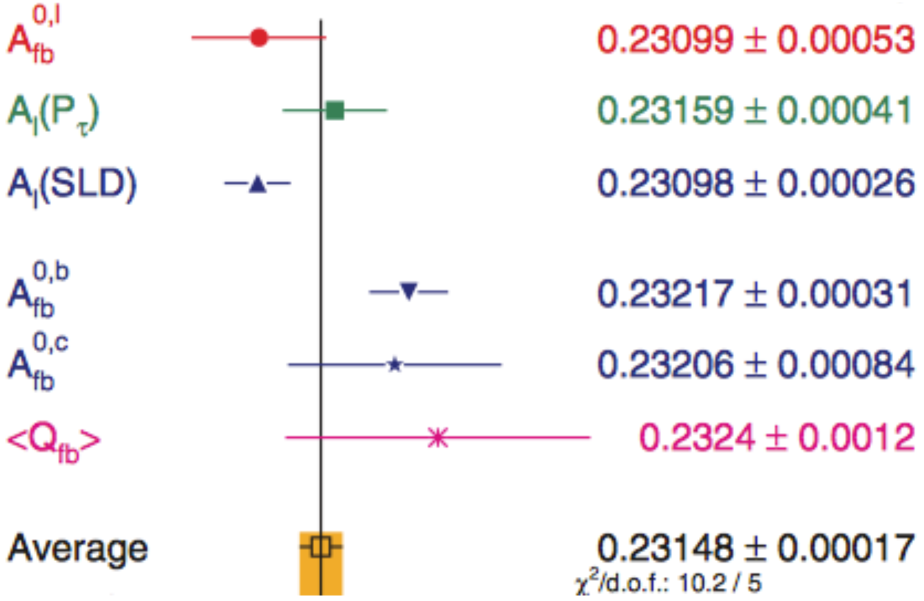
If one thinks of future e+e- colliders with 10^9 Z or 10^{12} Z It will be a challenge to control the energy systematics correspondingly!!!



Asymmetries

The interplay of Vector and Axial vector couplings of the Z produces asymmetries in the angular distributions. The observed A_{FB} usually include the product of 2 effects the Gv/Ga of electron which polarizes the Z and the Gv/Ga of the decay channel. There are two exceptions the case where the incident electron are polarised “at the source” as was done at the SLAC linear collider SLC (this gives therefore a very sensitive result even with the lower number of events $0.5*10^6$) Or the case where the tau polarisation is measured.

Results summarised at the 2002 ICHEP are shown on the fig They give the value of $\sin^2(\theta_w)$ (Sw) by various measurements: for the lepton the Gv/Ga=(1-4*Sw) while for c-quarks Gv/Ga=(1-(8/3)*Sw) and b quark Gv/Ga=(1-(4/3)*Sw). There is a tension between results from b quark and A_L from SLD. The understanding (if not stat fluctuation) has to wait eventual data at the Z at a future collider. I cannot help in these lectures!!! I will review some asymmetries.



Tau lepton asymmetries (I)

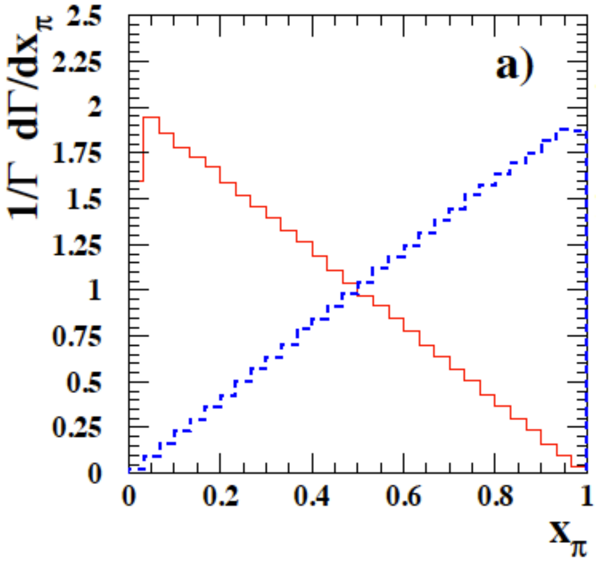
Before the start of LEP the idea to use the tau polarisation (actually longitudinal P or helicity) was already detailed. The idea was that the tau helicity can be observed for example in the decay τ => πν there is the an asymmetry of the decay angle

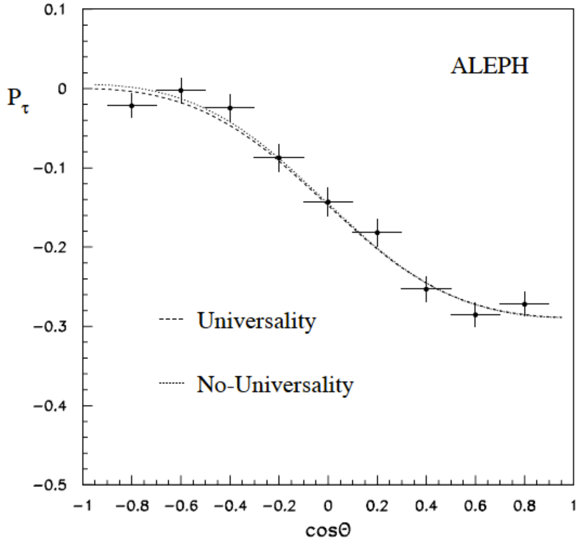
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\pi} = \frac{1}{2}(1+\mathcal{P}_\tau\cos\theta_\pi)$$

After the Lorentz boost from the tau C.M. to the Z C.M. the distribution is observed as an asymmetry in the π energy distribution according to the value of Pτ as shown on the plot(a). The τ polarisation at the Z depends on the τ production angle as given in the formula below and in the plot of Aleph data.

This allows to extract Ae and Aτ that are equal in the universality hypothesis

$$\mathcal{P}_\tau(\cos\theta_{\tau^-}) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta_{\tau^-})+2\mathcal{A}_e\cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-})+\frac{8}{3}A_{FB}^{\tau}\cos\theta_{\tau^-}}.$$





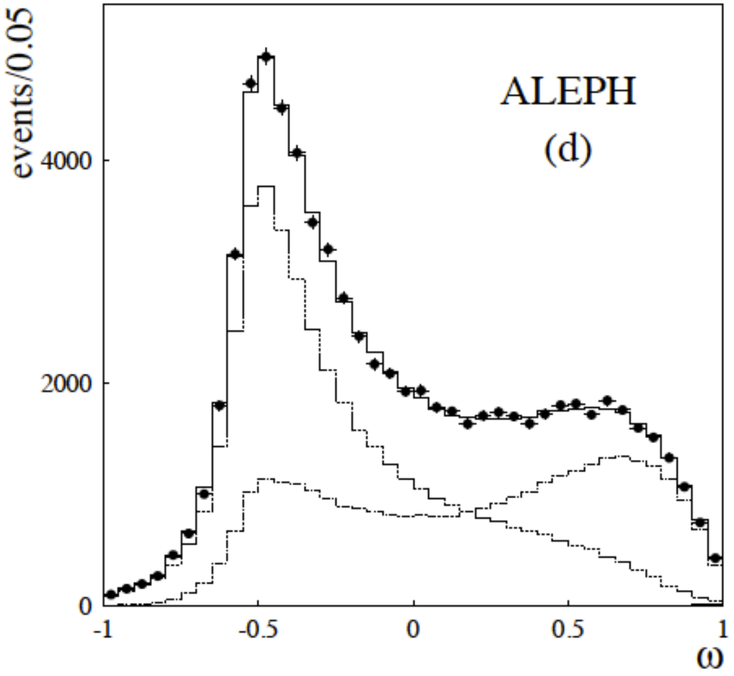
Tau lepton asymmetries (II)

The π decay channel was the only one used in early physics "toy analysis" before LEP data taking, but it has only an 11% branching ratio. In the ρ decay channel the ρ can have m=0 or m=1 spin state, and these have opposite ρ energy asymmetries, however by observing the $\pi^{\pm}$ and π^{0} of the ρ one can reconstruct the spin state and the ρ decay channel then become as sensitive as the π one.

Actually 3 physicists from ALEPH found and published (01/1993) that, for all decay modes there is a linear variable ω which is the optimum variable to analyse the polarisation and contains the maximum information

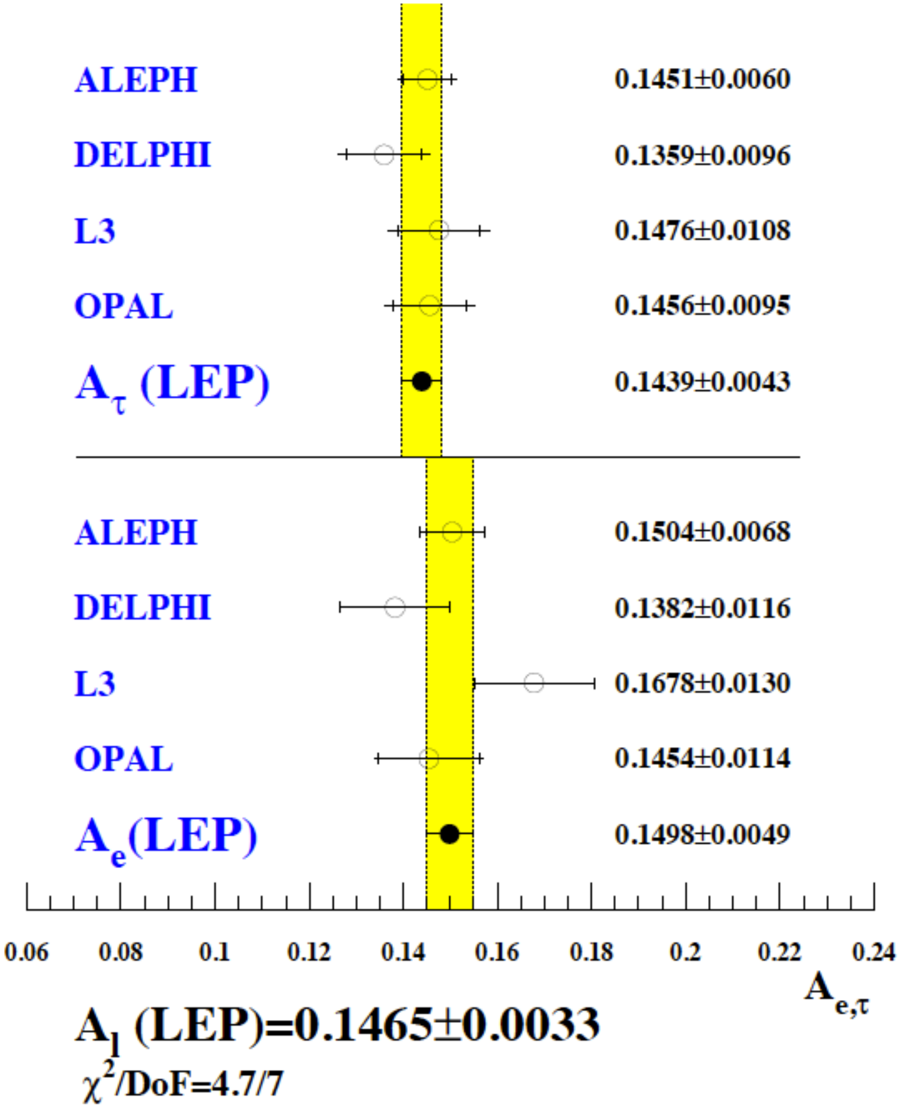
This is shown in the formula below, W+ and W- are the distributions for full opposite polarisations. A plot showing the ρ channel data is shown together with the curves expected for full polarisation. Similar fits were done for all decay channels ($3\pi^{\pm}$, $\pi^{\pm}2\pi0$ etc…) All 4 LEP expts used later the formalism.

$$\omega_\rho = \frac{W_+(\theta^*,\psi) - W_-(\theta^*,\psi)}{W_+(\theta^*,\psi) + W_-(\theta^*,\psi)}$$



Tau lepton asymmetries (III)

More sophisticated methods were used in the case where both τ's in Z=>τ+τ- decayed to hadrons, in this case (only 2 missing ν) the τ directions can be reconstructed up to an ambiguity, improving further the sensitivity. The final LEP results are shown on the right. Note that the ALEPH results are more precise by about < 1/sqrt(2) This was, in very large part, linked to capacity of the ECAL and the TPC to disentangle complex events, with small opening angle from the decay of 45 GeV τ's



B quark asymmetries (I-leptons)

The B quark asymmetry is one of the most sensitive input to the $\sin^2\theta_w$ determination (slide 28). To obtain the asymmetry one should solve 2 problems: first, separate the B events from the other Z=>qqbar events and second to determine which jet is from a q and which from a qbar. Historically the first way to solve both problems at once was to rely on the presence of a lepton (e,µ) with sizeable Pt from semileptonic decay of the B hadrons. At least for ALEPH the fiducial angular zone covered was $-0.9 < \cos(\theta) < 0.9$ which was larger than the acceptance of the LEP1 Vertex Detector Nevertheless if lepton tracks were within the VDET acceptance the information was used. Difficult backgrounds were c=>l or b=>c=>l but could be separated (see fig)
Another problem was the mixing of B hadrons changing the sign of leptons, but this could be identified from events with 2 opposite leptons of the same sign.

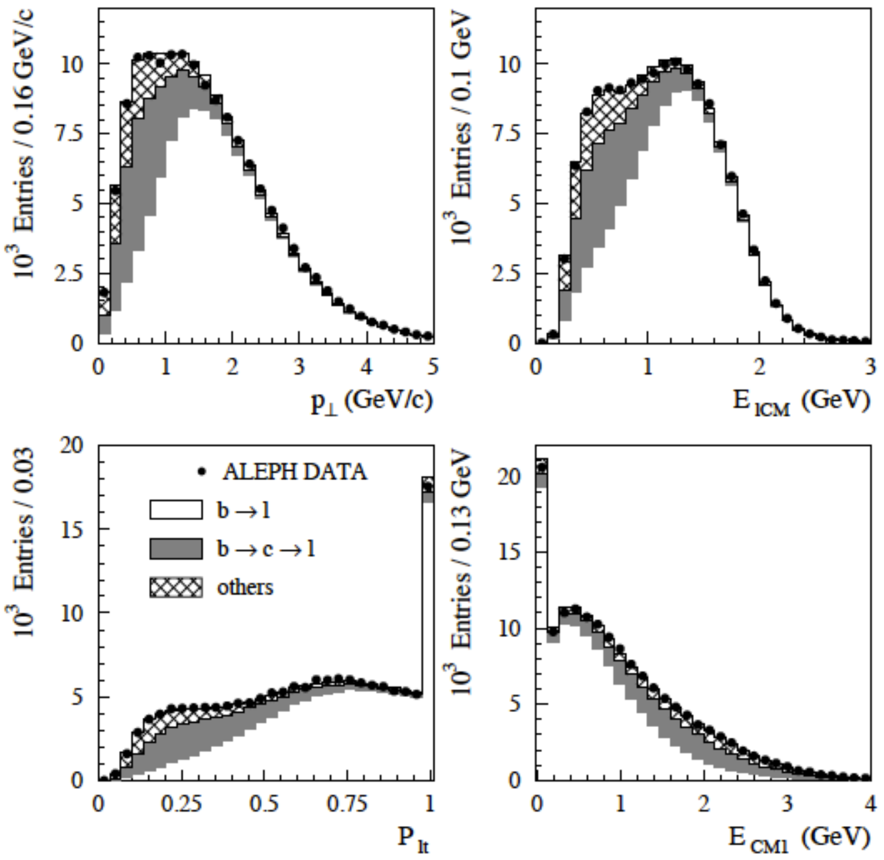
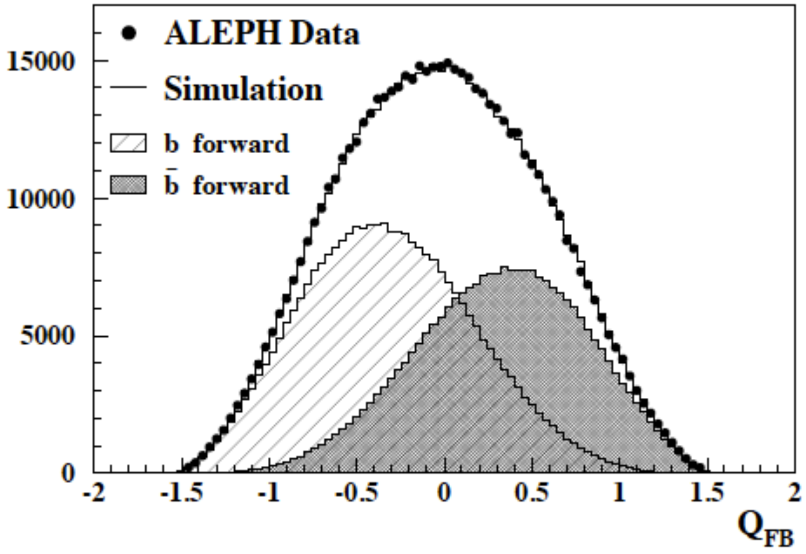
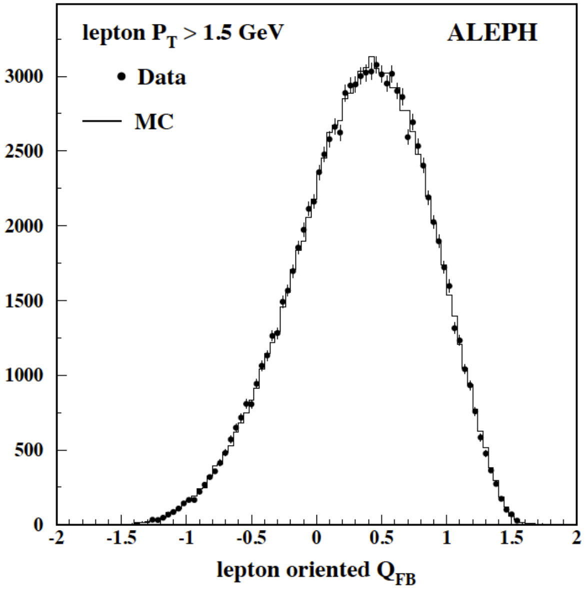


Figure 3: Distributions of four discriminating variables used for b → ℓ tagging in data and simulation, for events satisfying a tight b tagging cut $N_b > 0.96$. In the simulation, for b → ℓ decays, the lepton energy in the b hadron rest frame is reweighted according to the ISGW model.

B quark asymmetries (II-Jet charge)

The other possibility is to identify a b-bbar event using essentially vertex separation as will be discussed for Rb. Then the assignment of the b or bbar side is done by a combination of charge at the vertex (not very effective) and jet charge. The jet charge is obtained from an algorithm => it uses a weighted sum of the charge of particles, the weight being the longitudinal momentum to the power κ. On the fig is shown the result of data and simulation, in the simulation because of A_{FB} there are more b forward. The charge separation is obtained by correlation of charge measurement (in first order=> $\bar{\delta}_f^2 = \sigma^2(Q_{FB}^f) - \sigma^2(Q_{tot}^f)$) the information on the jet charge of lepton signed jets are also used. => Subtle but sensitive analysis.

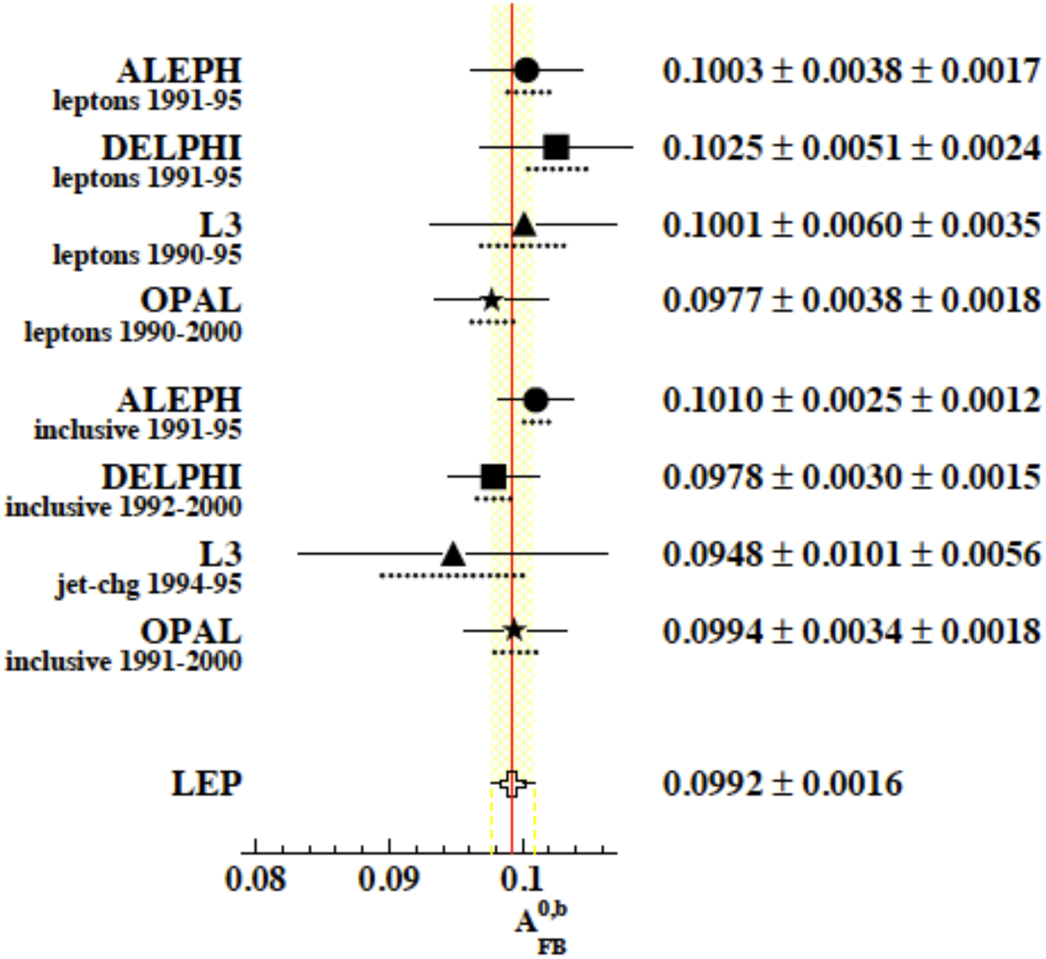




B quark asymmetries (III)

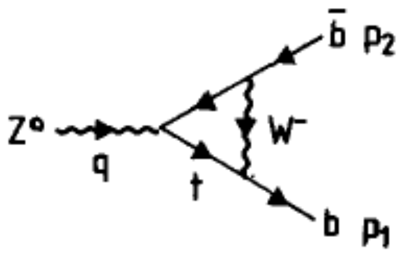
The results from the 4 LEP experiments are shown on the Fig below.

The results called inclusive are the jet charge ones.
Results are also obtained for c-quark asymmetries by a similar method, but the accuracy to determine Sin^2(θw) is much worse so I will not detail them.



Rb(I)

R_b is defined as Γ_b/Γ_h it was of high interest because it is modified by the vertex diagrams corrections shown in fig 1a,b.
These corrections are negligible for non-b quarks hadrons because of lower CKM couplings. They are ∝ to $(Mt/Mw)^2$ and are about 1.2% for Mt =175 GeV



1 (a)

1 (b)

In the summer 1995 conferences there were some excitement because the measured value of R_b was 0.2219 ±.0017 from the 4 LEP expts about 3.5 σ from the S.M. prediction…. And experiments agreed! For ICHEP 1996 ALEPH presented 2 new (correlated) measurements which were more precise than the average of all other measurements. It is also a nice memory because the first result (using a lifetime-mass tag) was essentially from a brilliant young fellow Ian Tomalin. And the second result (including information from the first analysis and 20% more precise) was the work of a group led by Jack Steinberger (it was Jacks last personal analysis work in ALEPH) I happened to be the ALEPH internal referee and I remember it was very nice to follow the physics.

R_b(II)

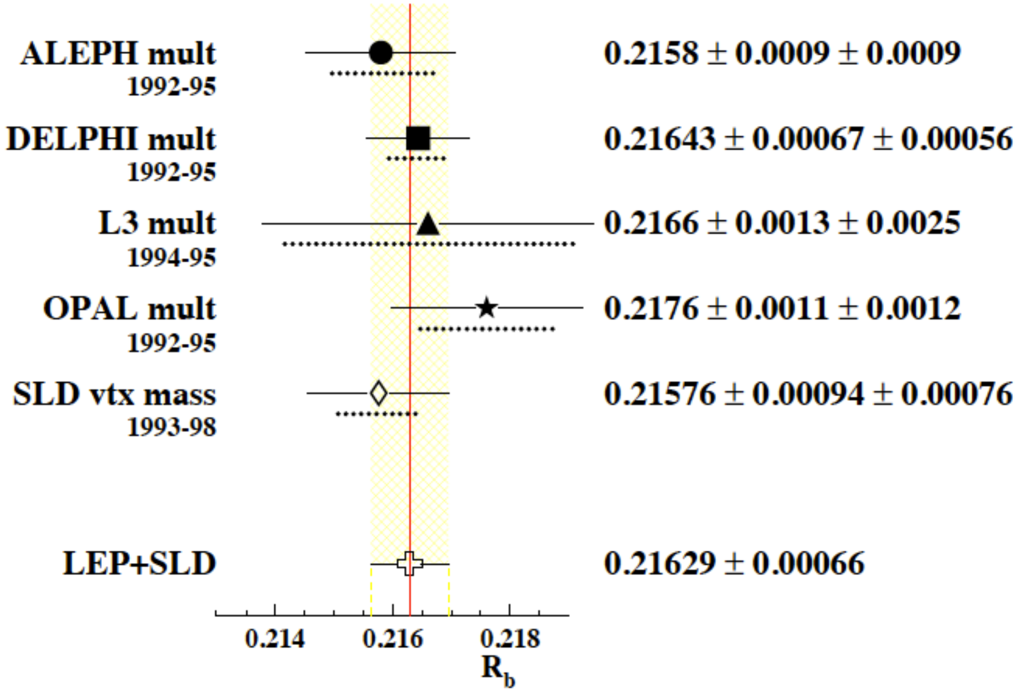
The point common to all R_b analyses (including previous ones) was to divide all events in 2 hemispheres by a plane perpendicular to the thrust axis of the event: then (neglecting background for the moment) the fraction of hemispheres tagged as b is $R_b*\varepsilon_b$ where ε_b is the tag efficiency while the fraction of events with both hemisphere tagged is $R_b*\varepsilon_b^2$. Therefore one can solve and obtain R_b and ε_b . Of course the subtlety is that these equations are not exact: there are background of other quark events (especially in the single tag), and there are correlation among both side modifying the ε_b^2 estimate.

The lifetime tag was based on the the impact parameter's significance of all tracks from an hemisphere , in the case of the B some tracks are found not coming from the main vertex. The mass tags looks at the combined mass of N tracks not coming from the vertex, it is useful to reject Charm events since the combined mass is always $< M_D$. For the first analysis u,d,s,c backgrouns and b correlation, were obtained by Monte Carlo simulations.

Compared to previous measurements (before 1996) the primary vertex was evaluated independently for each hemisphere. This was not done before (for all LEP expts) and may have given a correlated systematics for all expts??? Delphi originated this idea…

R_b(III)

The other ALEPH analysis used a 5 exclusive tags algorithm; what was powerful was to have a tag especially efficient for c-quark and one for uds. Then there are more equations correlating both sides and the results depends less on Monte Carlo. The main systematics was from evaluation of udsc event contamination by gluon=>b-bbar The 5 tag analysis decreased stat and syst errors by about 20%

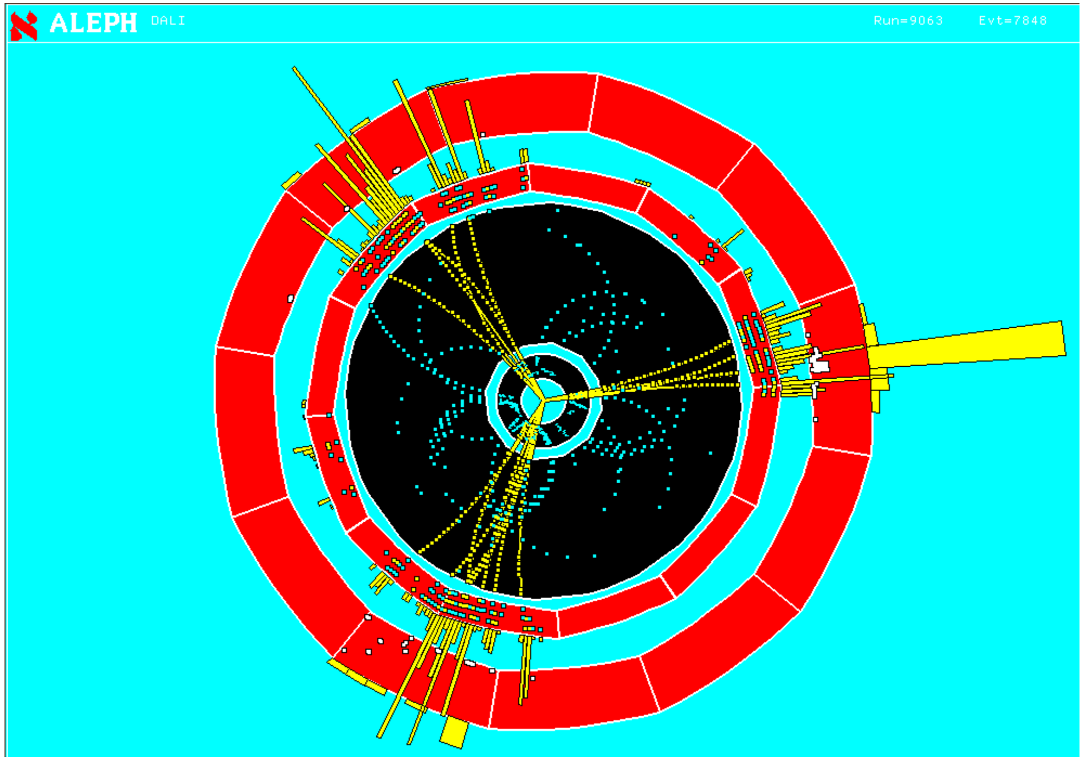


At the 96 ICHEP, ALEPH result on R_b was more accurate then the other results combined and was compatible with the S.M. evaluation. Above are shown final results (2005 paper) Even if SLD had only 600kZ events compared to the 3.8MZ events of each LEP , the very small beam focus and vacuum chamber => similar accuracy. The DELPHI results profits from the higher acceptance of their VDET. Results agree with the S.M. $R_b = 0.2157$

QCD(I)

QCD was an extremely important subject of LEP, there was truly a before and after LEP in the confidence in QCD and the level of precision. Actually a large part of the progress can be seen as different ways of measuring α_s .

The first measurements came from analysis of 3 jet events. Measurements of α_s =0.118±.008 were obtained but the analysis used theory of jets accurate at α_s^2 and therefore not very precise furthermore the scale was not obvious, was it the Pt of the jet or Mz?
Scaling violation studies between lower energy and Mz gave similar results.
Theorist however calculated up to α_s^3 terms the QCD corrections to $\Gamma_h=(1+K_{QCD})\Gamma h_0$



$$K_{QCD} = \frac{\alpha_s}{\pi} + 1.41\left(\frac{\alpha_s}{\pi}\right)^2 - 12.8\left(\frac{\alpha_s}{\pi}\right)^3 - \frac{Q_f^2}{4}\frac{\alpha\alpha_s}{\pi^2}.$$

This was the most precise measurement, now α_s= .119±.003

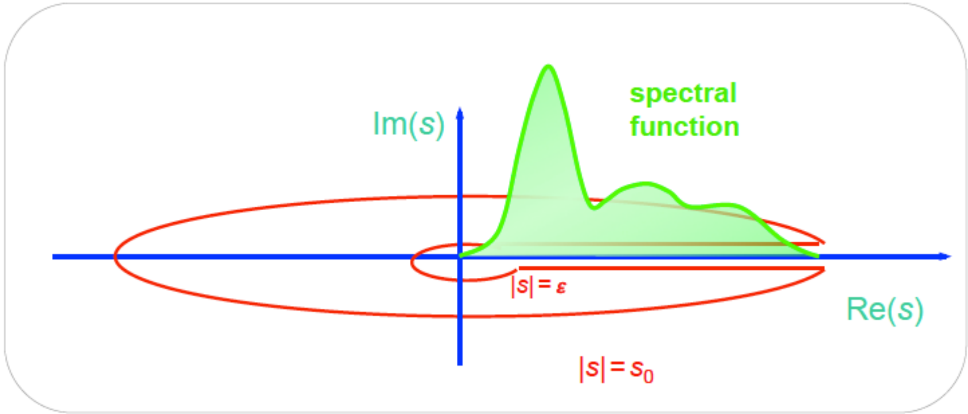
QCD (tau results-I)

As we have seen, the value of α_s can be obtained from the QCD correction to the ratio Z=hadrons/Z=>leptons, in a similar way it can be obtained from the ratio τ=>hadrons/τ=>leptons . But naively one could think that “the scale or Q^2 ” is undefined in this case (contrary to the Z case where it is obviously M_Z the total mass of the hadron system). Here the hadrons form a spectrum.

The non-obvious trick is to use Cauchy theorem to integrate over a circle in the complex plane.

Then one sees that the integral over the spectral function is like the integral over a circle at fixed s $=M_\tau^2$ So the scale is well defined. Because of the low tau mass the alphas value is bigger and when evolved using QCD equations to the Z mass the value and the error shrinks

$$R(s_0) \propto \int_0^{s_0} ds\, w(s)\, \mathrm{Im}\prod(s+i\varepsilon) \Leftrightarrow -\frac{1}{2i}\oint_{|s|=s_0} ds\, w(s)\prod(s) \qquad \text{with } s_0 = m_\tau^2$$



QCD(tau results-II)

The integral of the spectral functions (V,A,S) when compared to the leptonic branching ratio have QCD corrections: there are perturbative correction in α_s, α_s^2, α_s^3 … used to calculate α_s but also non-perturbative corrections (OPE terms). The break-trough was to do different integrals with factors like

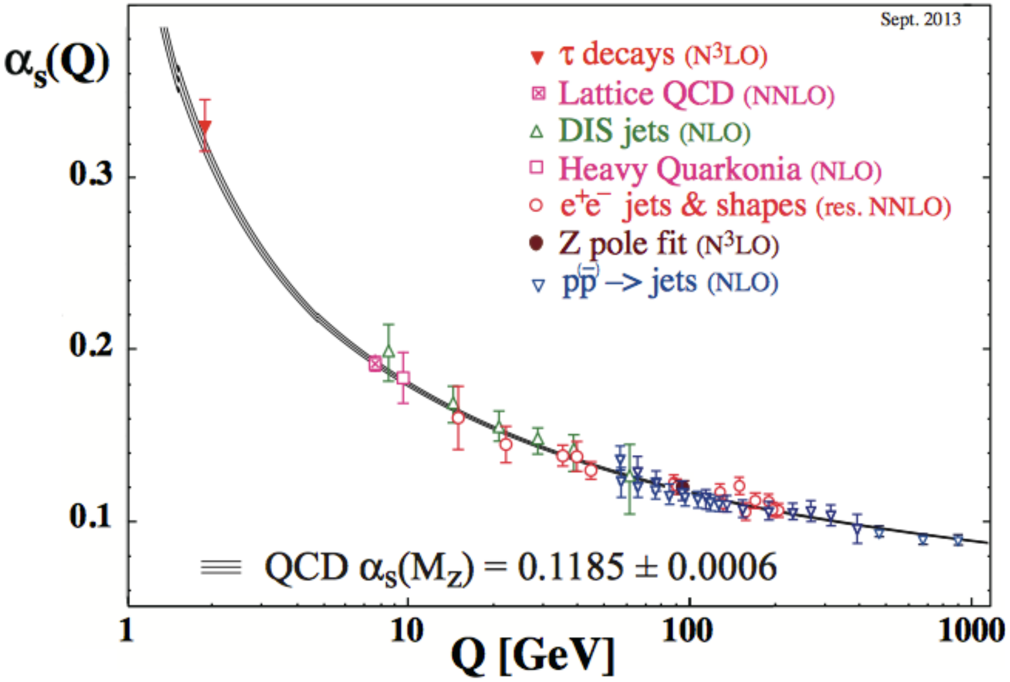
$$R_\tau^{kl}(s_0) \equiv \int_0^{s_0} \mathrm{d}s \left(1 - \frac{s}{s_0}\right)^k \left(\frac{s}{m_\tau^2}\right)^l \frac{\mathrm{d}R_\tau}{\mathrm{d}s} .$$

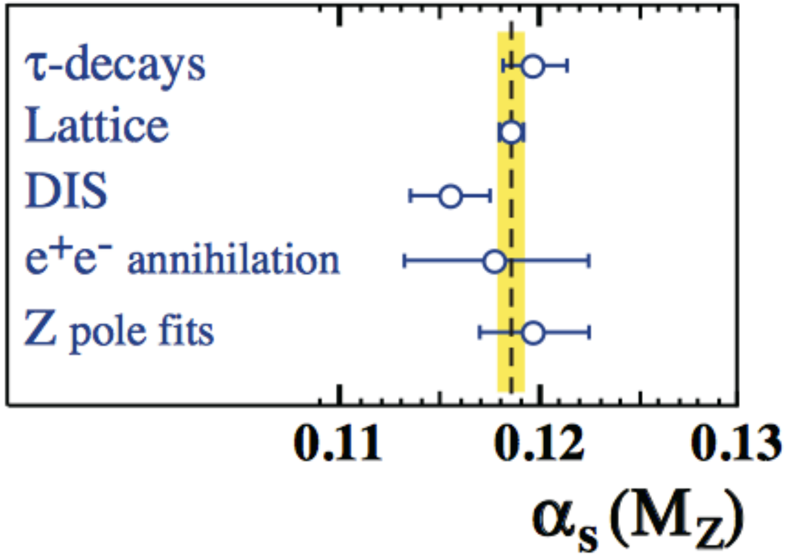
With this additional information, it was possible to extract α_s and the non-perturbative terms (and show that they are small)

It was a pleasure to hear discussion at our weekly meetings on this physics, actually the ALEPH publication of results was preceded by a theory article of one of the ALEPH physicist (F. LeDiberder) and a theorist (A.Pich) to specify the formalism . Than we published our data followed after by Opal and then Delphi.

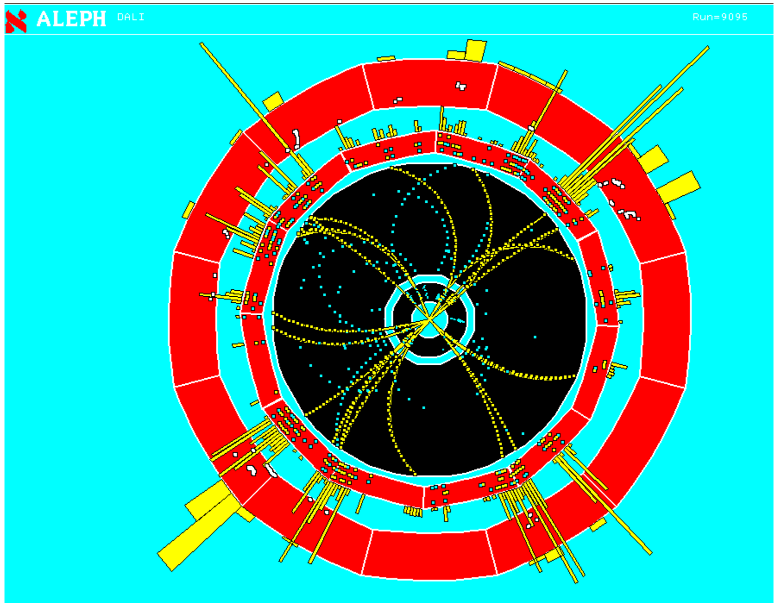
QCD (tau results-III)

I think these results were an remarkable support for QCD.
I show below (left) the present PDG values of α_s but already in 1992 it showed in the most accurate way the running of α_s from the τ mass to the Z mass.
Actually once evolved to the Z mass the input from the τ mass gives a more accurate value as shown below (right)





QCD(4-jets events , interest)



4-jet events were observed in LEP experiments: while 3 jets are “obvious”, 4-jets are somewhat less “obvious to the eye” but can be cleanly selected (6% of events).

While 3 jet events are produced by a gluon bremsshtrahlung, 4 jet events can have different causes:

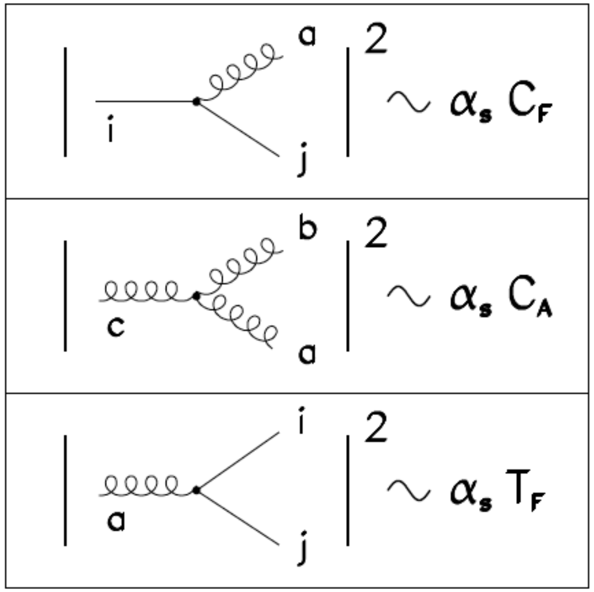
1) 2 gluon emission from quarks which can be calculated since 3 jets are “known”
2) A gluon splitting to a qqbar pair
3) A gluon splitting to two gluons this is something linked to the non-abelian nature of QCD and has no equivalent in QED contrary to 1 and 2 and hence the interest.

The different couplings are given to the right and the C,T are called the colour factors. They would be different in various strong interaction theory.

QCD predicts $C_A = N_C = 3$

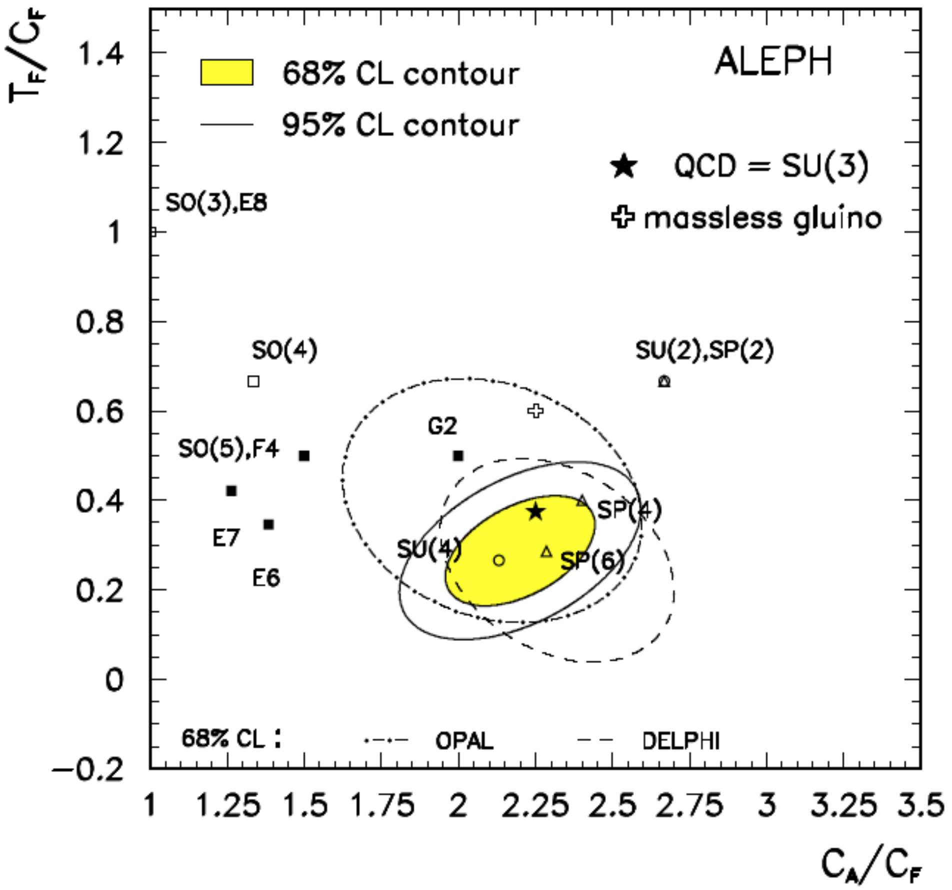
$C_F = (N_C^2 - 1)/2N_C \quad = 4/3$

$T_F = 1/2$



QCD(4-jets events , Results)

ALEPH energy flow was used for the jets, the separation among the different topology is based on jet angle differences. When I heard of the idea, in 91, from one of our QCD experts I was enthusiastic, I still think it is beautiful! First results were published in 92 (I think ALEPH was first). On the right is shown the 1997 publication based on the 5millions ALEPH Z
Z.PHYS C76 (1997) 1.
As shown on the figure results agree with QCD
CA/CF=2.2±0.09±0.13 QCD=9/4
TF/CF=0.29±0.05±0.06 QCD=3/8
ALEPH and OPAL published an update in 2001 with slightly more accurate results.



Conclusions on ALEPH

It is clear that in a lecture I could only give a few examples of all analyses in ALEPH at LEPI, There were a large number of analyses on searches for new particles … as you know none were found but interesting limits given. I did not mention either the B spectroscopy which was also the subject of many analyses and papers.

For me, but I believe also for most members, ALEPH was a wonderful experience this was in an important way shaped by the good team spirit dating from the origin. It is not my field of expertise but most Aleph members insisted on the quality of the software system, certainly it was quite easy to use (even for me in some cases!) This certainly helped also the cohesion.

Well even good things have an end… for me it came before the physics of LEPII since I was asked to become Director of LAL from 1994-1998 and then I was nominated to the CERN Scientific Policy Committee from 1994 to 1999 but I was elected chairman for 1996-97-98 and this + LAL directorship made it impossible for me to remain active in ALEPH… with sadness!

Photos of a good moment

At the end of my 3 year of ALEPH spokesman, I was succeeded by Lorenzo Foa… and there was a party… with some occasions for discussions, drink… and laughter!

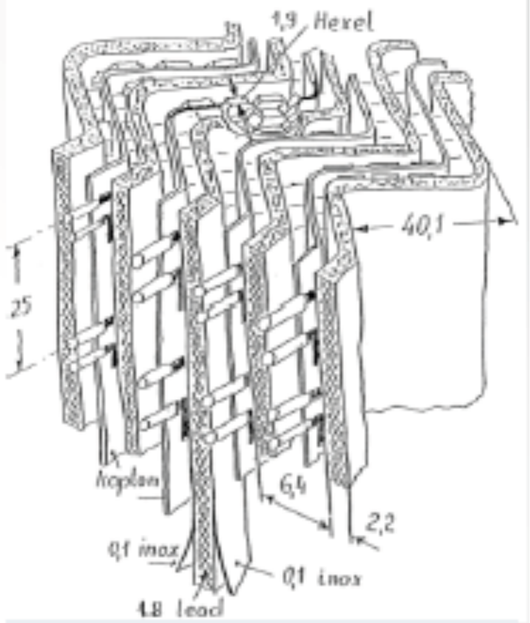
Reserve: accordion

Why small granularity Liquid Argon ECAL became possible at LHC: the accordion idea

Invented January 1990 by Daniel Fournier LAL-Orsay => used for Atlas

Accordion EM Calorimeter

- Fast shaping can reduce pileup effects, but requires low inductance from detector to preamps.
- Accordion geometry reduces interconnects, and allows this fast rise time even for high granularity.
- Hermetic coverage in ϕ with minimum modulation in response



RD3, CERN/DRDC/90-31

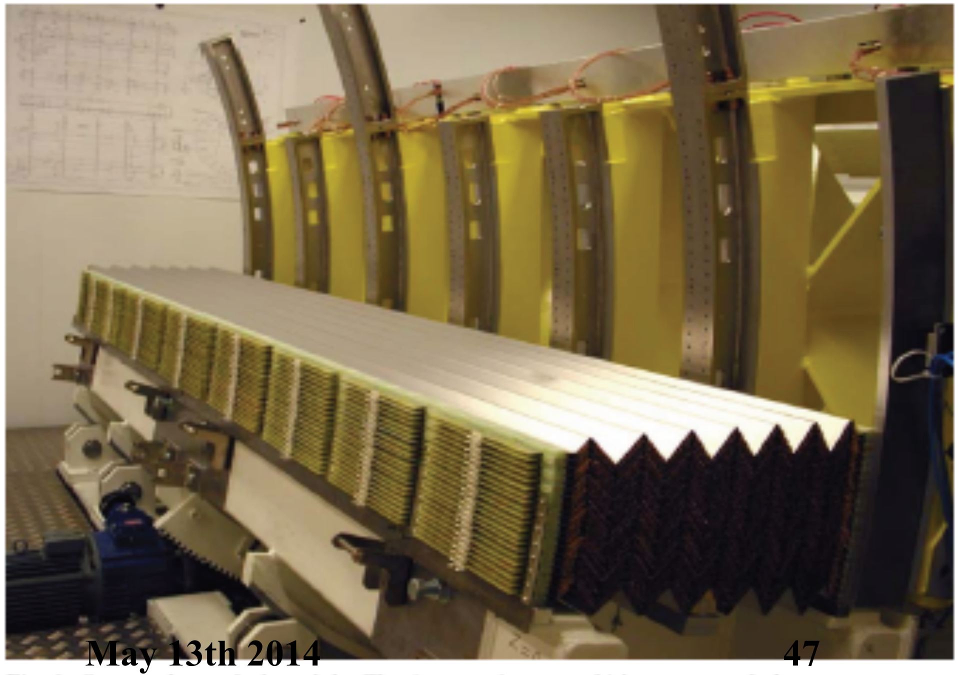
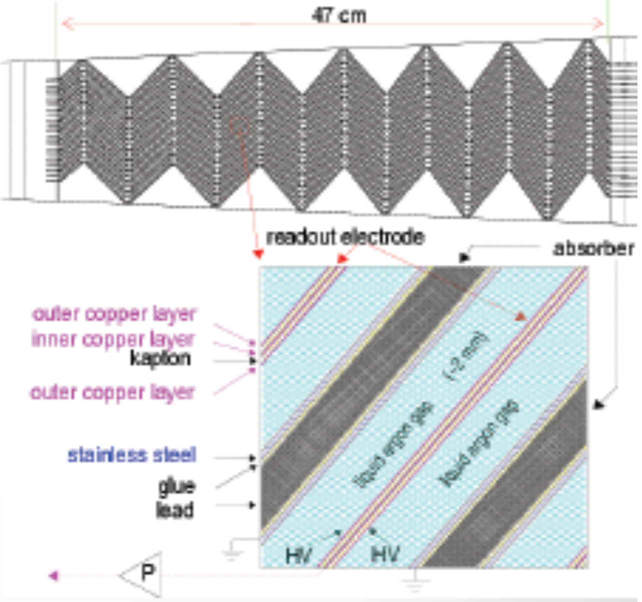
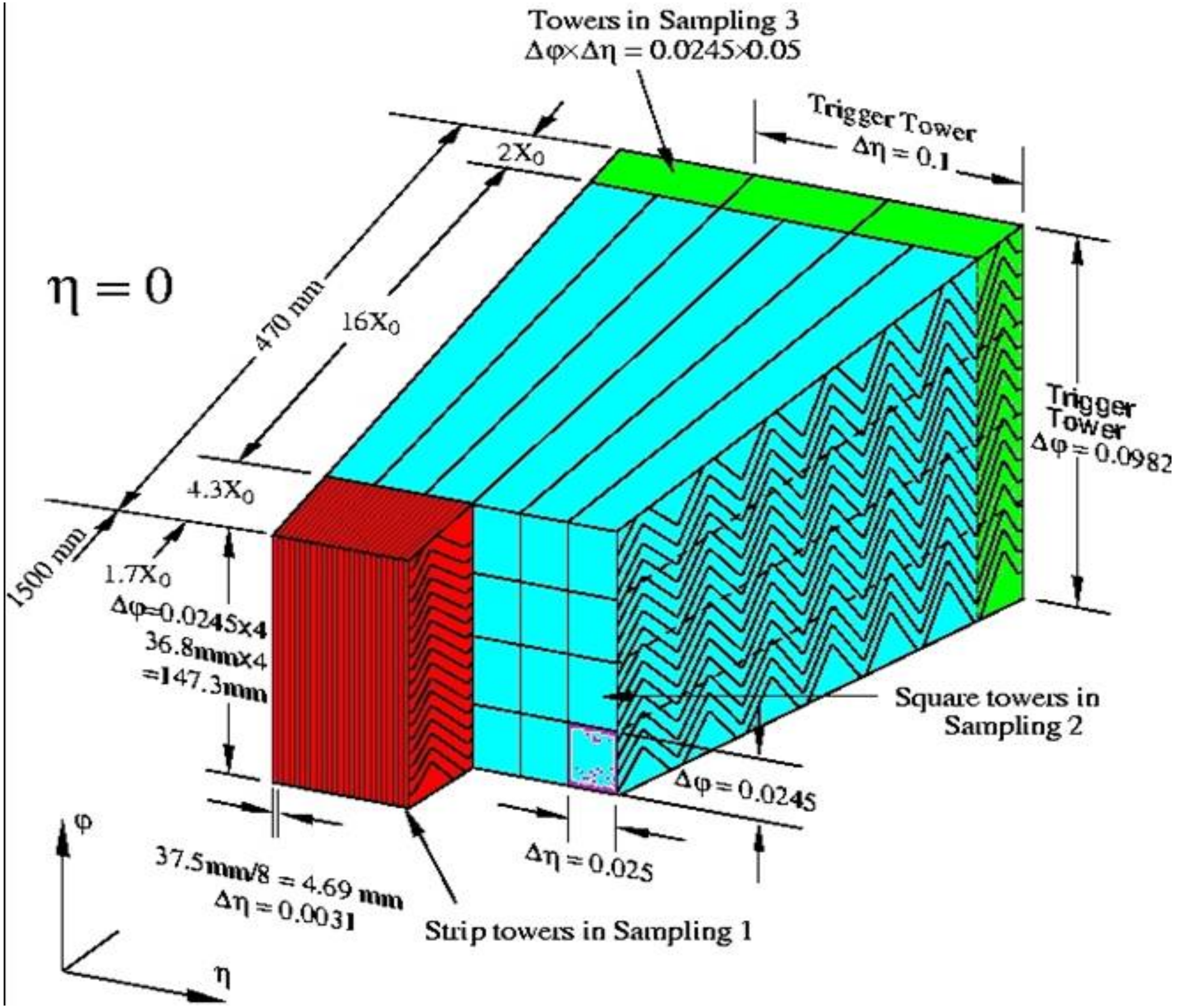


Fig. 2. One partly stacked module. The 6 outer rings on which are screwed the absorbers can be seen. Also the backbone (yellow part) and the assembling bench



ATLAS EM Barrel


Towers in Sampling 3
$\Delta\varphi\times\Delta\eta = 0.0245\times0.05$
Trigger Tower
$\Delta\eta = 0.1$
$2X_0$
$\eta = 0$
470 mm
$16X_0$
Trigger Tower
$\Delta\varphi = 0.0982$
$4.3X_0$
1500 mm
$1.7X_0$
$\Delta\varphi$=0.0245x4
36.8mmx4
=147.3mm
Square towers in Sampling 2
$\Delta\varphi = 0.0245$
φ
$\Delta\eta = 0.025$
37.5mm/8 = 4.69 mm
$\Delta\eta = 0.0031$
Strip towers in Sampling 1
η

Reserve : Sharing of construction in ECAL Barrel

- In 1983 after the decision of building an ECAL with small towers we had to share ECAL Barrel construction responsibilities.
- This is somewhat similar to what Jack had to do for the main parts of ALEPH, with the same constraints:
  - Leave some autonomy responsibility and “pleasure” to physicist responsible for parts
  - But maintain consistency between various parts and consistency with overall goal
  - Mobilise resources in different labs (5labs) for a work intensive project
- Marseille and Clermont where at this time smaller labs
  - Marseille takes responsibility for gas system (Xenon CO2) circulation, pumping, monitoring small chambers => gas gain consistency
  - Clermont takes responsibility for HV boards (540) , transform fuse idea from just an idea to a practical system (about 100,000 fuses) electronic responsibility of wire amplifier, HV supplies etc…
  - LAL-Orsay, Saclay, Ecole Polytechnique were very close sites => integrated jobs for module construction

Reserve : Sharing of construction in ECAL Barrel(II)

Module construction

Alu extrusion plane construction: LAL + glue HV board from Clermont

Move to Saclay => solder of 25µ wires then moved to LAL Orsay

Graphited cathode + pads made at Ecole polytechnique => moved to Orsay

Orsay measurement of lead layer thickness

Piling up 45 layers lead +MWPC in Orsay

Cabling of half modules in Orsay half in Saclay => cosmic test in Saclay

Overall mechanical design (preformed thin front plate+ thick back plate) Orsay

Insertion tool to put 12 modules inside magnet : Saclay

Electronics

Front end amplifiers LAL Orsay

ADC card Saclay

Data Acquisition Modules reading ADC card to computer : Ecole polytechnique