A Few experiments in particle physics
or
“ the adventures of a particle physicist 1959-2015”

When Dr Yuanning Gao proposed to me to come and give these lectures I was very pleased but also worried.

How can an audience in large part young, and therefore knowing of a world with P.C.’s and smartphone take pleasure in hearing of experiments which at the beginning had no computers! And no wire chambers!

Then I tried to reassure myself thinking that western film with horses, and saber-fighting chinese films are still appreciated!

Well I cannot pretend to have the charisma of John Wayne or of Chow-Yun Fat (周潤發) ? But films from previous time are interesting when we can find something common in them

Things common in past and present particle Physics

- The pleasure we can have in working and <u>understanding</u> together in a team (from 3 to hundreds!)
- The importance of a good apparatus
  - It has to be state of the art (I have to my shame a counter example!)
  - But it should not be “too much in advance” the criteria is to do good physics not to be “beautiful” it should be as simple as possible.
  - It should be affordable!
  - The accelerator is somehow part of the apparatus, it is part of things to understand. I will give a few examples.
- The pleasure of contributing to “put things in order” => needs to do complete ensemble of experiments… I encounter this in my thesis but other examples are parametrising with CKM observables; or in LEP electroweak physics parametrising with 3 possible deviations from S.M ($\varepsilon_1,\varepsilon_2,\varepsilon_3$).

Plan of 4 days

1)Prehistory 1959-1972

pn polarised scattering at Harvard 150 MeV cyclotron

Recoil proton polarisation in e-p scattering at LAL Orsay

ρ, ω, φ physics at ACO Orsay 550 +550 MeV e^+e^- storage ring

2) Moving to CERN PS and SPS 1973-1982

Very brief story of hyperon beam at PS (streamer chamber an error!)

NA3 Drell Yan physics at SPS, the K factor.=> beauty of Standard model

3) ALEPH at LEP 1982-1996-7

Choice of apparatus, criteria, impact

Some of the beautiful physics Electro-weak, QCD, Beauty, Searches

4) LHCb 1998-now

Some history and choices (input from Tatsuya before I arrived)

Apparatus optimisation =>" LHCb light"

Example of problems at commissioning time

A study of B=>K*ee

1959 PHd at Harvard

Started experiment with Dick Wilson thesis advisor + Ed Thorndike (post doc ,future CLEO spokesman!) “R parameter for proton-neutron scattering at 140 MeV” + A parameter thesis of R.A. Hoffman

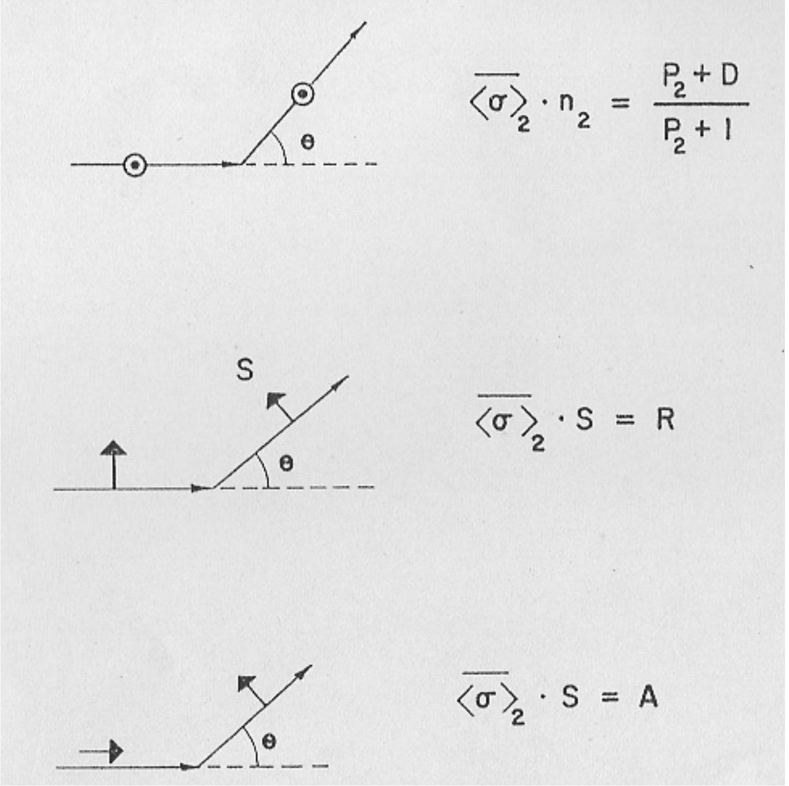
I was sure p-p p-n scattering was very fundamental physics (at 140 MeV, how naïve! But 1959!)

Wilson’s idea to do a complete program: xsection, polarisation, change of polarisation vector in collision Depolarisation D Rotation R, A longitudinal to transverse. If interested consult Wolfenstein (Ann.Rev.Nucl.Part.Sci. 6 (1956) 43-76) Same Wolfenstein as CKM parametrisation !

If one does enough measurement (9?) the full scattering matrix is know: the program is complete. Phase-shift analysis helps 9=>5 measurements are enough

Scattering on carbon polarises the proton beam (vertical spin if scattering horizontal) , then eventually rotate spin with solenoid or magnet, then scatter on H_2 or D_2 then scatter on carbon to measure polarisation. (amount of spin alignment, and direction)

3 observables studied at the Harvard cyclotron



D =Depolarisation: incident proton spin perpendicular to scattering plane

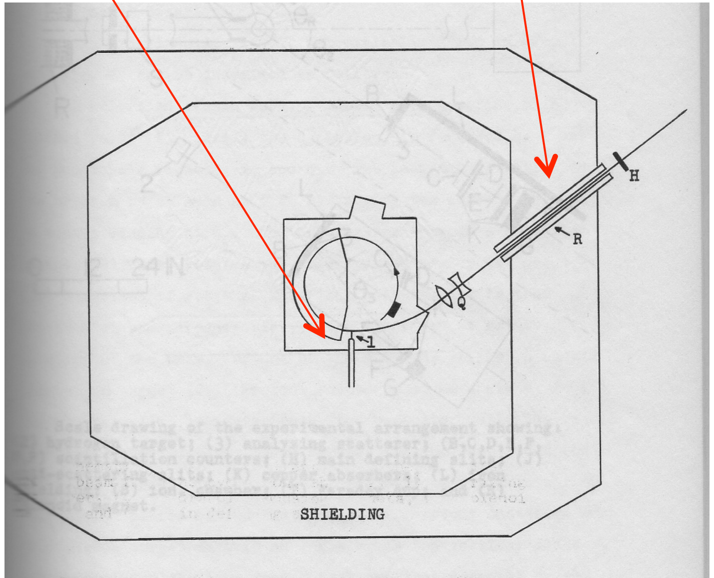
R=Rotation: incident proton spin in scattering plane (obtained by solenoid) (on Deuterium my thesis)

A => incident proton spin longitudinal (thesis of Dick Hoffman =colleague)

Synchrocyclotron +Apparatus

Carbon target
extracts
polarised beam

solenoid

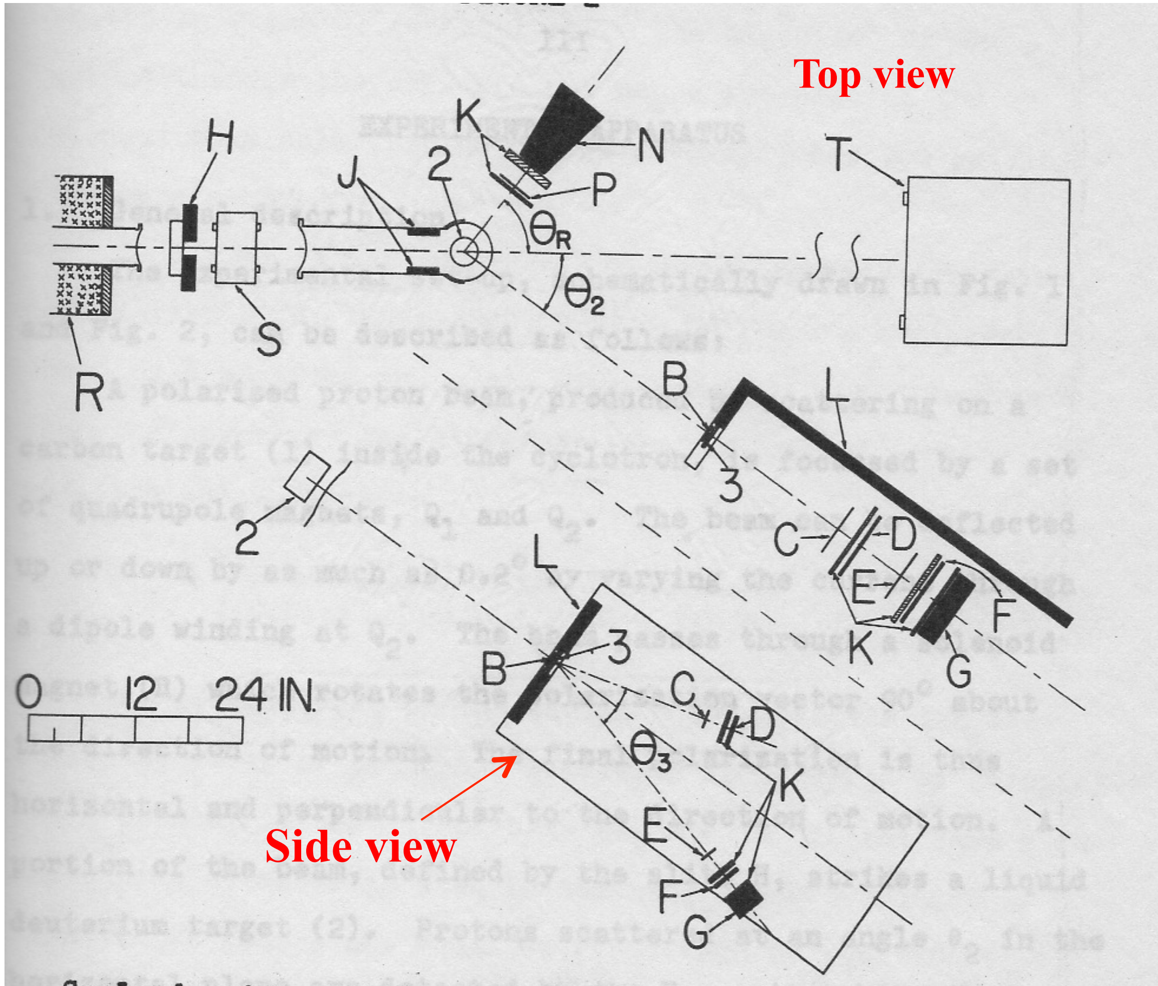


Schematic drawing of extraction of the polarized proton beam from the cyclotron, showing: (1) polarizing scatterer, (Q) quadrapole focusing magnets, (R) solenoid magnet, and (H) main defining slits.

N,P recoil neutron, proton counter .
Vertical scattering on carbon target B measures R.

Top view

Side view



Scale drawing of the experimental arrangement showing:
) hydrogen target; (3) analyzing scatterer; (B,C,D,E,F,
P) scintillation counters; (H) main defining slits; (J)
ti-scattering slits; (K) copper absorbers; (L) iron
ielding; (S) ion. chamber; (T) Faraday cup; and (R)
lenoid magnet.

Measurement and challenges

Measurement on liquid Hydrogen target done by Ed Thorndike (I collaborated during his last 6 months) The "scattering table" was developed then.

Then scattering on deuterium

Proton recoil detected => should be same result as H2 target

No proton recoil but neutron recoil detected => measurement of p-n scattering

So development of neutron counter (scattering of neutron in big block of scintillator)

But big background in neutron counter => random coincidence between "scattering table" counters and neutron counter

Thesis put in danger ☹ Three reasons for large random (false) coincidence rate

- Large background -> hard to fight, use some shielding
- Rather large coincidence time (20ns) in "radio-tube" coincidence circuits (I decided to build first fast transistor electronics at Harvard cyclotron lab => <10 ns
- Bad duty cycle of Synchrocyclotron => occasion of a nice development ☺

Digression on Cyclotron and Synchrocyclotron

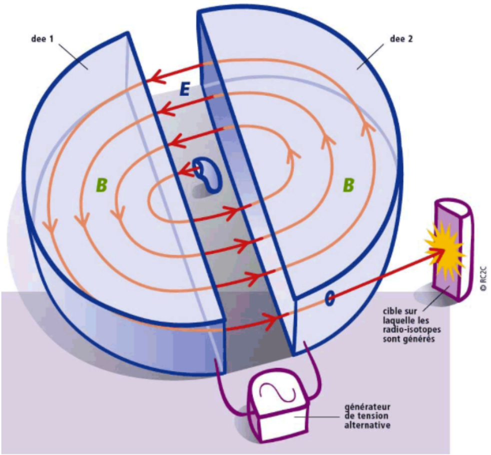
(sorry for the audience who knows all that!)

Cyclotron invented by Lawrence in 1931 : based on fact that the rotating frequency of proton (alpha etc…) is constant (at low energy, <10MeV for protons) $f=eB/M$ => give ≈ small ΔE each turn

But because of γ factor M increase as energy increase => synchronous frequency decreases => cyclotron stops working

Could change B with R => unstable trajectory => except for modern cyclotron FFAG

Macmillan and Veskler in 1946 invented Synchrocyclotron => change frequency: inject at high frequency and decrease frequency as energy is increasing



How to change frequency? Simplest if one has an oscillator with a resonant LC circuit is to change C called rotating condenser.

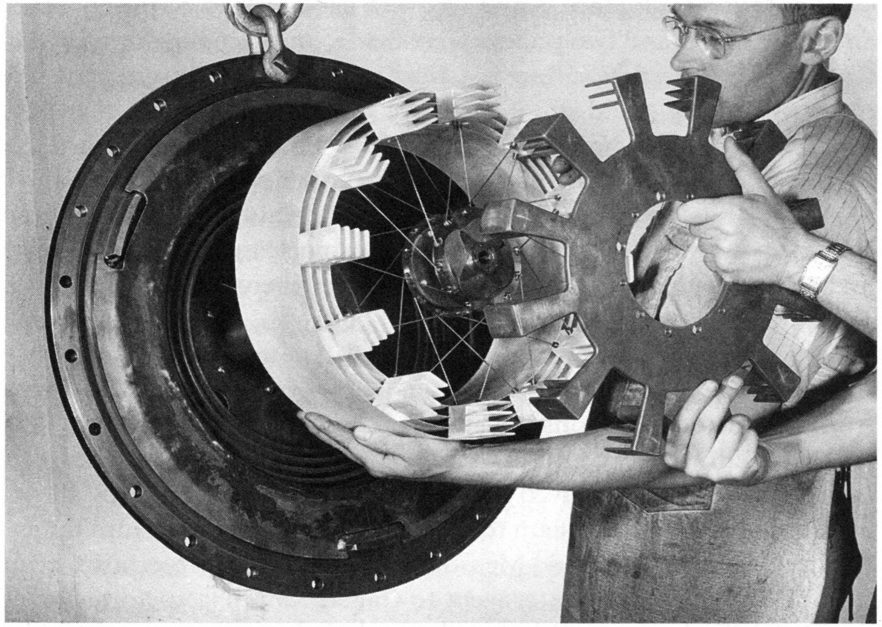
The teeth of the condenser!

To modify f modify C

Use a fix part (stator) and and a rotating part (rotor), about 25 rotation/s :Capacity is bigger when the teeth of rotor are in front of teeth of stator

A slow servo can engage (disengage) teeth deeper or less deep, moving the whole frequency curve down or up.

The beam is extracted during the frequency interval Δf corresponding to ΔE: the energy band where protons hit internal target



Rotating condenser with teeth (before Jacques LeFrançois made his modification to the shape of those teeth).

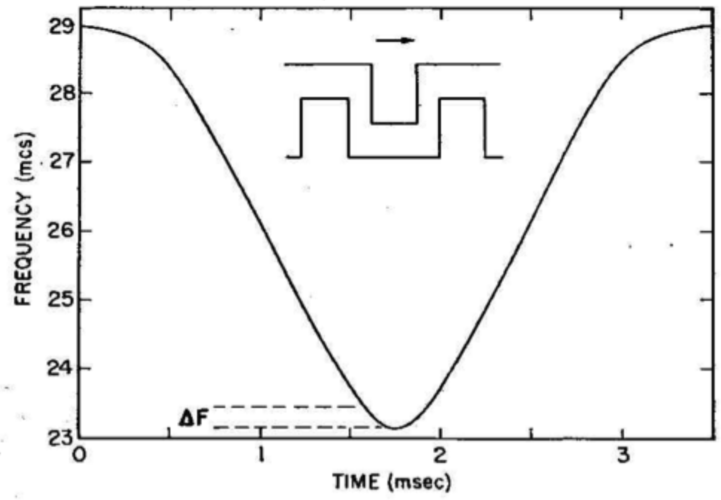


FIG. 1. Frequency curve and tooth shape for original rotating condenser.

Filing the teeth!

I thought : why not modify the shape of the teeth? Spare condenser exist! Andy Koehler head of machine agrees => beautiful result: gain factor> 6 in beam extraction time. Never tried before! Subtlety : the servo “engage-disengage” needed a feed back (which I built) to locate accurately the slow part of the curve at the right f.

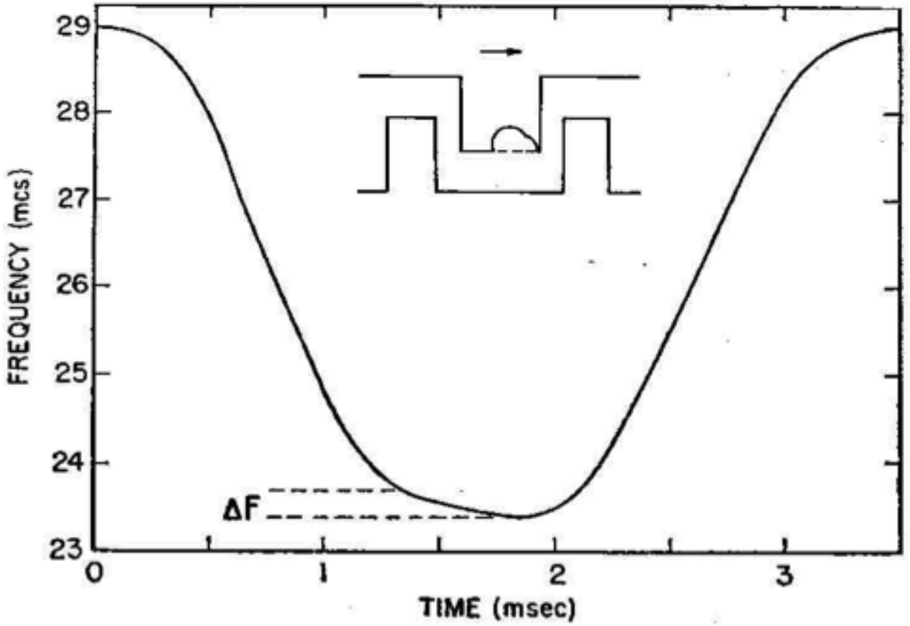


FIG. 2. Frequency curve and tooth shape for redesigned rotating condenser.

Whole project done in about 2-3 months

OK can take data and do thesis

Curve of extraction

Before and after the rotating condenser change

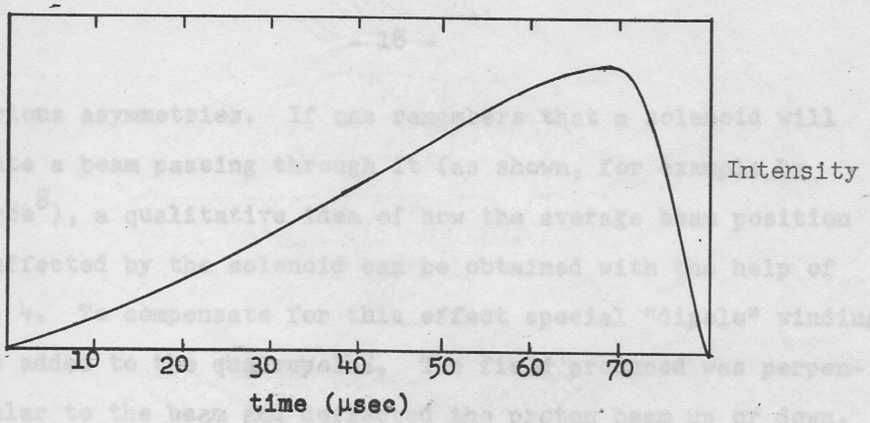


FIGURE 3a

With original rotating condenser

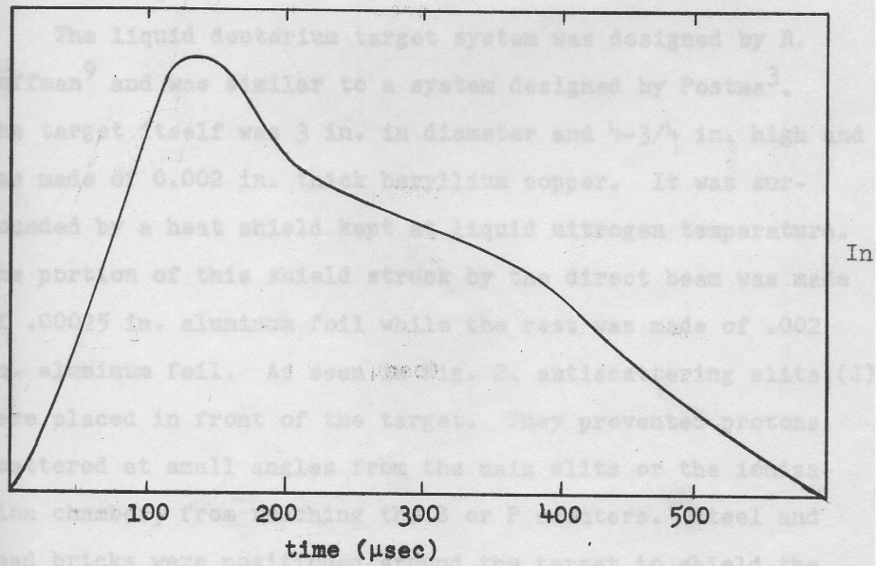
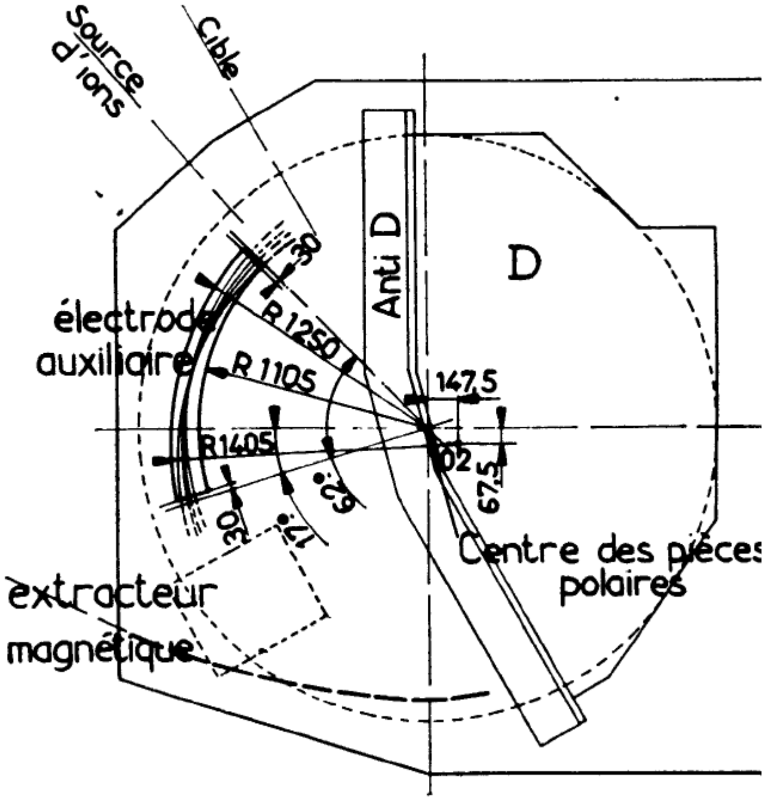


FIGURE 3b

With modified rotating condenser

IPN ORSAY synchrocyclotron



— Synchrocyclotron d'Orsay. Plan de l

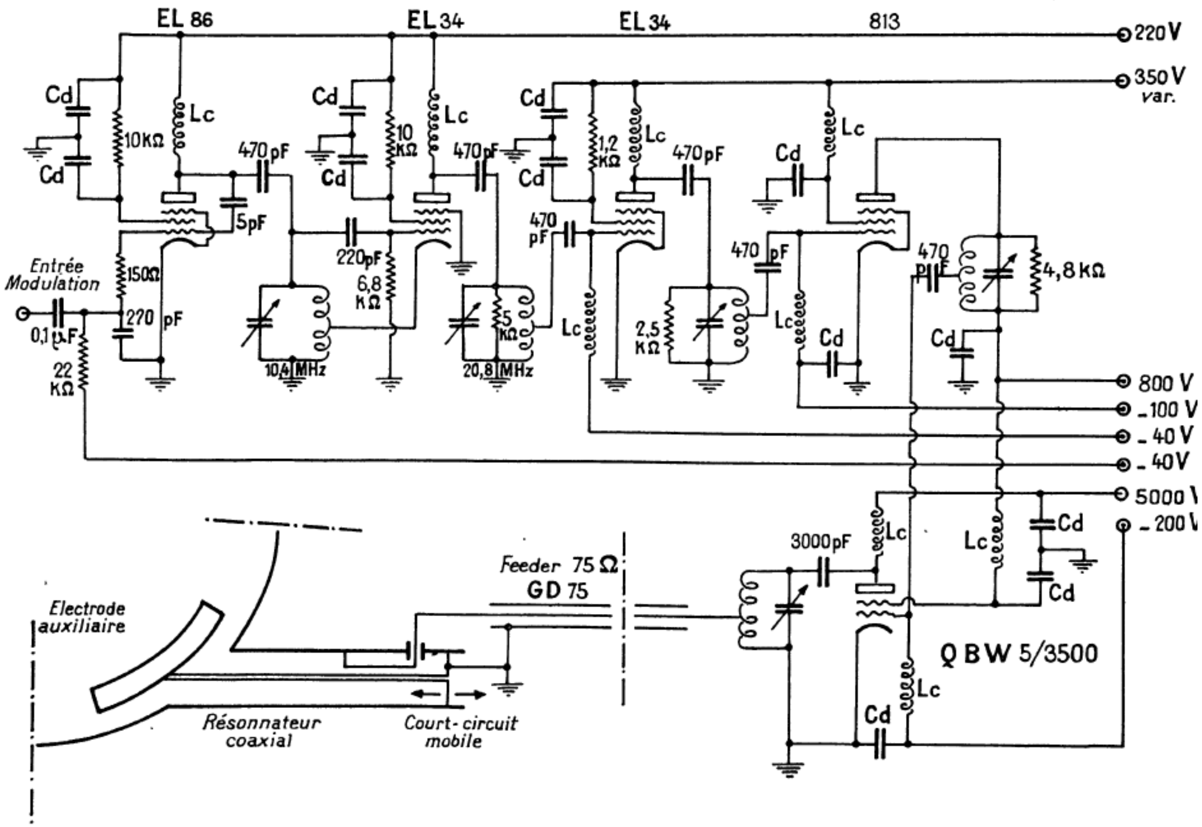
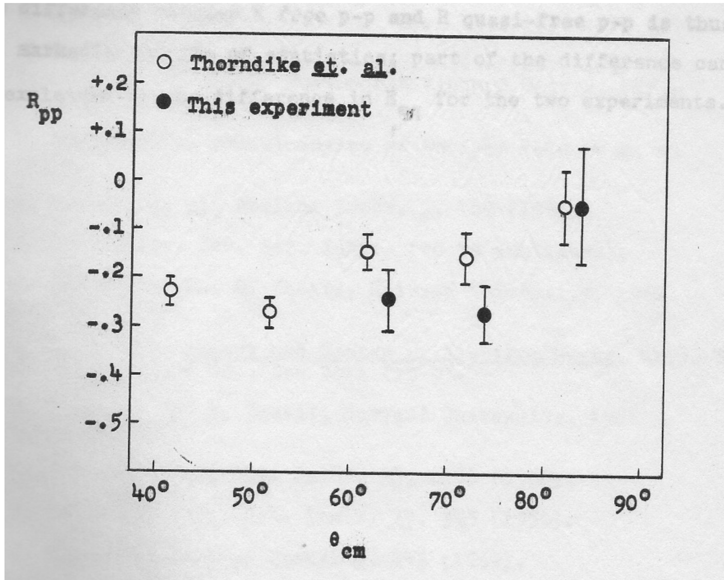


Fig. 6. — Générateur H. F. auxiliaire. Lc, self d'arrêt H. F. ; Cd, découplage, 1 000 à 2 000 pF.

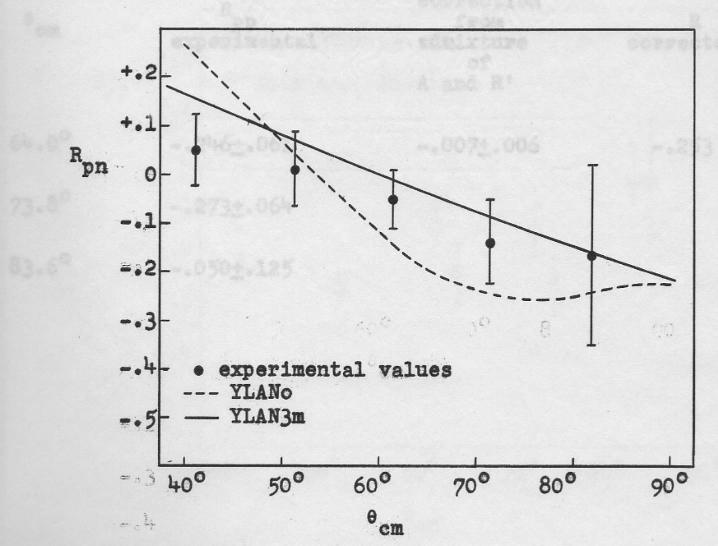
The increase of duty cycle was also obtained later on the Orsay IPN synchrocyclotron modifying the vacuum chamber, installing a new electrode with an independent high voltage frequency system: big project marginally better.

Data

Results **p-p** **p-n**



R for quasi-free p-p scattering vs. center of mass scattering angle θ_{cm}. Also shown are the values of R for free p-p scattering as measured by Thorndike et. al.[22] .



R for quasi-free proton-neutron scattering vs. center of mass scattering angle θ_{cm}. Shown also two predictions of Hull et al[15] YLANo and YLAN3m.

Ylan0, YLAN3m are 2 theorist phase-shift analysis results => favor Ylan3m

Conclusion from Harvard PhD

Pros and cons

Con: the physics was not “fundamental” Good to have theorist around close to expt program as at Columbia studying Parity Violation, Neutrino scattering with advice from C.N.Yang (Stony Brook) and T.D.Lee (Columbia)

Pro: I learned the importance and satisfaction, of working in a “complete program”

Pro: It was a pleasure to be free to invent electronics and modify the accelerator. Lesson learned : Do not always need complicated projects for improvements! Not as simple now for a PhD to ask to modify the accelerator (Think of the LHC! => but example of major impact from PostDoc will be given for LHCb)

Pro: A good thesis advisor recommends a good postdoc position!: Dick Wilson suggested me a job at LAL Orsay => still there after 54 years

Move to LAL Orsay 1961

L.A.L name is from Linear Accelerator Lab (in French it also works ;-)) In 1962 it was ready to accelerate electrons to 1 GeV (e- produce photon beam by Bremsstrahlung) the beam was 1µA average. Spill= 1µs/50Hz

Most experiments were on photoproduction of π^0 or η^0 on hydrogen target studying N* resonances D_{13} F_{15} etc…bread and butter at the time=> requested by theorist

Most experiments were on general purpose spectrometers, with a few counter at the focus to detect scattered electrons or recoil protons (not much fun!).

But there was one nice experiment (suggestion of J.Perez y Jorba, group leader group= 5 physicists)

: measurement of the polarisation of the recoil proton produced in 1 GeV e-p scattering => polarisation = my first love ☺

E-P scattering

Physics case: is there a contribution from 2-photon exchange in e-p scattering?

If only 1 photon exchange, the amplitude is real in Born approximation => P=0

Since P = interference between a real amplitude and an imaginary spin dependant one. (Can check in Wolfenstein's article)

But P can exist in 2-photon exchange since N* are excited => imaginary amplitude

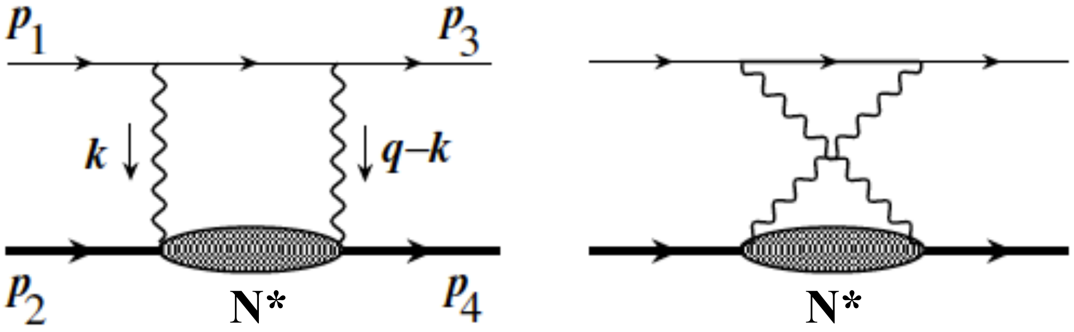


FIG. 1. Two-photon exchange box and crossed box diagrams.

Apparatus using spark chambers for first time in Orsay

Digression on Spark Chambers
The rise and fall of a beautiful idea(I)

Until 1960 the experiments in particle physics were done by two types of instruments (very often (almost always!) physicist specialised in one of the two)

There were Visual device experiments using first cloud chambers and then bubble chambers after its invention 1952.

- These were rather low rate experiments typically 1 picture per accelerator cycle (few seconds) and only a few tracks 10-20 per picture and therefore < 10-20 tracks/s
- Not very flexible: the liquid was the target and detector (there are exceptions! (H_2+Ne)…)
- But the information was extremely detailed. Wonderful success for SU3 resonances studies including the discovery of Ω baryon in 1964 , neutral current in neutrino interaction etc…

And “Counter experiments” , using scintillators of various shapes and numbers, read by PMT.

- They were flexible could count up to MHz of interaction, change geometry etc…
- could use PID with Cerenkov etc…
- but the number of counters was limited by the price of PMT and electronics (< 100’s of channels?) => the granularity was very bad

Spark Chambers (II)

Invented by 2 Japanese physicists in 1959=> spread like fire!

For those who have never seen or heard => simple description

- Assembly of 2 plates (later wires) +HV pulse ≈10KV/cm => gas of Helium-Neon => sparks at place of track ionisation => then photograph
- gap of about 5mm to 1.5cm (compromise granularity – low capacity (rise time)
- permanent clearing field about 100V => clearing time about 1μs => can tolerate high rate of incident particle 10^5/s +> should decide trigger to send HV pulse in < 1μs (adjustable with clearing field)
- Very inexpensive and very flexible apparatus.
- Maximum trigger rate is few Hz (dead time of metastable ions & speed of camera)

Caught very rapidly most counter physicist integrated them in apparatus

Made possible experiments otherwise impossible (neutrino, storage ring)

An early example : $\nu_\mu \neq \nu_e$ experiment 1961

Beautiful, very large apparatus 10 tons AL plates, detailed view of tracks

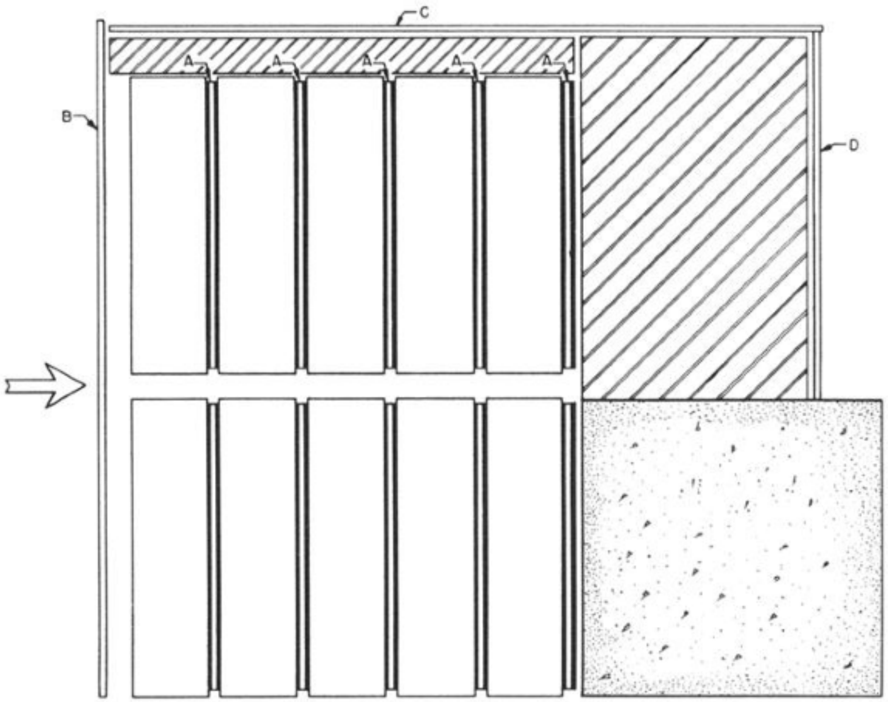
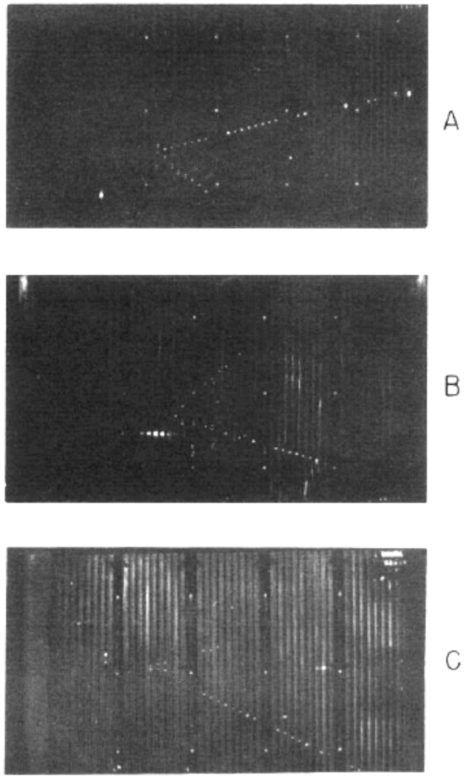
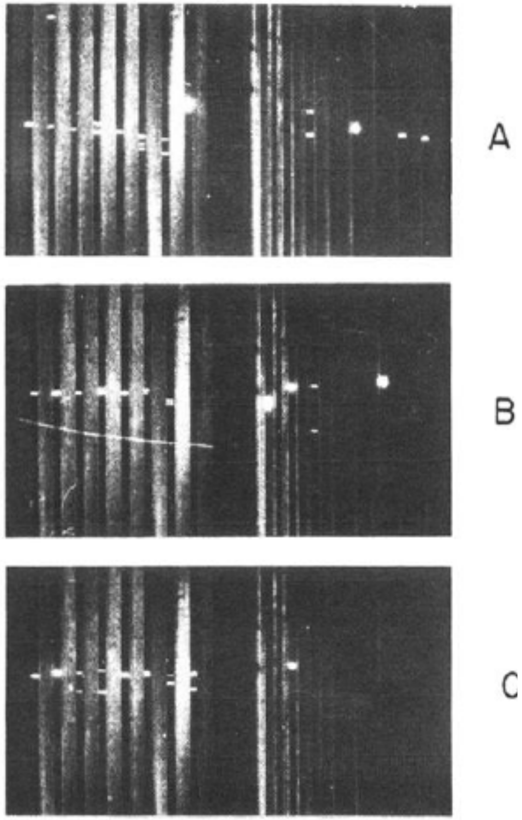


FIG. 3. Spark chamber and counter arrangement. *A* are the triggering slabs; *B*, *C*, and *D* are anticoincidence slabs. This is the front view seen by the four-camera stereo system.



6. Vertex events. (A) Single muon of $p_\mu > 500$
and electron-type track; (B) possible example o
two muons, both leave chamber; (C) four prong star
one long track of $p_\mu > 600$ MeV/c.



400-MeV electrons from the Cosm

The drawbacks and end of Spark Chambers

The rate of event was still quite limited (camera+ spark recovery)

The view could be very detailed but had to be examined by eye + measurement table (like bubble chambers) => army of scanners measurers (small army compared to bubble chambers)

In later year direct connection of data to computer (remember in 1970 DAQ computer had about 12 Kbytes of core memory =>special funding to buy 4K more!!!)

Spark chambers with wires => sonic readout or magnetostrictive readout => directly to computer

Streamer chambers => aborted sparks in gas (no plates, 3D pictures like bubble chambers => scanning and measuring)

But in 1968 G.Charpak invented the MWPC possible because cost of amplifiers was dropping => rapid end of spark chambers within 2-5 years

MWPC still with us! But so intoxicated with visual device we needed event display for many years!

Back to Orsay and e-p scattering

Recoil proton spectrometer, then carbon block. Tracks measured before (spch1, spch2) and after (spch3,spch4) scattering in carbon.

Position in spch1 selects elastic e-p scattering, range in brass plate of spch4 selects elastic scattering in carbon

Q^2= 0.64 GeV/c2 => recoil proton energy 300 MeV decrease to=>170MeV in carbon 20000 pictures scanned 10000 measured => P=0.038±0.038 (1963)

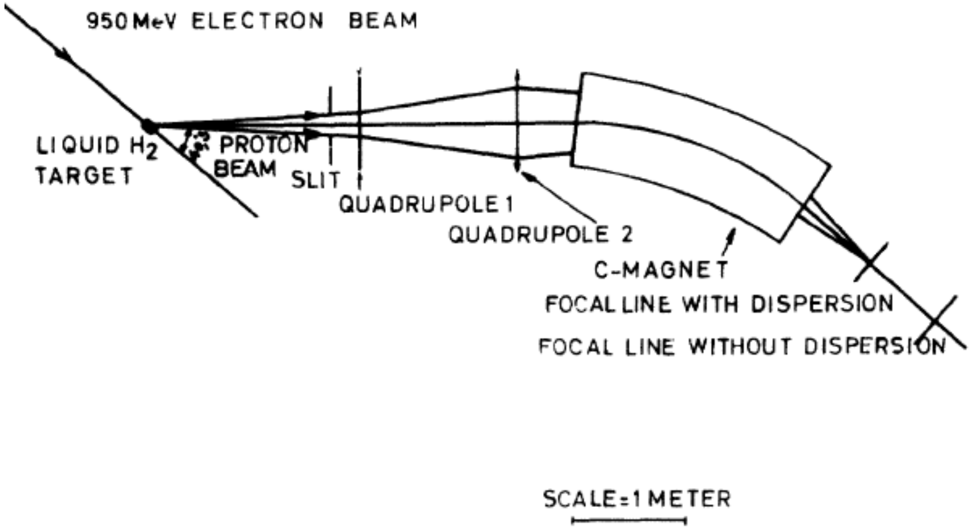


FIG. 1. Experimental setup: optics.

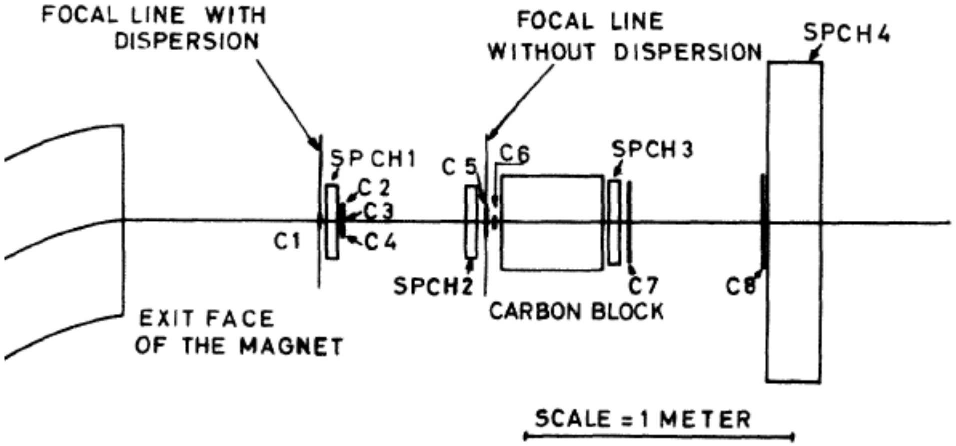


FIG. 2. Experimental setup: polarimeter. c = scin- lators, SPCH = spark chambers.

e+e- Storage rings in LAL ORSAY

The idea of storage ring originated with G. O'Neil (to my knowledge) who proposed an e-e- 300+300 MeV ring in 1956. This was built 1958-1962 at SLAC and measurements done in 1965.

Meanwhile Touschek in Italy (and independently Baier and Budker in Russia) thought in 1960 of a single ring e+e- collider, explaining it was easier, but, more important, that by annihilation one could create "vacuum excitation" with creation of muons and pions. Remember that the ρ meson was only discovered in 1961.

Frascati started to built the first e+e- machine ADA which was moved to Orsay, on the suggestion of P. Marin, since the linac was a better injector.

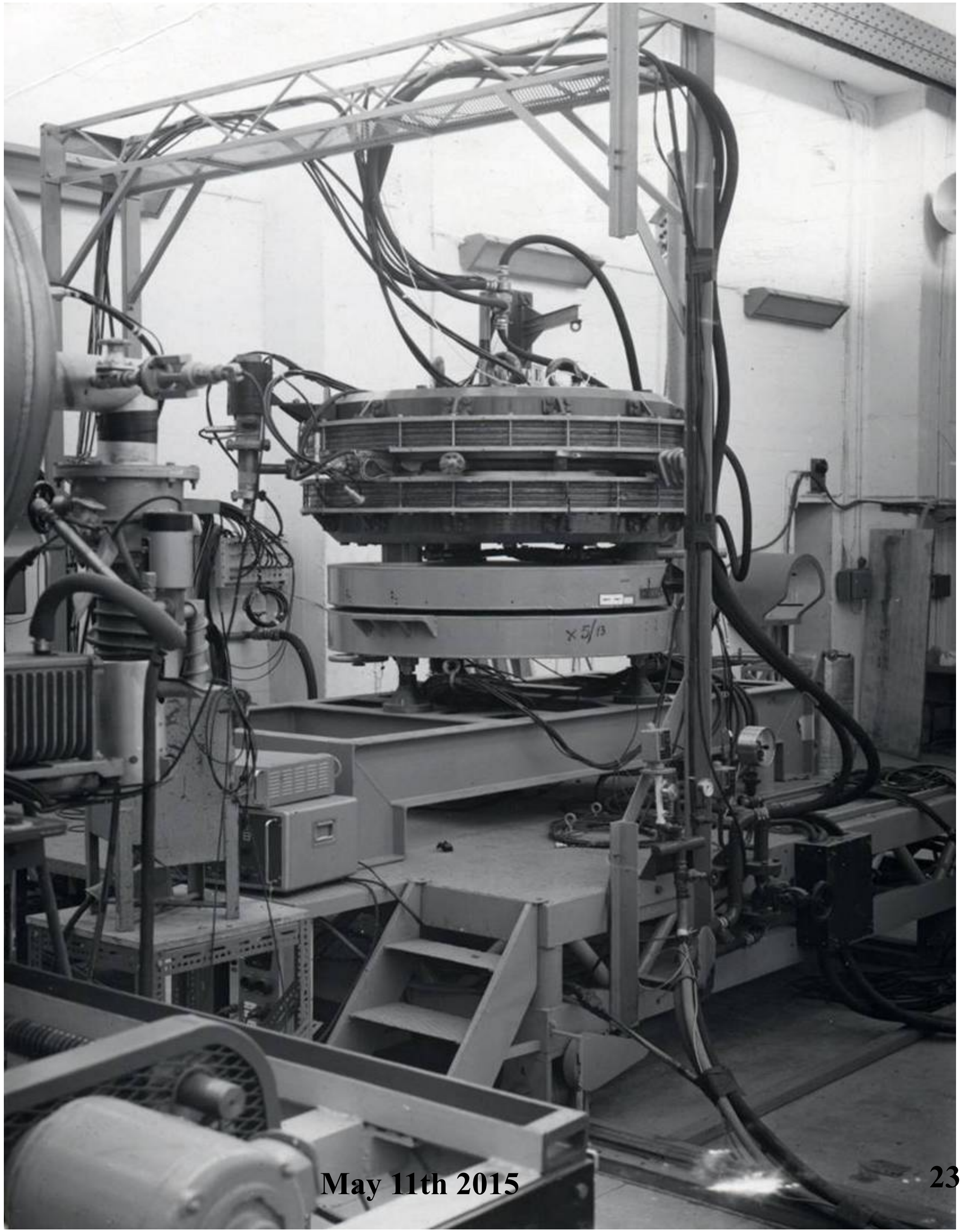
Test done in Orsay

Marin suggested and built the first "physics e+ e- collider" (together with VEEPII in Novissibirsk)

Started to take data in 1965

I only joined the program on the first detector in 1967 to do some ω studies

But in 1968 with small group of young physicist we proposed φ3C apparatus



At the beginning AdA*

1962-1965

First e^+e^- storage ring, designed and built in Frascati then moved to Orsay

First experimental evidence of e^+e^- collisions in a storage ring were observed here 50 years ago!

Very innovative and fruitful machine observing what is called the "Touschek effect " (*Large-angle Coulomb collisions in the electron or positron bunches)* and many other beam dynamics effects

Parameters:

Diameter: 1,2m

Energy: 205 MeV

Luminosity: 2.5 10^{25}cm^{-2}s^{-1}

Intensity: 0,242 mA

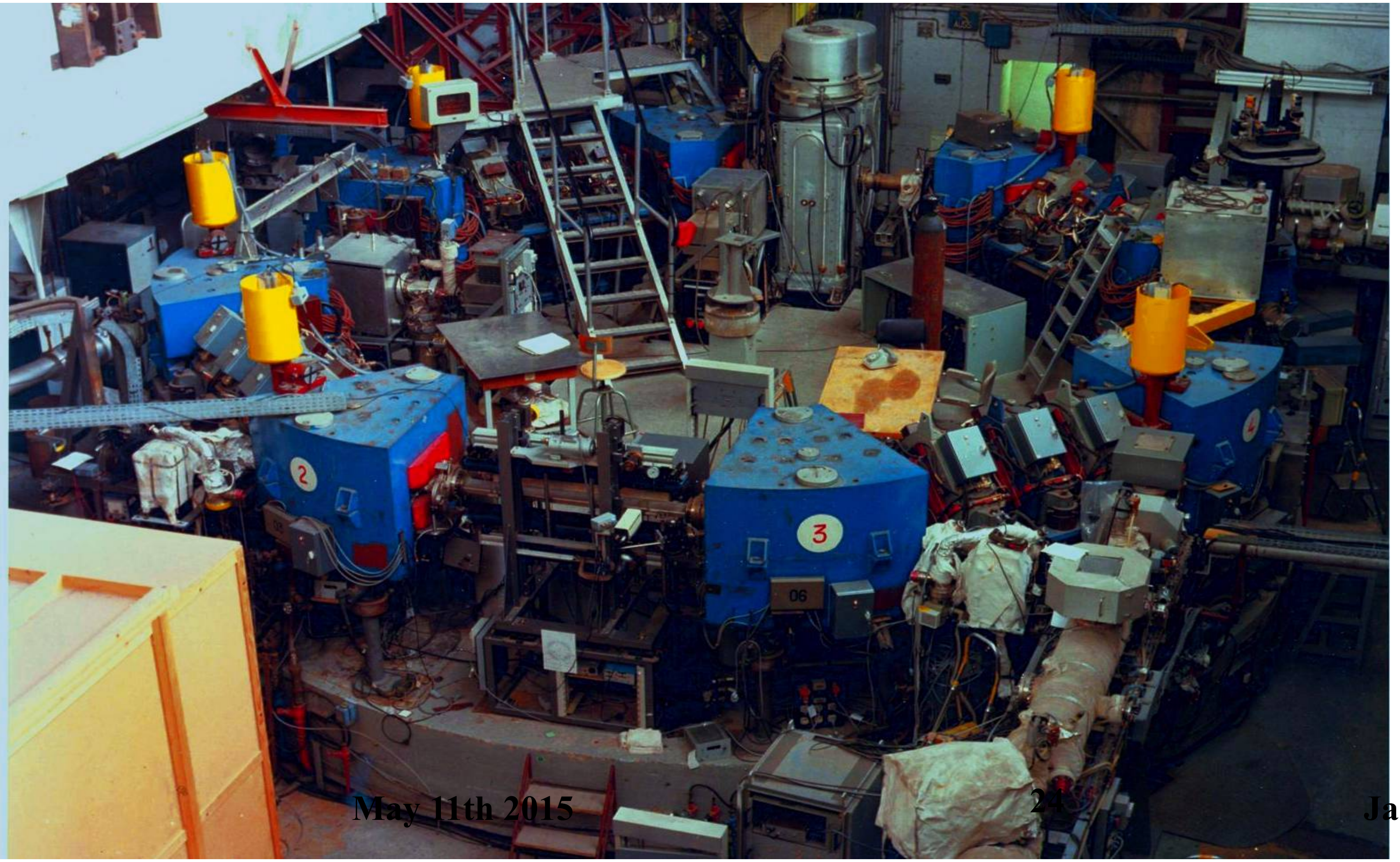
ACO for Hep (1962 to 1975)

First strong focusing e^+ e^- storage rings machine.

Lot of machine studies: Beam-Beam effect, Beam polarization, etc

6 experiments: ρ^0, K^+K^-, ϕ3C, μ+μ-, M2N, DMA and 18 thesis passed

Study of ρ,ω,φ resonances, vector dominance



Diameter: 16 meters

Energy: 2 x 540 Mev

Beam current : 12mA

Luminosity $3\text{x}10^{31}$/HOUR(!)

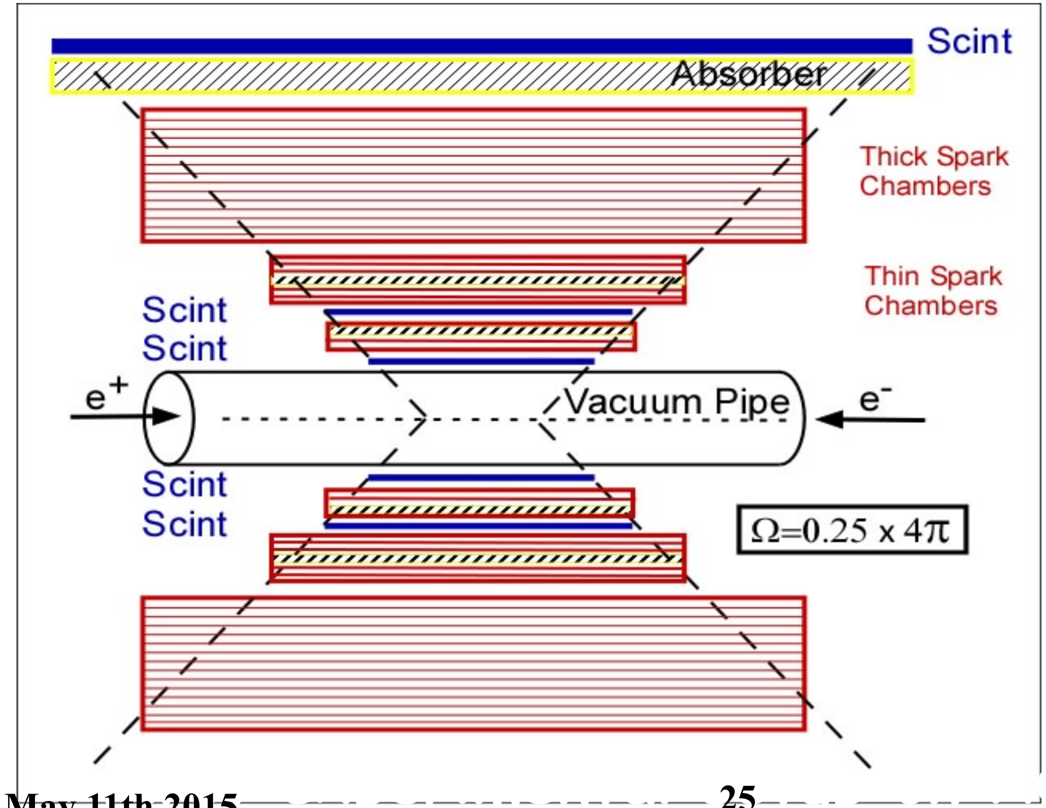
Initial Hardware on ACO

1962-1967, plane optical spark chambers were used.

Events triggered by scintillators were recorded on a film by a camera

The thick brass plate spark chamber was used to separate μ from π by range (typically 21cm vs 17cm) and electrons by shower (not very good in brass plate!)

Modest trigger rate (<<1 trigger/s).



φ3C Experiment

State of the art cylindrical spark chambers

Motivations:

Gain in angle coverage and compactness =>0.6X4π vs 0.25X4π before

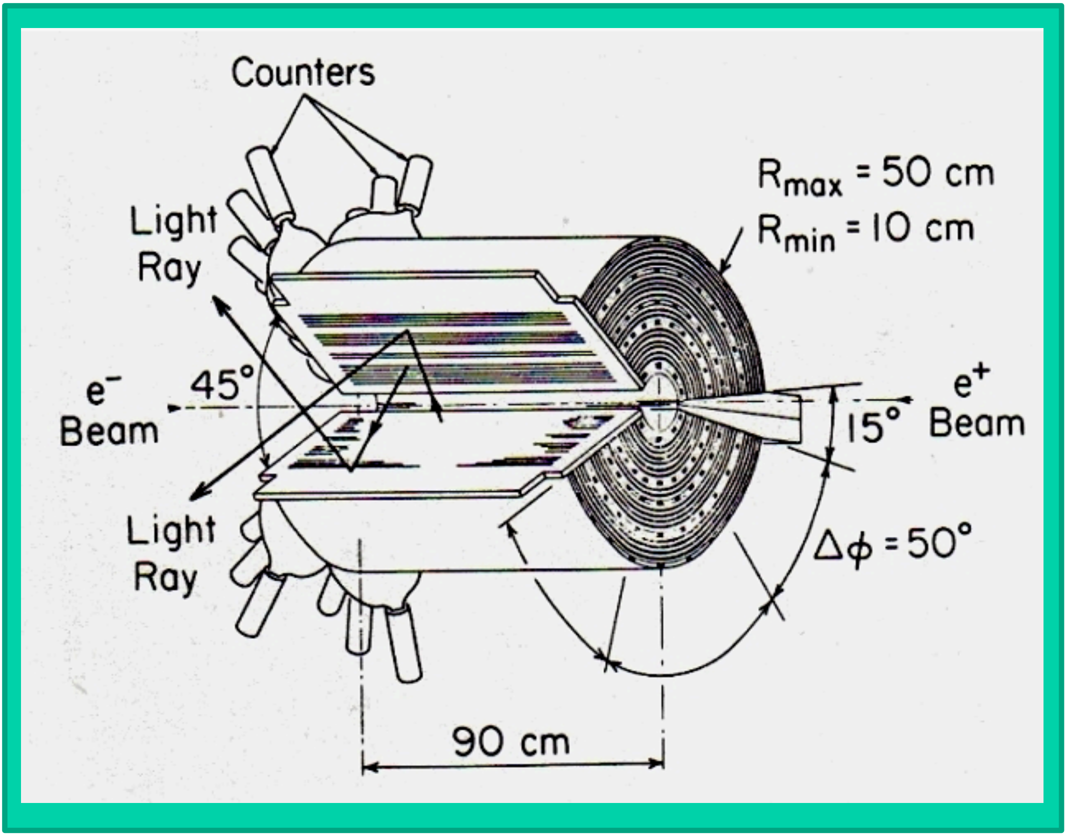
Better π/μ/e identification and γ shower sampling by using lead absorbers

Difficulties:

Need for good optical quality

Good multitrack efficiency

Very tricky mechanical design



- Solution:

Sandwich made of:

- Self supporting chambers with thin walls made of low density foam material glued on each side to a Mylar and an aluminum foil
- 11 lead Sheet curved 0.5 X/X^0
- 4 scintillators layers=> trigger on π or γ

φ3C Experiment

State of art cylindrical spark chambers

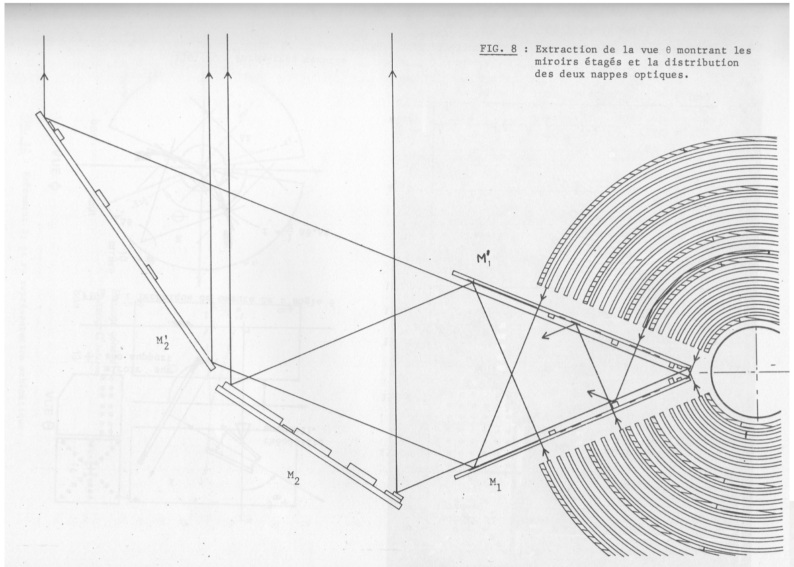
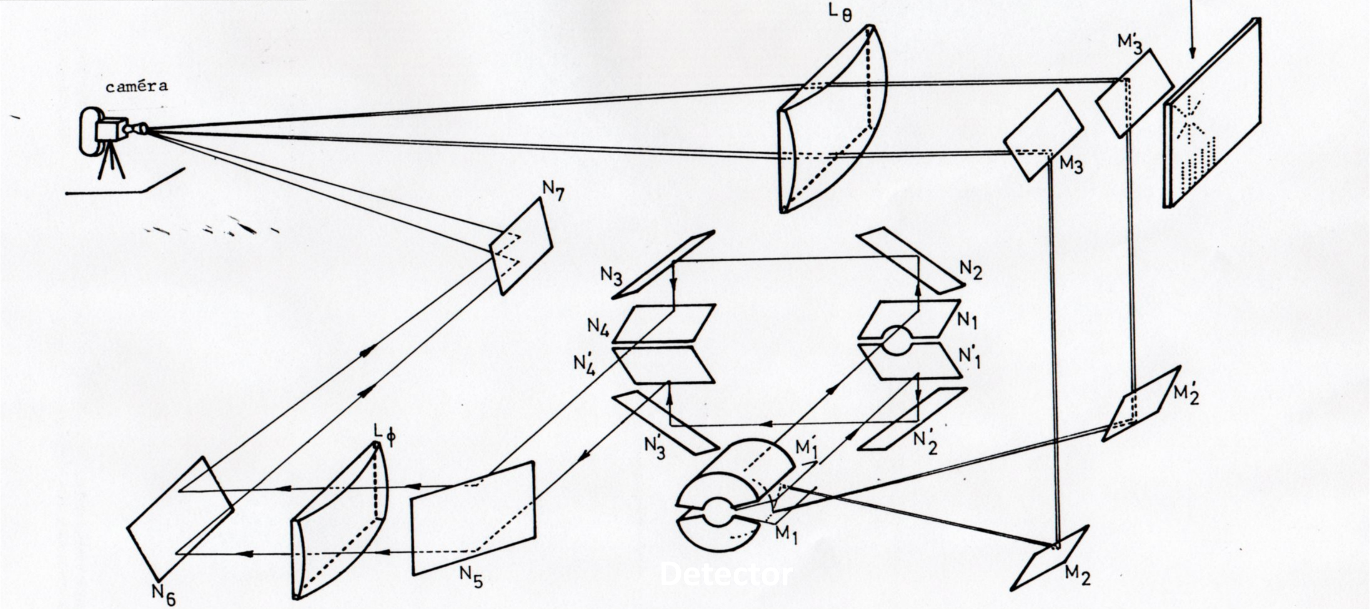


FIG. 8 : Extraction de la vue θ montrant les miroirs étagés et la distribution des deux nappes optiques.

To get the view in r-φ was not too hard but the r-z view needed staged mirror because of lack of space



Φ-3C apparatus

It was a pleasure to built:

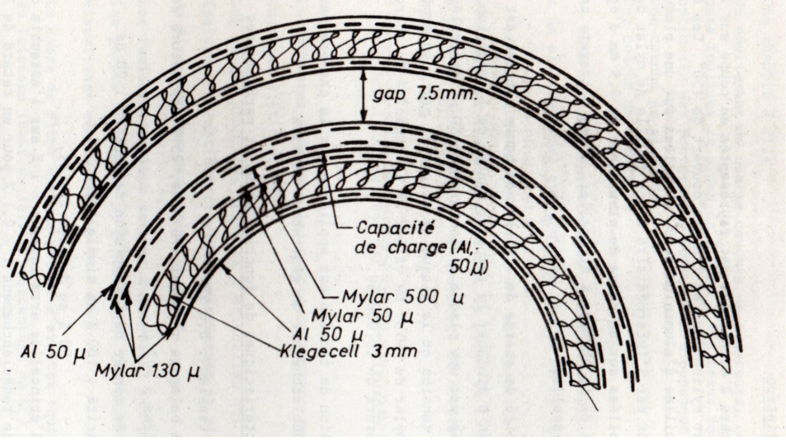
Occasion of many detailed tricks of construction

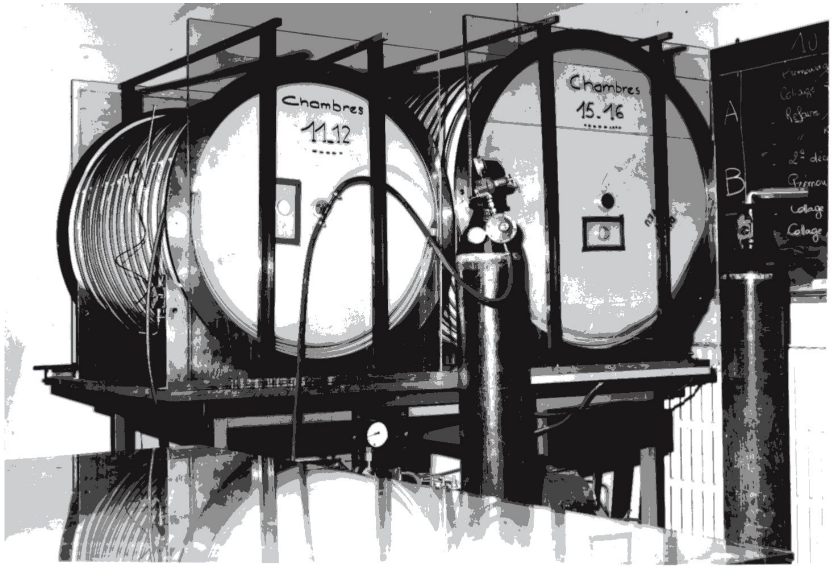
- The staged mirror to get 2 views shown preceding slide
- The chambers were made of sandwich of 3 mm foam and aluminium foil glued to mylar (strong plastic foil)
- The shape was given by gluing inside of machined iron cylinder heated by induction.
- The challenge was to obtain a very good multitrack efficiency (hard because 1st spark rob the energy of others => fast rise with distributed capacity (mylar +Alu) very short spark gap + increase resistance of sparks by adding something to Neon Helium gas (heptane= C_7H_{16}) => excellent multitrack efficiency
- First 5 chambers without lead (directions of particles) +11 with 0.5X0 of lead measure photon positions => angle not really energy but adapted to few body reaction
- Homemade simulation program used to predict showers (no GEANT program !)
- Hand made electronics to combine counters and trigger on charged and/or neutrals
- Fluorescent tape on detector +flash to see detector on each photo

Chamber construction

Good mechanical quality needed: constant gap to prevent spark robbing

Good surface to propagate r-z light by reflection

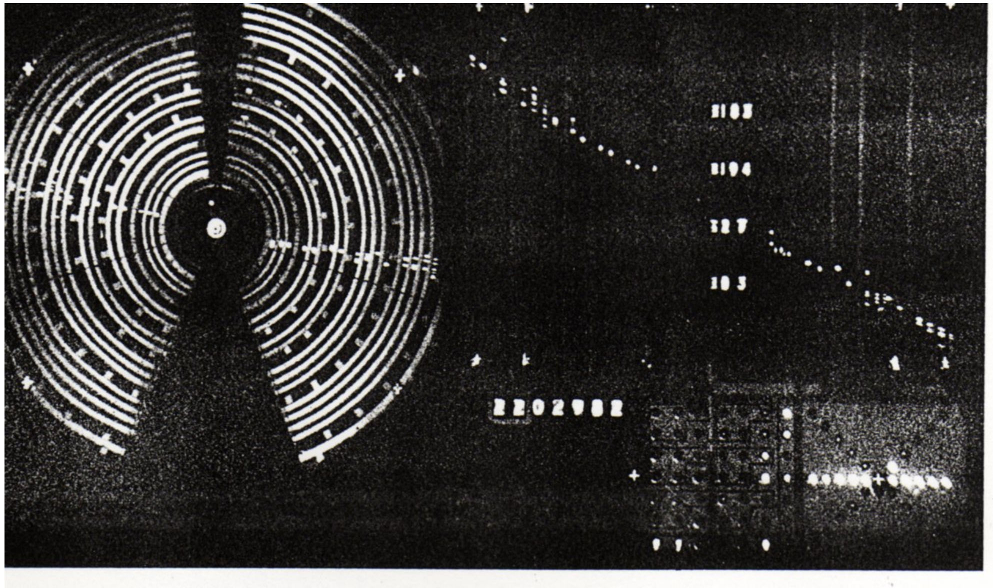


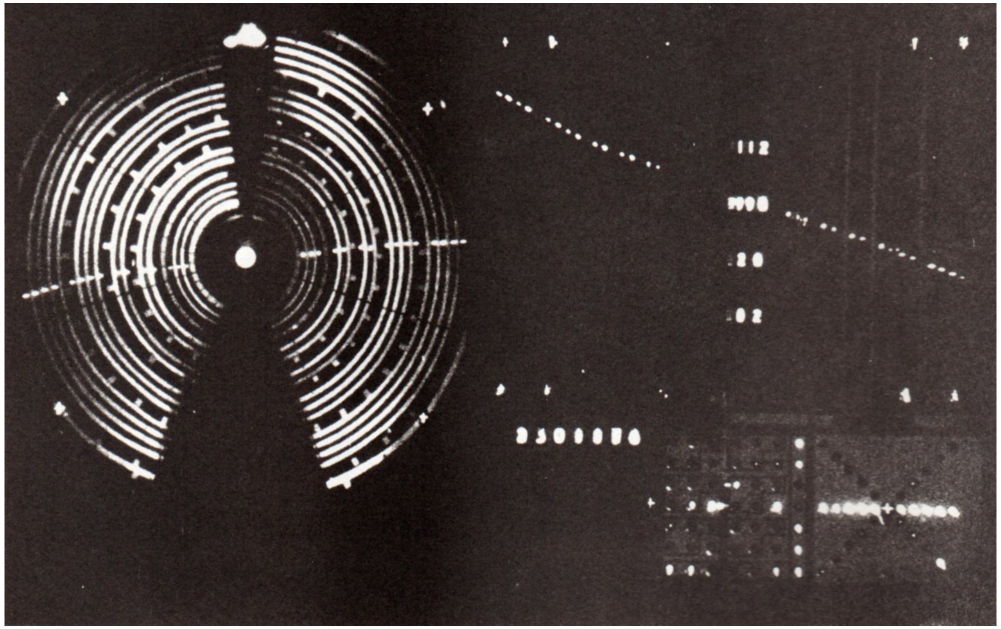


Pattern recognition calibration by scanning hiding ½ of picture

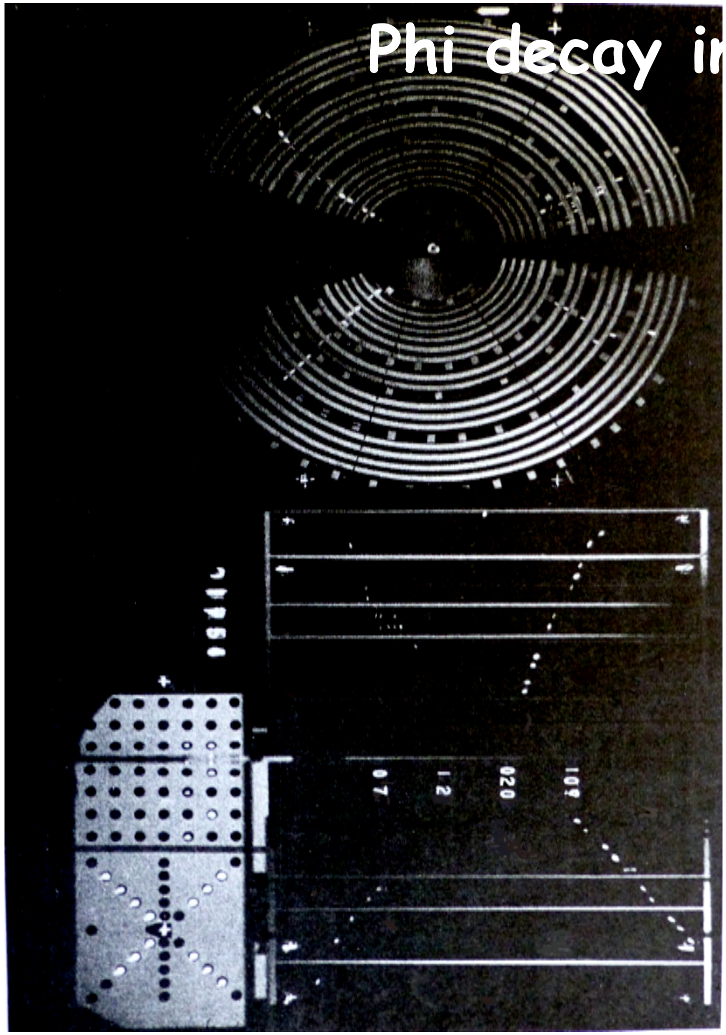
For example an e+e- event (left) and a π+π- event (right)
=>measurement of mis-ID each side e,π,unknown, then check conflict

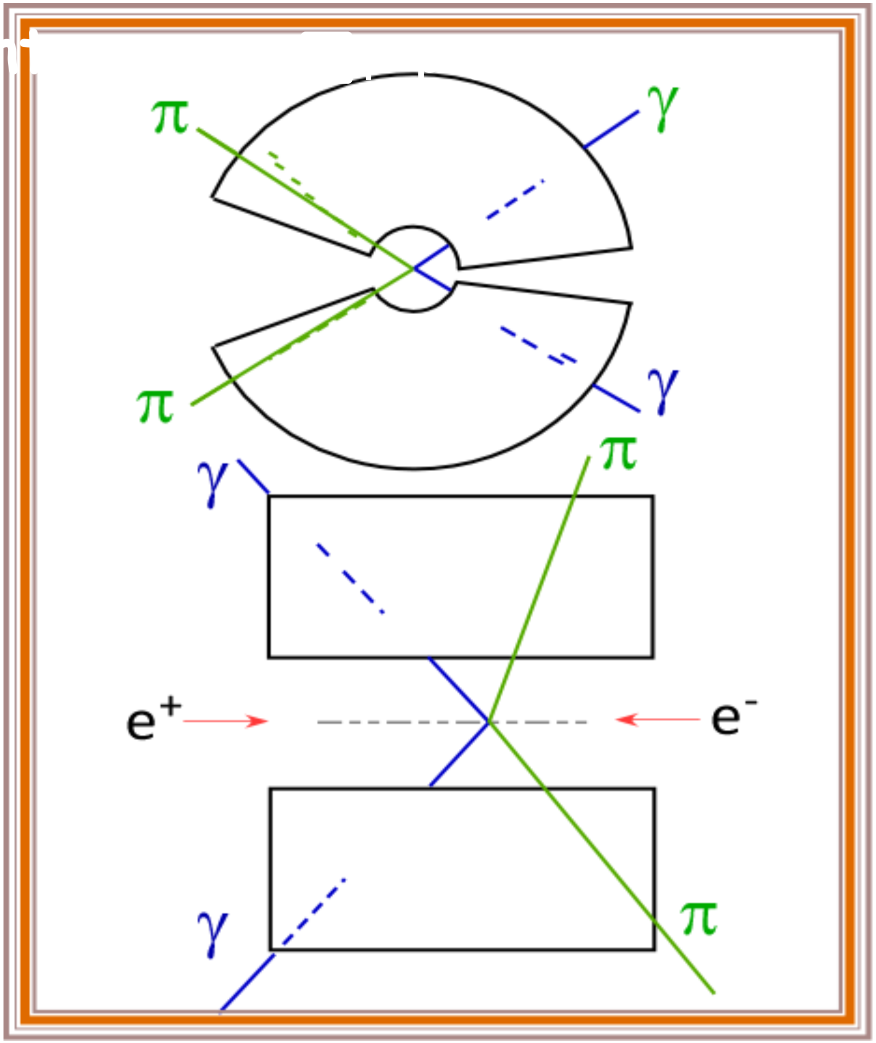
=>mis-ID with both side = 0.2%





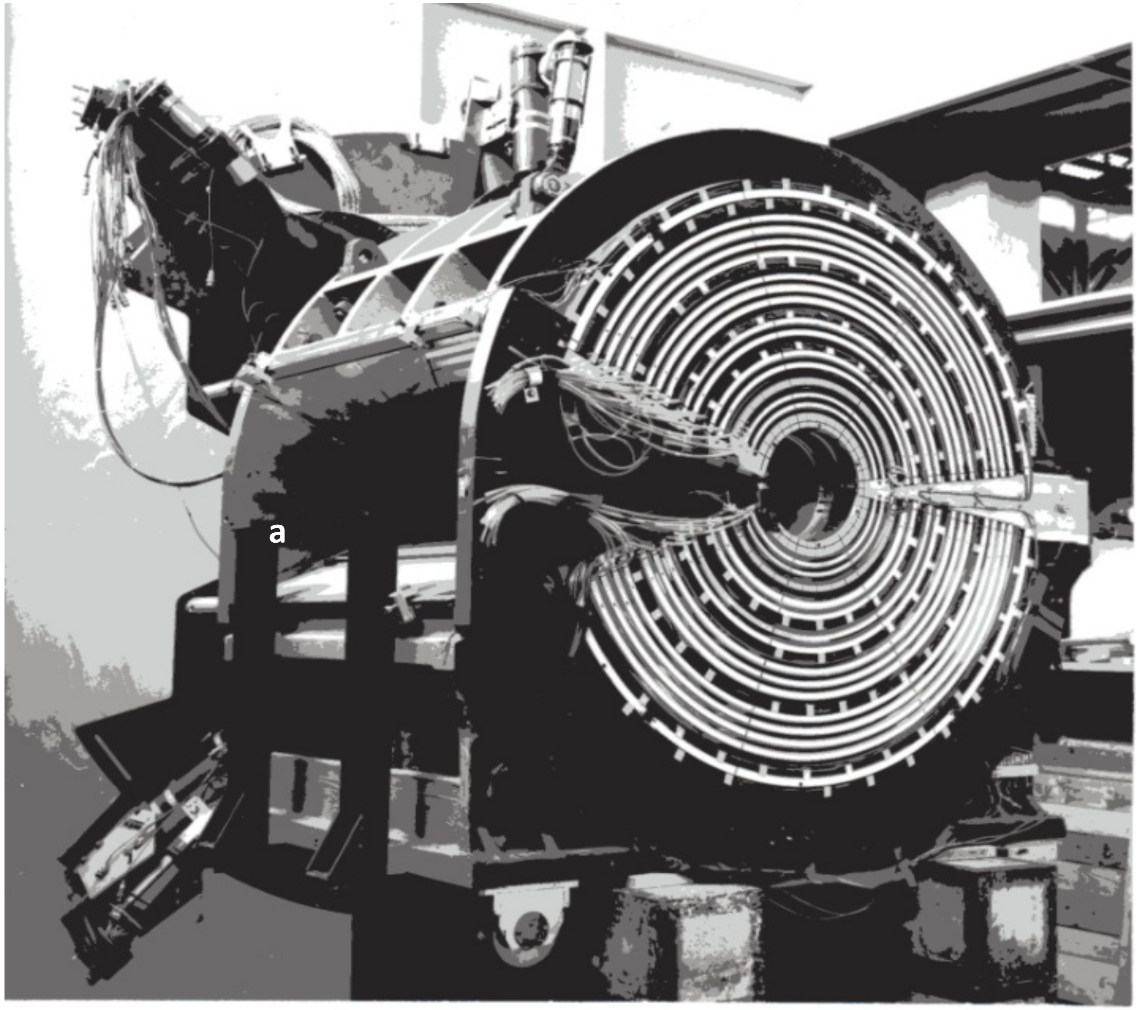
A $\pi^+\pi^-\pi^0$ event => $\pi^+ \pi^- \gamma \gamma$





φ3C Experiment

The detector after dismounting



The pros and cons of e^+ e^- storage rings

From the start of physics with e^+e^- at ACO, and VEPPII our competitor at Novossibirsk, the advantage of e^+e^- colliders (as predicted by BrunoTouscheck) were obvious: the cleanliness of the production process and experimental conditions.

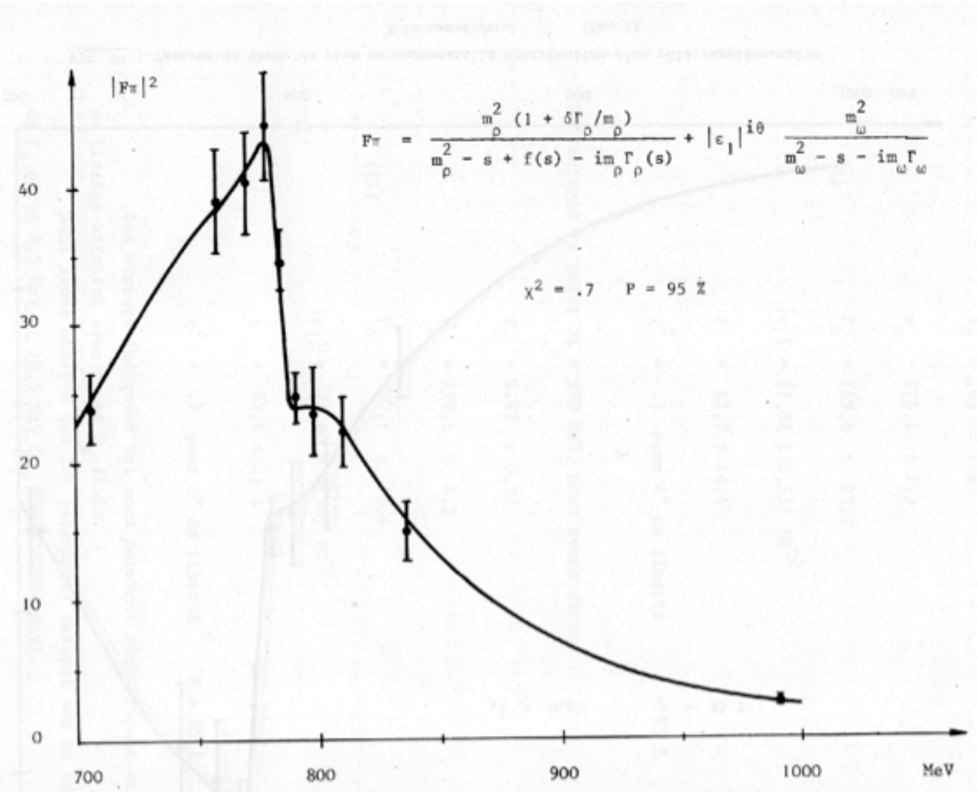
The drawback is the smaller production cross section.

One example of physics possible with cleaner conditions was the isospin violating decay $\omega \Rightarrow \pi^+\pi^-$. Clearly the omega amplitude will interfere with the $\rho \Rightarrow \pi^+\pi^-$ amplitude but in case of hadronic production it is hard to be sure of the production phase, the coherency and spin state and therefore understand the interference condition while this is obvious in e^+e^-

By the way, one could imagine that $\omega \Rightarrow \pi^+\pi^-$ isospin violation can be calculated as $\omega \Rightarrow \gamma \Rightarrow \rho \Rightarrow \pi\pi$ which can be calculated once $\omega\gamma$ and $\rho\gamma$ coupling are known. But things are more complicated, the intermediate state can be $\pi\gamma$ etc…

$\omega \Rightarrow \pi\,\pi$ and $\rho \Rightarrow \pi\,\pi$

Br $\omega \Rightarrow \pi\pi$ =3.6+2.4-1.8%
The relative decay phase is 86±5°
PDG 2014 Br is 1.53+-.12%
Generally from the peak cross-section
$e^+e^- \Rightarrow X \Rightarrow$ hadrons,
which is equal to:
$(12\pi/(M_x))$*Br (x=>e+e-)*Br(x=hadrons)
The curve allows to determine:
Br $\rho \to e^+e^- = 4.1 \pm 0.5 \times 10^{-5}$
And $\Gamma\rho$ = 161±16 MeV $M\rho$ =778 ±6 MeV
PDG 2014 =>Br $e^+e^- = 4.7 \pm 0.05 \times 10^{-5}$
$\Gamma\rho$ = 148±.9 MeV $M\rho$ =775±.2 MeV



$$F_\pi = \frac{m_\rho^2 (1 + \delta\Gamma_\rho/m_\rho)}{m_\rho^2 - s + f(s) - i m_\rho \Gamma_\rho(s)} + |\varepsilon_1|^{i\theta} \frac{m_\omega^2}{m_\omega^2 - s - i m_\omega \Gamma_\omega}$$

FIG. 26 : Facteur de forme du pion en supposant la contribution d'un pôle supplémentaire à la masse du ω (Cas II)

Well PDG 2014 is 10 times more accurate! But the important thing was that the physics model was sound because the physics was "simple".

P.S. photoproduction results where also "rather clean"

$\omega \Rightarrow 3\pi$

From events observed as $\pi\pi 2\gamma$ or $\pi\pi 1\gamma$ one can identify the ω events (as separate from ρ) this allows to determine the ω mass and width

M=783.4MeV and Γ=9.1±.8MeV

This was the most accurate measurement at the time. The Γ PDG at the time (without us) was:

Γ=11.4±0.9MeV

The Γ PDG 2014 is: Γ= 8.5±.08 MeV

One cute point is that in a 4 body decay measuring only angles and using the 4 energy momentum constraints of kinematics one can calculate all particles' energy… and for example calculate the π^0 mass for $\pi\pi 2\gamma$, as shown below.

The branching ratio $\omega \Rightarrow e^+e^-$ was also obtained

Br $\omega \Rightarrow e^+e^- = 8.3 \pm 1.0 \cdot 10^{-5}$

PDG2014 => $7.3 \pm .14 \cdot 10^{-5}$

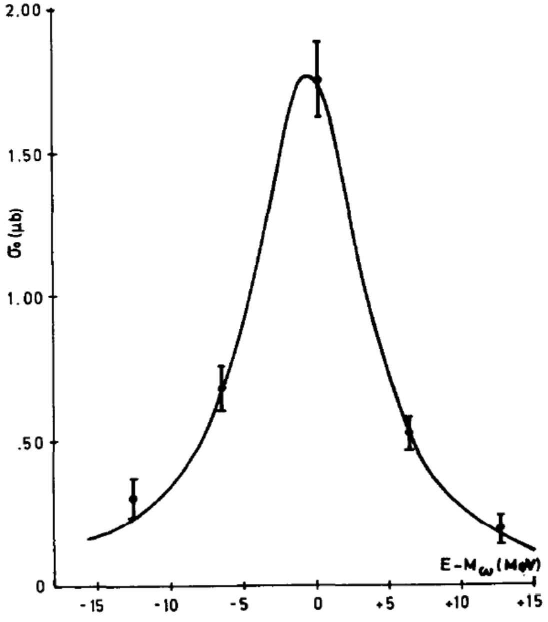


Fig. 6. Excitation curve of $e^+e^- \to \omega^0 \to 3\pi$.

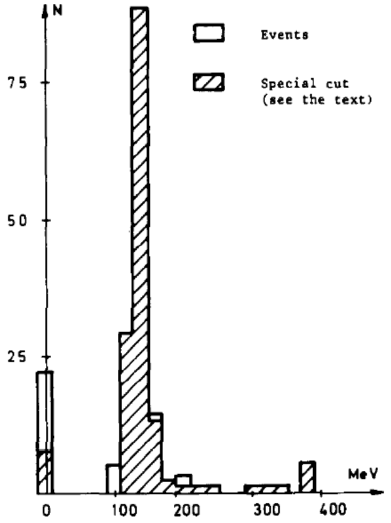


Fig. 2: The π^0 mass spectra.

φ => 3 π

In case of ideal octet singlet mixing (tg(θ)= 1/sqrt(2)) the φ meson would be a pure ssbar state and Br =>3π would be 0

Br to 3π was measured using ππ1γ and ππ2γ events, the normalisation was through the Bhabha rate and then compared to φ=>K^+K^- measured in a previous experiment with a thin wall vacuum chamber and detector (very low energy $K^\pm$)

=>Br=.172+-0.02 (PDG 2014: .153±.003)

Actually it was shown later(1974) that the 3π cross section is the sum of ω + φ Breit Wigner over all masses with a constructive interference in between (related to the octet singlet mixing angle sign)

From these measurements and the coupling to e^+e^- one obtained information on mixing angles but relations were not simple (finite width corrections of about 20%)

Omega-phi interference in e^+e^- =>3π

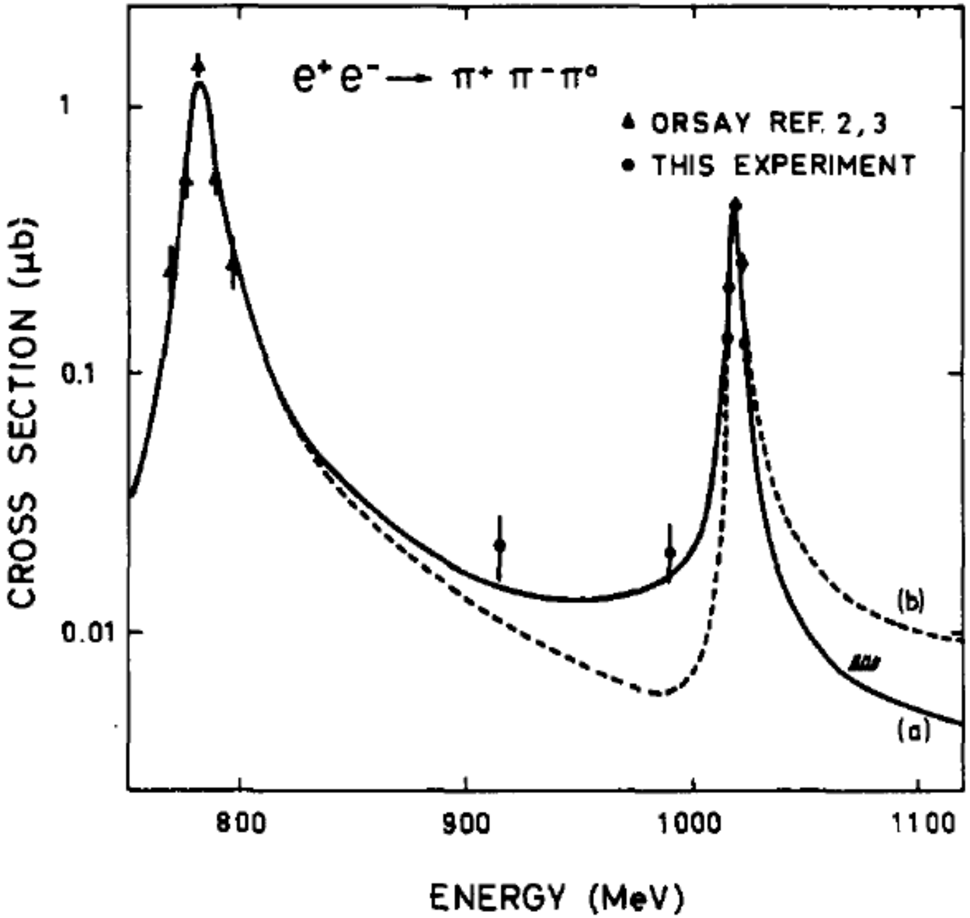
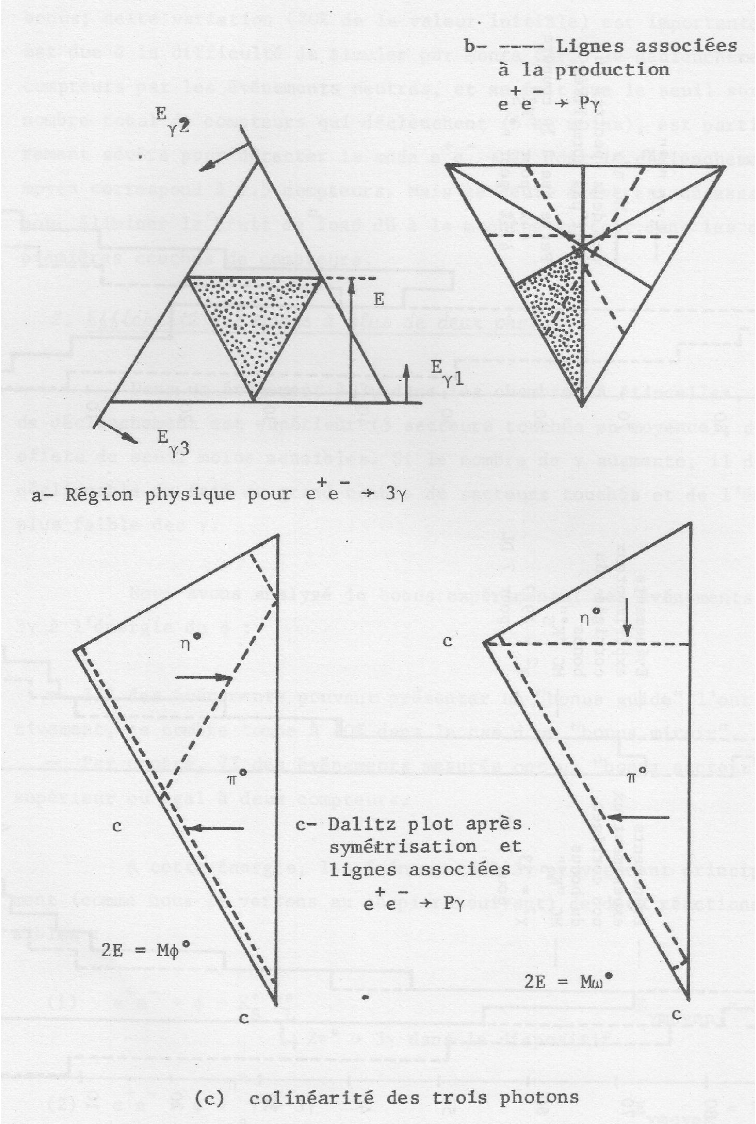


Fig. 1. $\pi^+\pi^-\pi^0$ data from 770 to 1076 MeV. a) Full curve: opposite sign between $g_{\gamma\omega}\, g_{\omega\rightarrow 3\pi}$ and $g_{\gamma\phi}\, g_{\phi\rightarrow 3\pi}$. b) Dotted curve: same sign.

$e^+e^- \Rightarrow \pi^0\gamma, \eta\gamma \Rightarrow 3\gamma$

- **The background (for example from $\varphi \Rightarrow K^0_S K^0_L \Rightarrow 2\pi^0 + X \Rightarrow 4\gamma + X$) is reduced from the information using the 4C constraint => coplanarity of the 3γ and Dalitz plot**
- **From simulation one obtains the size of the signal bands**



a- Région physique pour $e^+e^- \to 3\gamma$

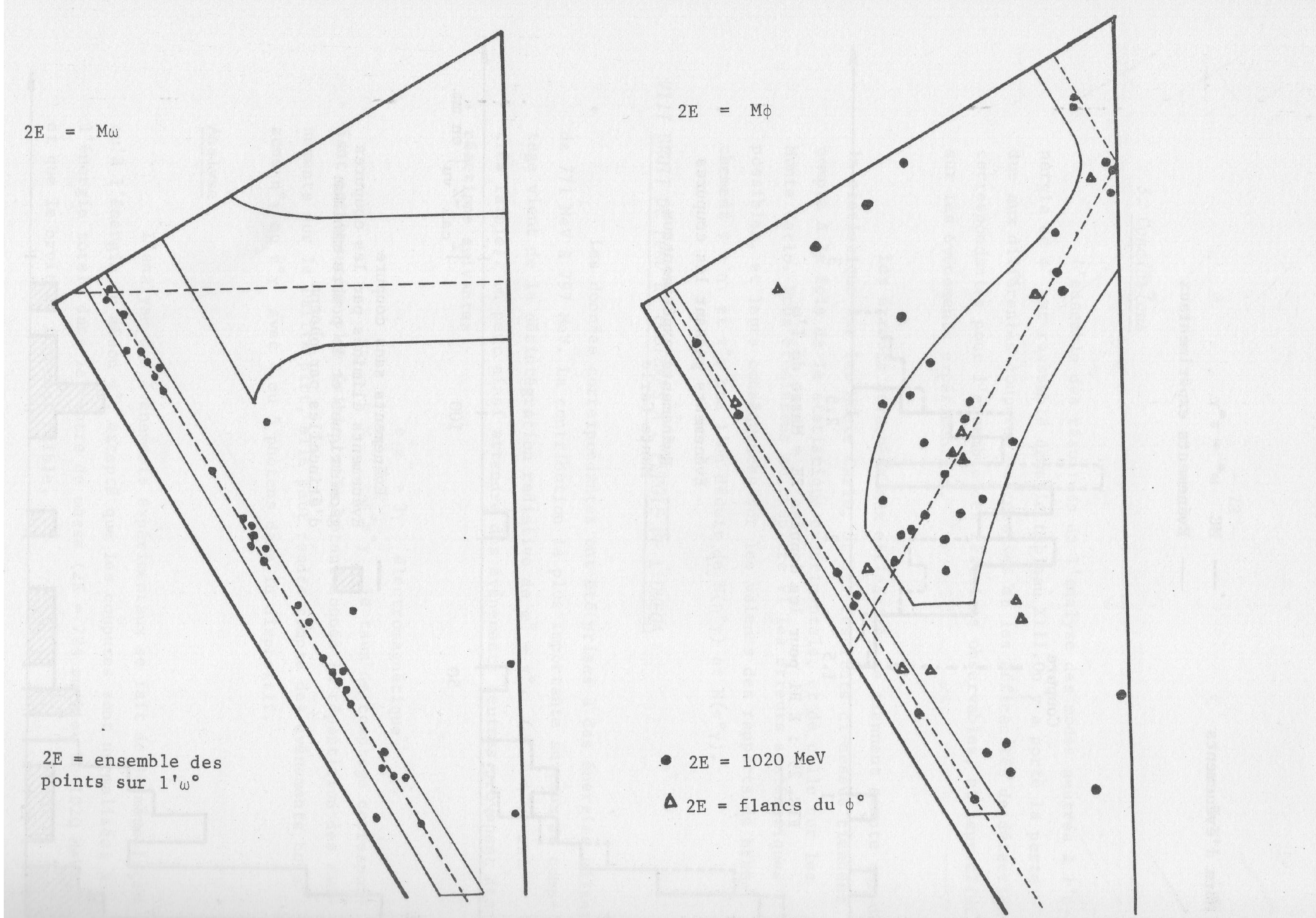
b- ---- Lignes associées à la production $e^+e^- \to P\gamma$

c- Dalitz plot après symétrisation et lignes associées $e^+e^- \to P\gamma$

(c) colinéarité des trois photons

FIG. 20 : Dalitz-plot $e^+e^- \to P\gamma \to 2\gamma$

Dalitz plots



$\omega \Rightarrow \pi^0\gamma$

$\varphi \Rightarrow \pi^0\gamma$, $\varphi \Rightarrow \eta\gamma$

3 γ results

Measurement of ω => $\pi^0\gamma$ ((10.0±2.3)%) already known in 1972

Br ω => $\pi^0\gamma$ ((7.8±0.7)%) PDG 2014: (8.5±.27)%

just a check for us

First measurements of

Br φ => ηγ ((2.6±.7)%) PDG 2014: (1.3±.024)%

and Br φ => $\pi^0\gamma$ ((.25±.12)%) PDG 2014: (.13±.006)%

φ=>ηγ is bigger because of the ssbar content of the η

One then used Vector Dominance to link φ=>3π to φ=>$\pi^0\gamma$

φ=>3π = φ=>ρπ and one can replace a ρ by a γ using our measured coupling ρ=>γ=>e^+e^- The predicted φ=>$\pi^0\gamma$ was (.19±.02) %

One then compared the ηγ branching ratio to prediction using the vector meson and pseudo scalar mixing angles

Conclusions

The ACO results on the vector mesons (and their decays) where seen as nice test of the validity of SU3, mixing angles, sum rules etc…

The V=>e^+e^- Branching Ratios were used to obtain the photon coupling and therefore the parameters of the Vector Dominance model for example to obtain a prediction for the total hadronic photon cross section

It was gradually realised in the early ACO-VEPPII experiments that apparatus had to evolve to a full 2π acceptance in φ, this became possible with the use of non-optical detectors. (and then the use of solenoid) This was clearly the choice of MARKI at Spear built in 1971-1972 with spark chamber with electronic (magnetostrictive) readout but not for Adone detectors. The importance of general purpose detectors with photon detectors was also recognised but it took some time to have good 2-D detectors for ECAL (Well known it was a weak point of MARK1)