The Bubble Chamber

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Wilson chamber and emulsion were responsible for many unexpected discovery - positrons, muons, pions, strange particles, the study of cosmic radiation and e-m showers.

The systematic studies of pions and muons continues at the cyclotrons mostly with counters.

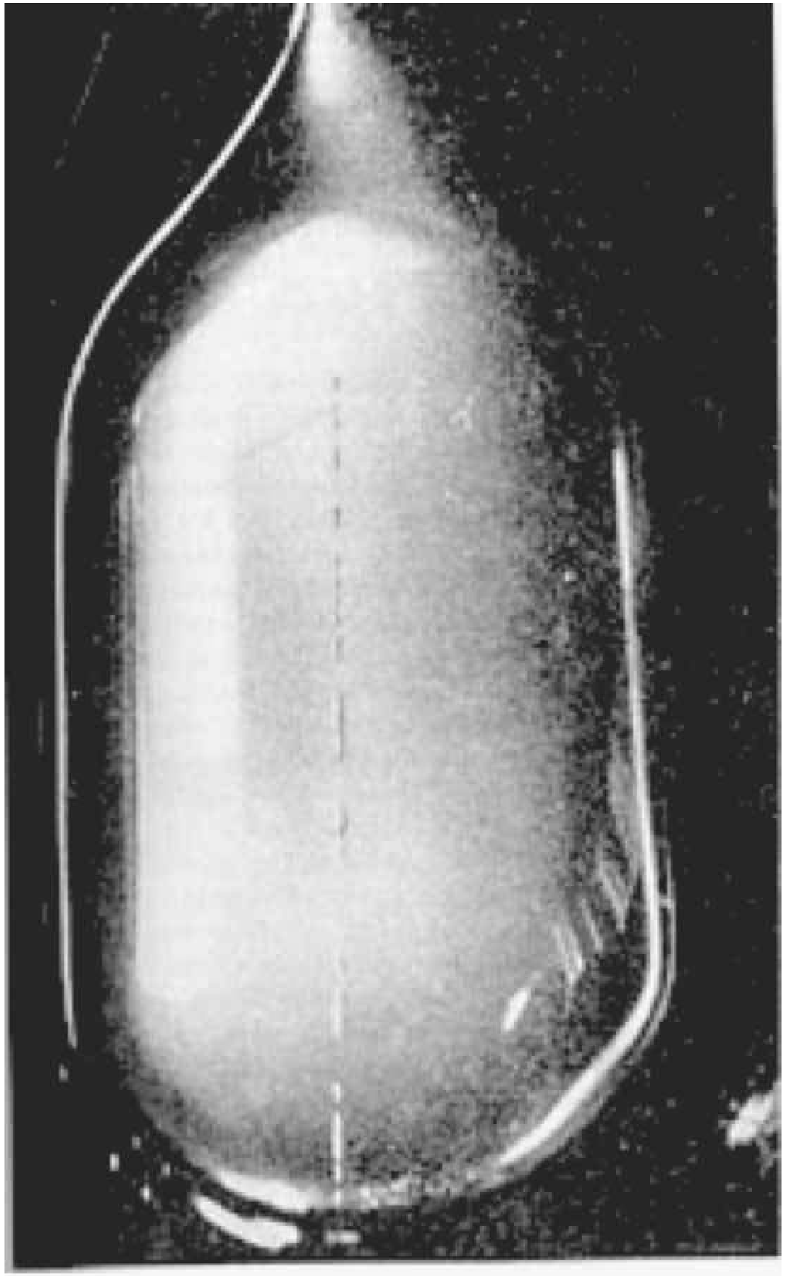
The advent of high energy accelerators - first the BNL Cosmotron accelerating protons to 3 GeV, require new techniques. The cloud chamber ends its contribution to physics with the confirmation of the associated production suggestion of Gell-mann and the K_1-K_2 (1956) suggestion of Pais and Gell-mann. Both experiments were performed at the Cosmotron.

Particle physics also enters a new era. Experimentalists and theorist are more in touch with each other and new ideas develop rapidly, requiring experimental tests.

Just as the cosmic ray discoveries of muon and pion led to the extensive studies of those particles at the synchro-cyclotron, the discovery of strange particles led to a new chapter in physics which could only be continued at more powerful accelerators. This begins at the Cosmotron and is largely dominated by the just invented bubble chamber.

Don Glaser invented the bubble chamber in 1953.* The first track in over-heated diethyl-ether is shown to the right.

A bubble chamber is a vessel with a "hot", pressurized liquid. After a fast expansion the liquid does not vaporize immediately. Ions along the tracks of an ionizing track provide nuclei for vapor bubbles formation. It all takes a few milliseconds. Recompression finishes the cycle in much less than a second and the chamber is ready again.

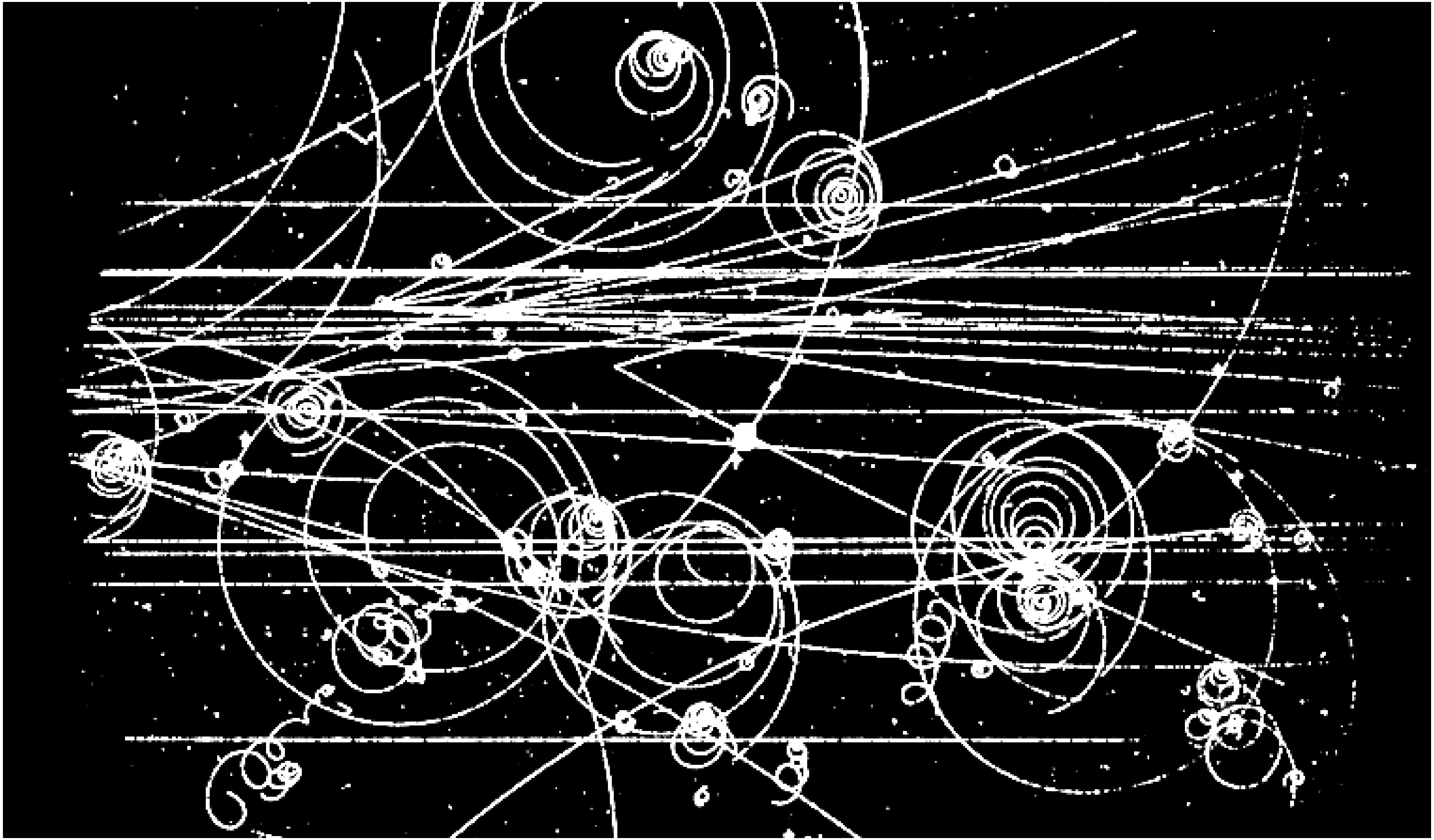


*the beer glass. . .

Any liquid will do. Choose the one you prefer. Hydrogen (C_3H_8) was favored at the beginning.

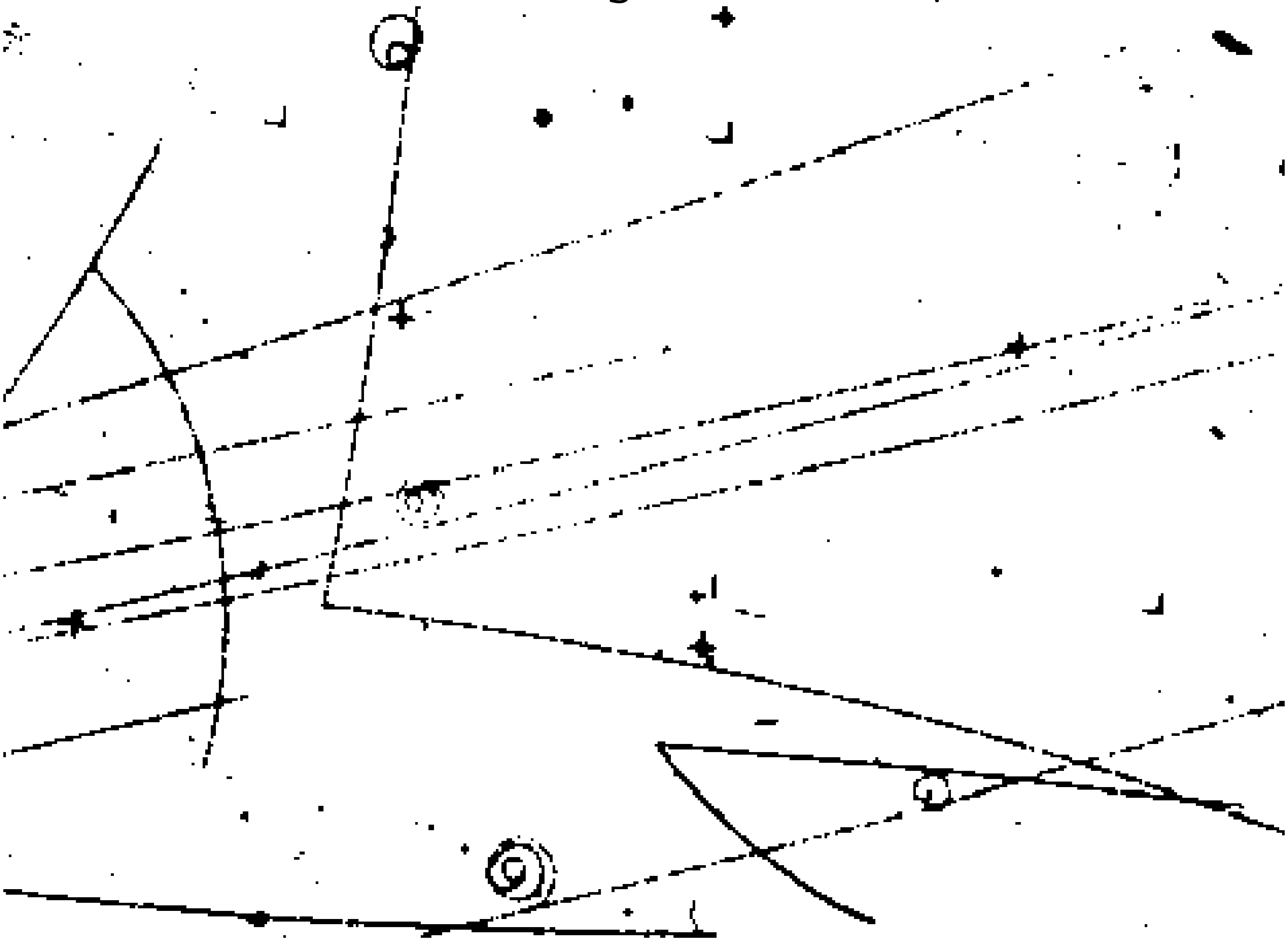
Liquid	Temperature	Density	Radiation length
	K	g/cm^3	cm
H_2	25	0.0645	968
D_2	30	0.14	900
Ne	35	1.02	27
He	3.2	0.14	1027
Xe	252	2.3	3.9
C_3H_8	333	0.43	110
CF_3Br	303	1.5	11
Ar	135	1.0	20
N_2	115	0.6	65

In 54 John Woods at LBL observes tracks in liquid hydrogen chamber. In 1955 Columbia had a 15 cm dia., propane chamber (without magnetic field) at the Cosmotron.
In 1956, 60 000 pictures were taken in the Columbia 30 cm dia. C_3H_8 and H_2 chambers with magnetic field, exposed to a beam of π^- of 1100, 1200 and 1300 MeV kinetic energy.
The bubble chamber is much superior in spatial resolution and therefore momentum accuracy, because bubbles can be kept smaller than 100 μm and there is no diffusion.
The complete cycle can be $\ll$1 s. In '59 10 Hz BC at Frascati.



Picture 000329 from CERN - as you would see it

From LBL - a negative of the picture



The way the bubble chamber took the first place in particle physics at accelerator was almost explosive.

Before the end of the 50's there were dozens of bubble chambers in the US.

LBL started physics with a 25 cm H_2 chamber in 1956, followed in '59 by the first giant of those days, the 72" or 1.8 m long H_2 chamber with a few more in between.

BNL in the 50s had a dozen chambers, including 5 from CU and 1 from Yale. In '62 the 2 m H_2 chamber was operating.

CERN started later. The first H_2 chamber was operating at the very end of the 50's and I was there when we measured the $\Sigma^0 - \Lambda^0$ parity. CERN did much better in the seventies – as we shall see...

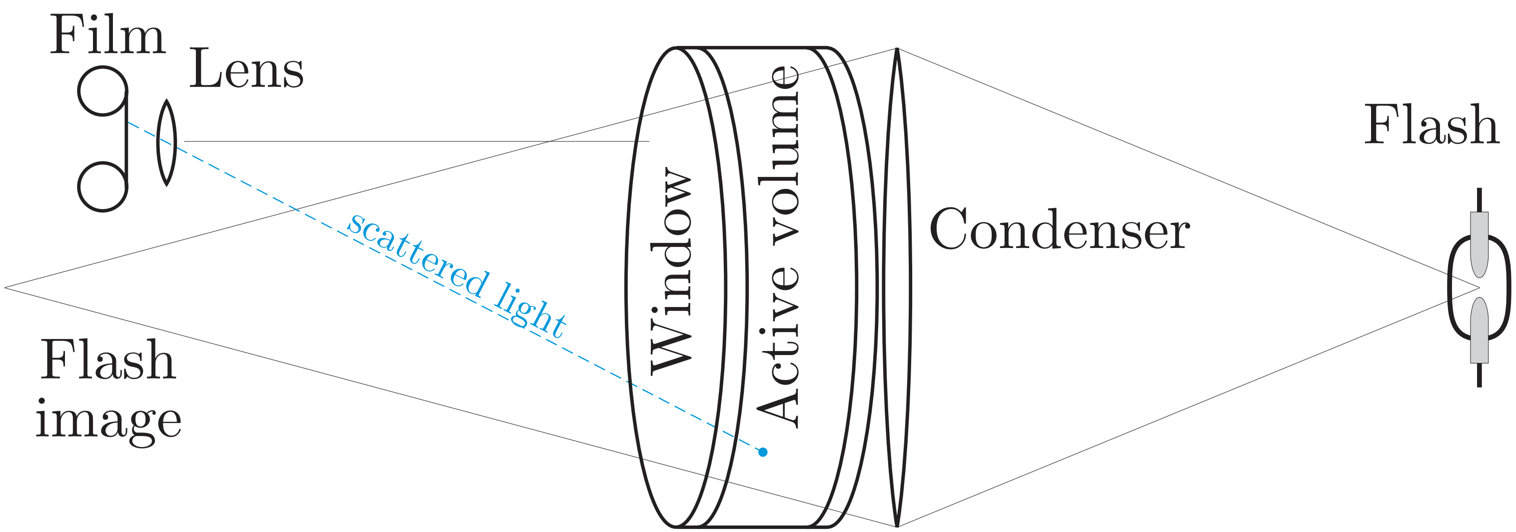
Chambers were built using deuterium (almost free neutrons), xenon, freons, neon and even helium - the reason for the last one was never clear to me.

H_2 and C_3H_8, propane, were the early liquids of choice.

We must remember that 45 years ago the proton was an elementary particle, almost THE ELEMENTARY PARTICLE and clean physics meant beginning with a pion or kaon beam incident on a target of protons.

The chamber geometry is quite similar to that of a cloud chamber. Illumination is by way of imaging a point light source behind the active volume to a point outside the entrance pupil of the camera lenses. This arrangement gives very high contrast images, bright bubbles on black background but requires two windows capable of holding several atmospheres of pressure.

One window can be replaced by a spherical mirror, placing the flash on the same side as the cameras.



The very first bubble chamber experiments were devoted to the study of strange particles, especially hyperons. In particular in a very short time came:

1. Discovery of the Σ^0 predicted by Gell-Mann and Nisijima, observing $\pi^- p \to \Sigma^0 K^0$ followed by $\Sigma^0 \to \Lambda^0\gamma$, with unmeasurably short $\tau(\Sigma^0)$
2. Lifetimes and spin of Σ and Λ
3. Selection rules in $\Delta S \neq 0$ decays: $\Delta S = \Delta Q$ and dominance of $\Delta I{=}1/2$.
4. Parity violation in hyperon decays, decays without neutrinos
5. Relative $\Sigma - \Lambda$ parity
6. Determination of Cabibbo parameters

The Bologna-Columbia-Michigan-Pisa experiment, 56-57, was the first estensive hyperon study:

$$\pi^- + p \to \Lambda^0 + K^0$$
$$\pi^- + p \to \Sigma^- + K^+$$
$$\pi^- + p \to \Sigma^0 + K^0$$
$$\pi^- + p \not\to \Sigma^+ + K^-$$

Parity

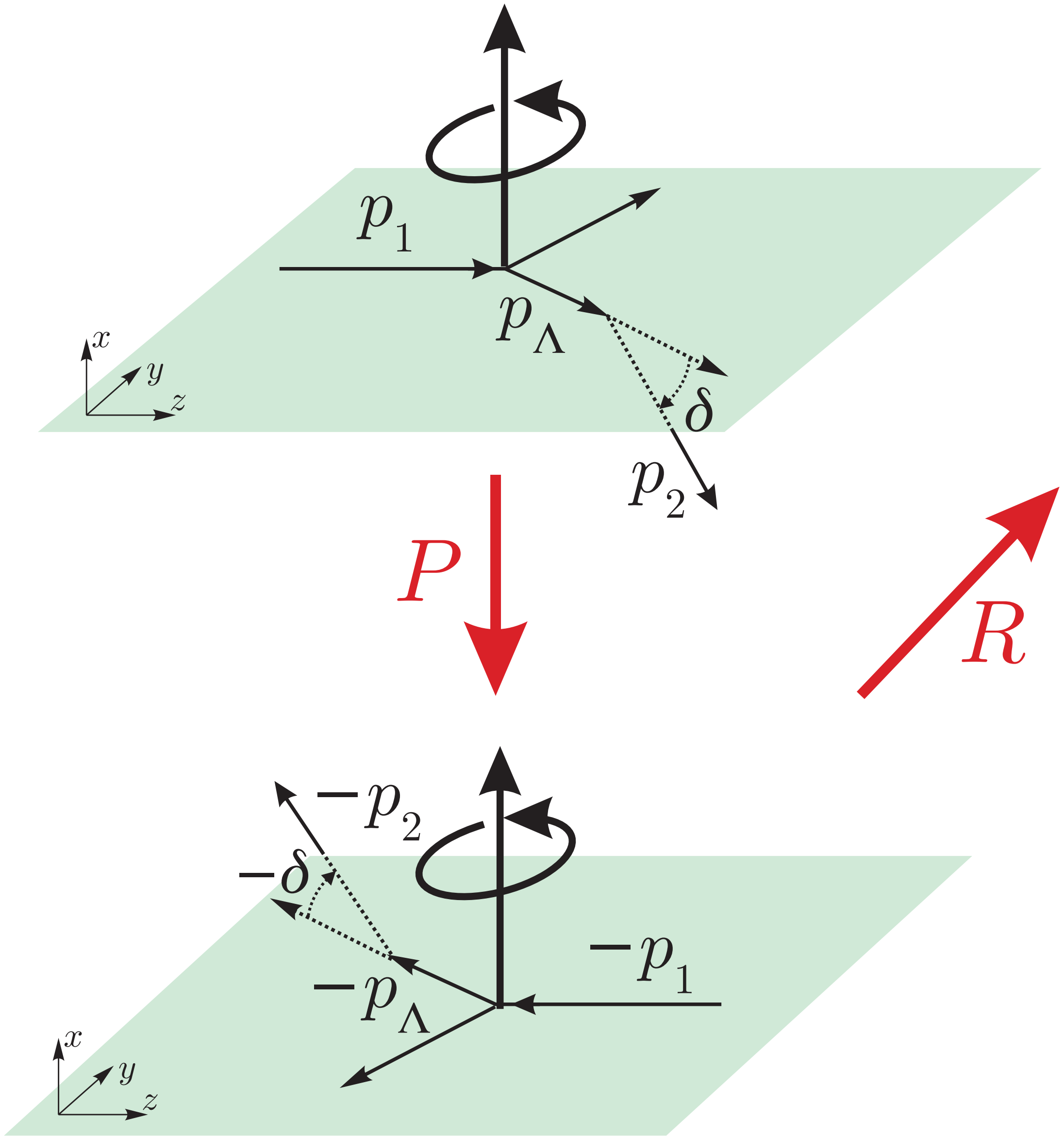
If $\langle PS \rangle \neq 0$ than $\not{P}$

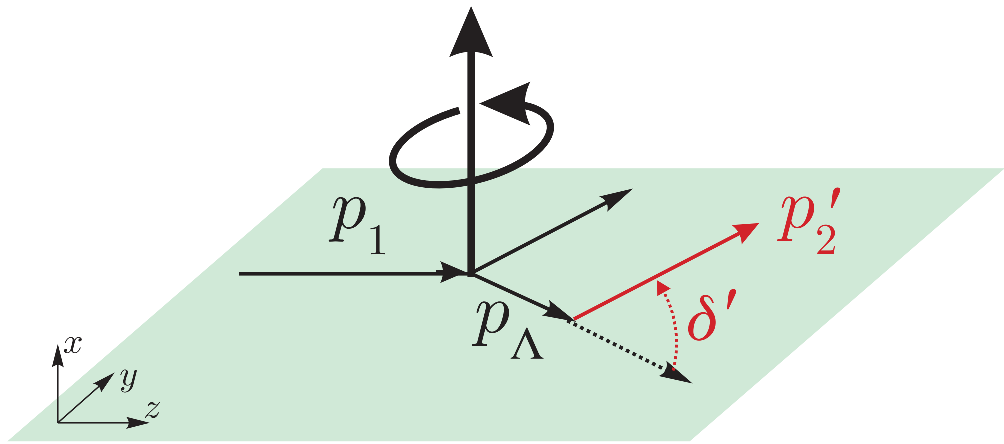
$\pi_1^- + p \to \Lambda^0 + K^0, \ \Lambda^0 \to \pi_2^- + p$

$\hat{n} = \vec{p}_1 \times \vec{p}(\Lambda) / |\vec{p}_1 \times \vec{p}(\Lambda)|$

$\hat{n}$ is an axial vector and $\hat{n} \cdot \vec{p}_2 = \cos\theta$ a pseudoscalar

$\not{P} \Rightarrow \ f(\theta) = 1 + \alpha \overline{P} \cos\theta$





$$\delta' = -\delta$$

$$I(\delta) = I(-\delta)$$

δ="dip angle"
q=polar angle
$\theta = \delta + 90°$

$\Lambda^0 \rightarrow p\pi^-$

June 1957 BCMP at BNL Cosmotrom

$$\alpha\overline{P} = 0.4 \pm 0.11$$

October 57 LBL at Bevatron

$$\alpha\overline{P} = 0.44 \pm 0.11$$

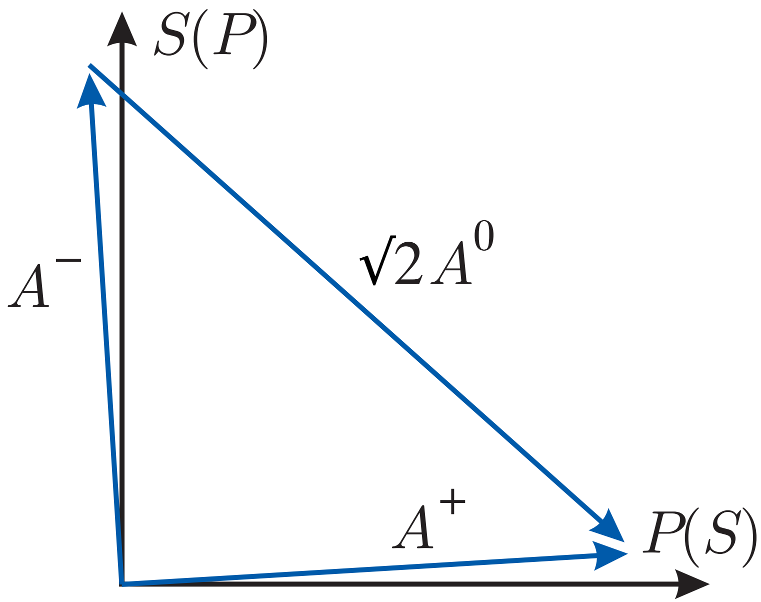
Parity is violated in a neutrino-less weak process.

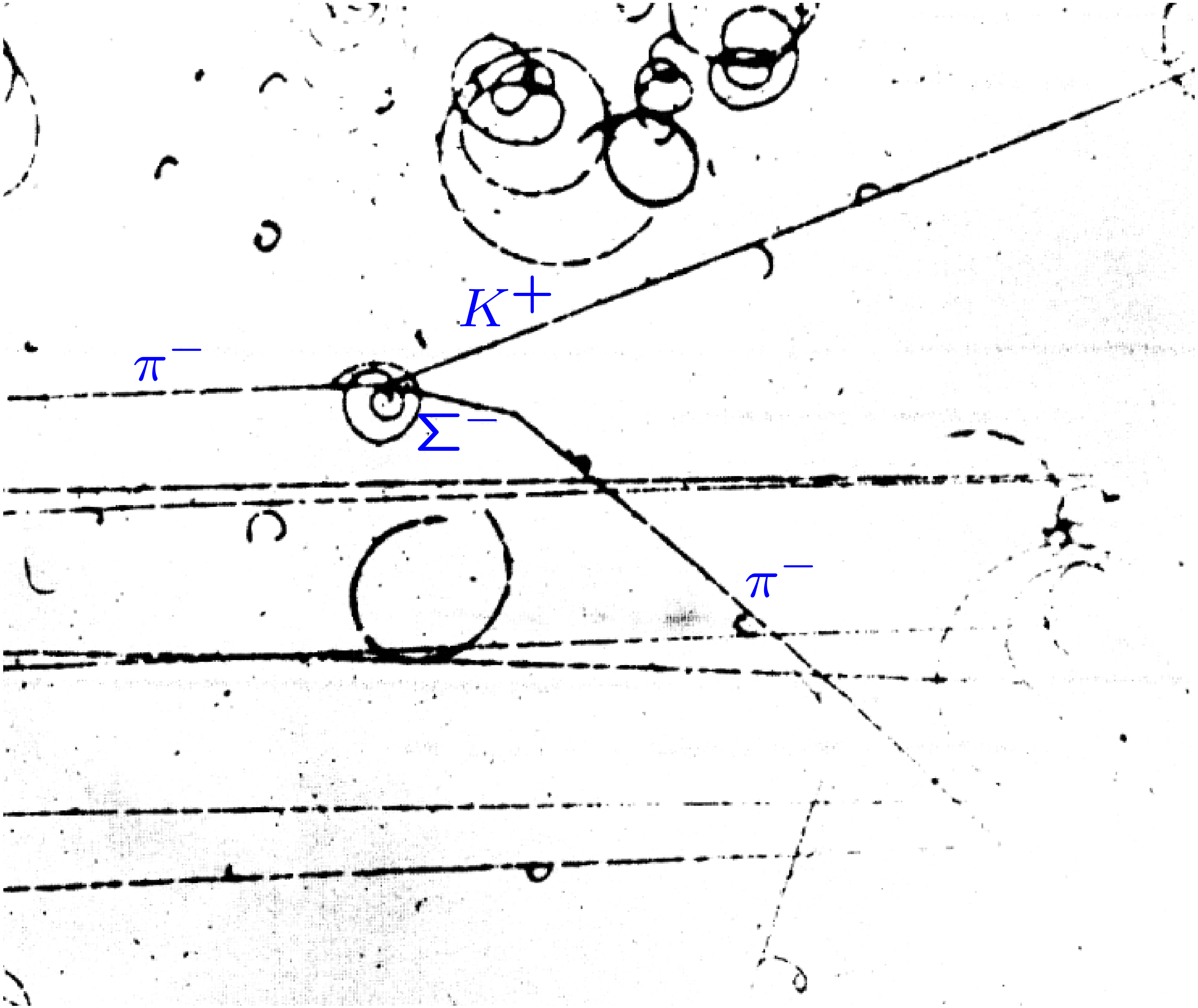
$\Sigma^- \rightarrow \pi^- n$

No P violation is observed in Σ^- decays. This was soon understood as due to ΔI=1/2.

$A^+ - \sqrt{2}A^0 = A^-$

$\alpha = 2\Re SP^*$





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Λ and Σ spin

$$\pi^- + p \to \Lambda(K) \to \pi^- + p$$

z-axis along $\vec{p}_{\text{inc}}$: $L_z^{\text{in}} = 0$

Initial state: $J_z = \pm 1/2$, incoherent mixture

Chose $\theta_\Lambda = 0^\circ$ or 180°: $L_z^{\text{out}} = 0$, $J_z(\Lambda) = \pm 1/2$

$J(p\pi^-)$, $J_z(p\pi^-) = S(\Lambda)$, $\pm 1/2$ (aligned state)

$\not{P} \Rightarrow L(p\pi^-) = S(\Lambda) \pm 1/2$

$S(\Lambda)$	$f(\lvert\cos\theta\rvert)$
$1/2$	1
$3/2$	$1/2(1 + 3\cos^2\theta)$
$5/2$	$3/4(1 - 2\cos^2\theta + 5\cos^4\theta)$

Lifetimes

We found, in '58

$$\tau_\Lambda = 2.29 \pm 0.14$$
$$\tau_{\Sigma^-} = 1.89 \pm 0.29$$
$$\tau_{K^0} = 1.06 \pm 0.07$$

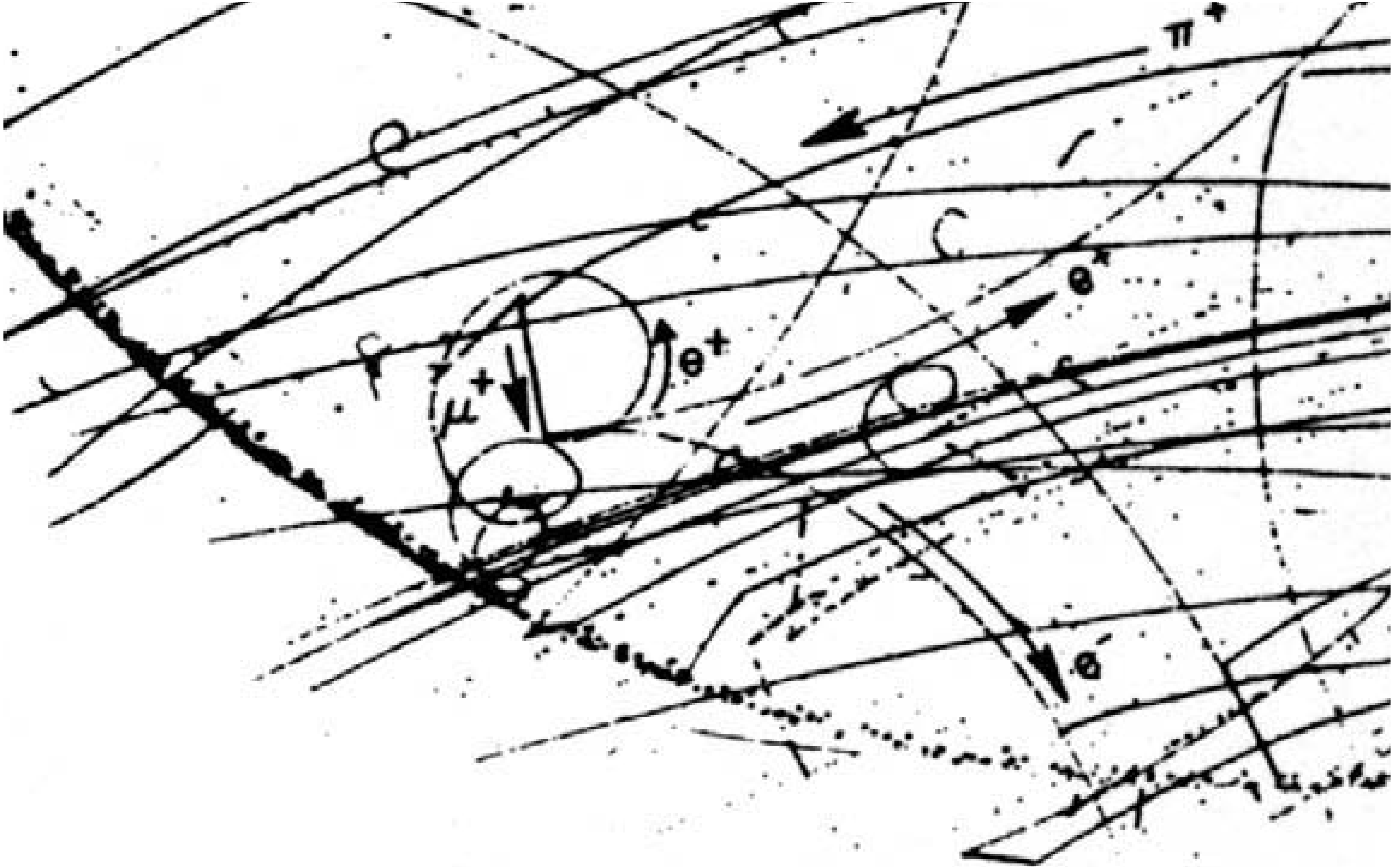
PDG, in '02

$$\tau_\Lambda = 2.63 \pm 0.02$$
$$\tau_{\Sigma^-} = 1.48 \pm 0.01$$
$$\tau_{K^0} = 0.894 \pm 0.001$$

We could have done better!

L_e and L_μ – '58

Suppression of $\mu^\pm \to e^+e^-e^\pm$



Extracting physics from BC pictures

1. Visual scan to find events
2. 3-D reconstruction of geometry and kinematics

Point 1. It was done at the beginning by physicists. Soon was transferred to "scanners", well trained but unskilled people.

Point 2. At the very beginning was done also by physicists, manually, with rulers and other tools, and mechanical calculators.

Very early however the electronic computers appears in the labs. Event reconstruction is done by measuring the coordinates of points on the tracks in each of 3 stereo views. The measured coordinates are manipulated by computers.

Beginning with each view, ultimately a fit to helix in 3-D is performed. Vertex recognition is helped tremendously by human judgement.

A kinematic fit of the entire event is performed, with various assumptions, imposing overall energy-momentum conservation and often additional constraints for intermediate masses.

Measuring is done by well trained but otherwise unskilled technicians on more or less sophisticated machines.

The LBL Frankenstein

Stopping K^-

Suppression of $\Delta S \neq 0$ processes. Cabibbo mixing, '63

Semileptonic decays of hyperons not observed - till '61[†].

Need larger samples of hyperons. Use stopping K^-

$$K^- + p \to \Lambda^0 + \pi^0$$
$$K^- + p \to \Sigma^- + \pi^+$$
$$K^- + p \to \Sigma^+ + \pi^-$$
$$K^- + p \to \Sigma^0 + \pi^0$$

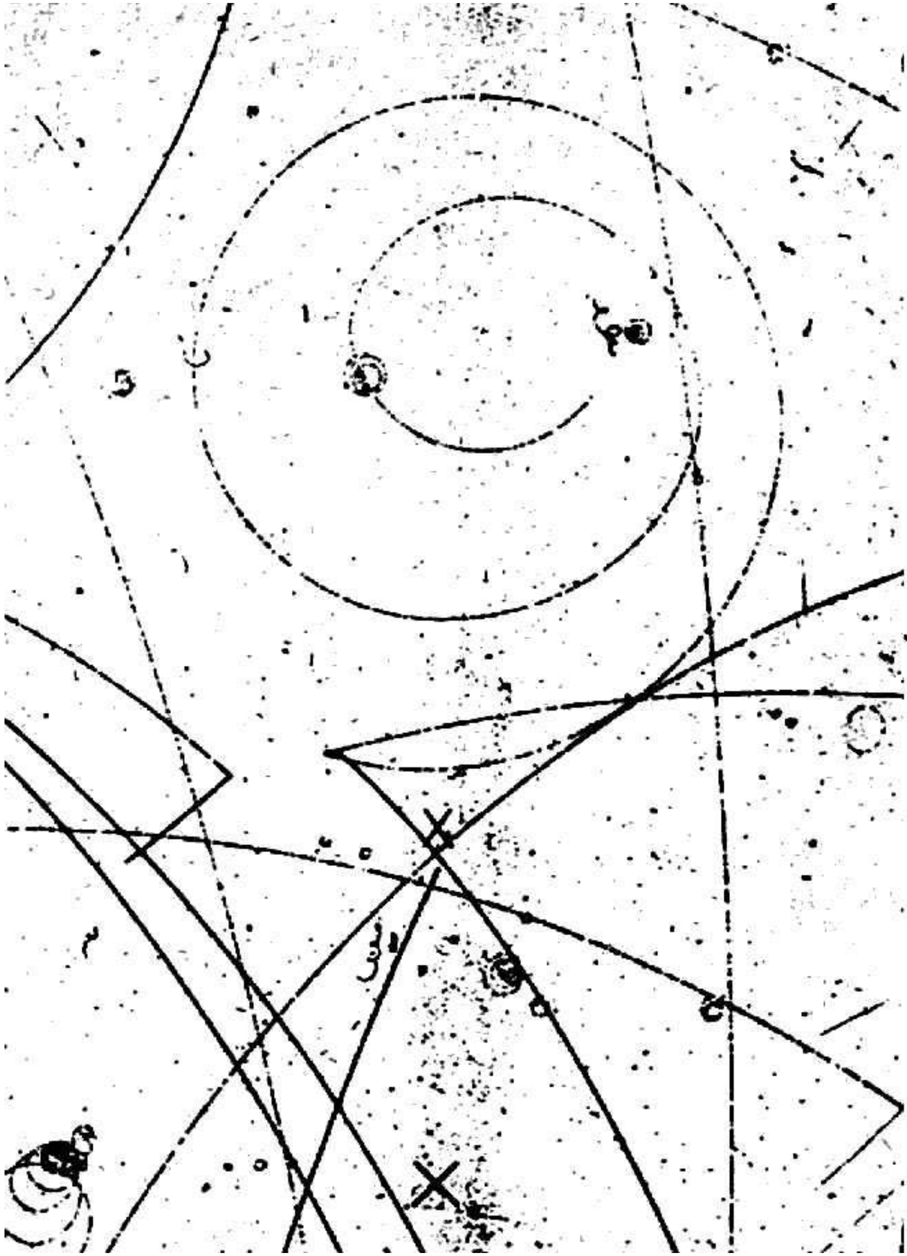
More than one hyperon per picture.

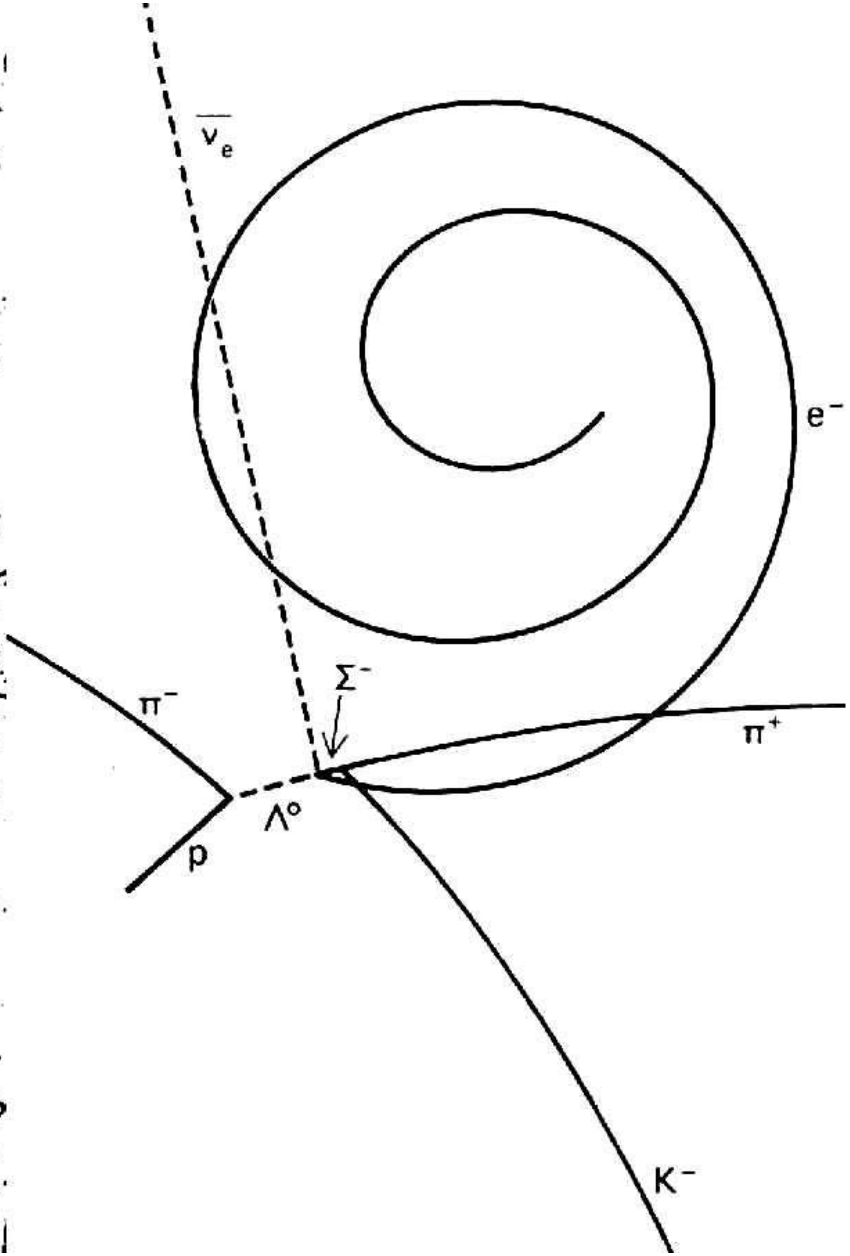
Measure $\Sigma - \Lambda$ parity. CERN wins the race. Study semileptonic decays of hyperons

Observe the $\Delta S = 0$ decay $\Sigma^\pm \to \Lambda^0 e^\pm \nu(\nu)$. CVC

Measure G_V and G_A, Cabibbo fits

[†]guess who





$K^- + p \rightarrow \Sigma^-\pi^+$; $\Sigma^- \rightarrow \Lambda^0 e^- \bar{\nu}$, CERN '62

Stopping antiprotons

In the 60s, stopping antiprotons in liquid H_2 seemed like a great idea. In fact, CPLEAR did just that, 25 years later with modern techniques and therefore orders of magnitude more events. And more significant results.

The only direct, unambiguous proof of C-invariance in SI, better than 10^{-4} in intensity, comes from our data. We also got sort of 50% limits on violation of the $\Delta S = \Delta Q$ rule. The rest of the work was on precise determination of resonance production mechanism, masses and other miscellania.

CERN took more pictures, but again, it was not superb physics.

New particles

The discovery of strange particles in CR, led to strangeness and soon after to the so called Gell-mann-Nishijina formula:

$$Q = I_3 + \frac{B+S}{2}$$

From the relation a very simple rule follows:‡

Singly strange baryons and non strange meson have integer I-spin

Non strange baryons, doubly strange baryons and strange meson have half-integer I-spin

Therefore, said Murray Gell-mann, there ought to be a Σ^0 of mass ~1190 MeV, decay $\Sigma^0 \to \Lambda\gamma$ and a Ξ^0, $S = -2$, mass ~1300 MeV, decay $\Xi^0 \to \Lambda\pi^0$. They were both found in BCs: CU and LBL.

‡that was really the way it came about...

Resonances

The BC also contributed to tremendous advances in the field of the so called resonances - today spectroscopy.

All members of the 1^{--} (ω, ρ, K^*), 2^{++} and 1^{++} nonets were discovered in bubble chamber. It is amusing to remember the ρ. Erwin and Walker exposed the Adair 14" chamber to 1.89 GeV pions at the Cosmotron in '62. They plotted the invariant mass spectrum of two outgoing pions and found a peak at $\sim$750 MeV with a 150 MeV width.[§]

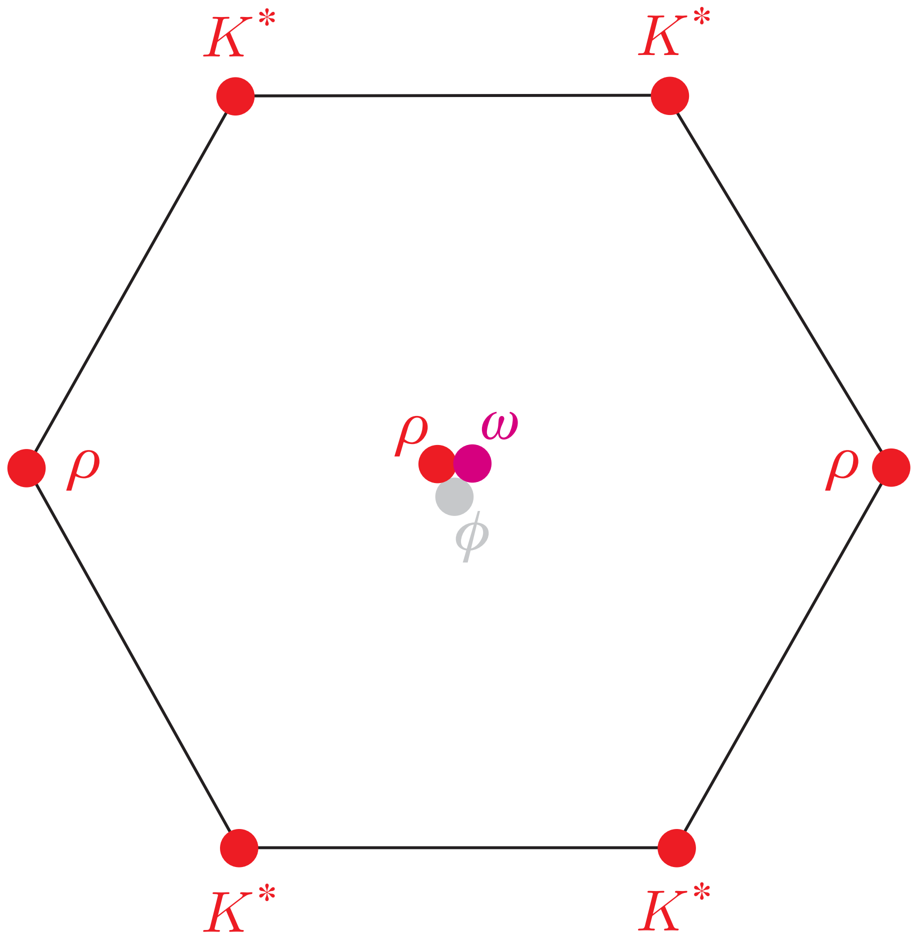
The same was true for baryons. LBL, from events with $2\pi\Lambda$ in the final state they found a peak at $M(\Lambda\pi)$=1380 and Γ=37 MeV. It was called Σ^*, with J=1/2.

[§]Remember G. Chew. . .

The large number of states rapidly discovered led to $SU(3)$ and later quarks.

It's important to remember that not just mass peaks were found, but J^{PC} assignments determined.

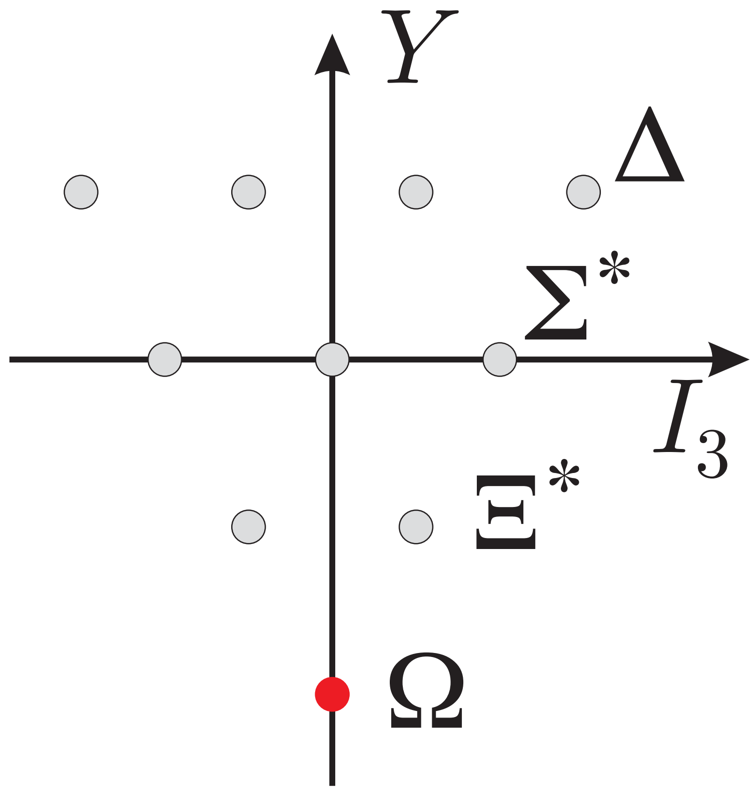
The 1^{--} nonet



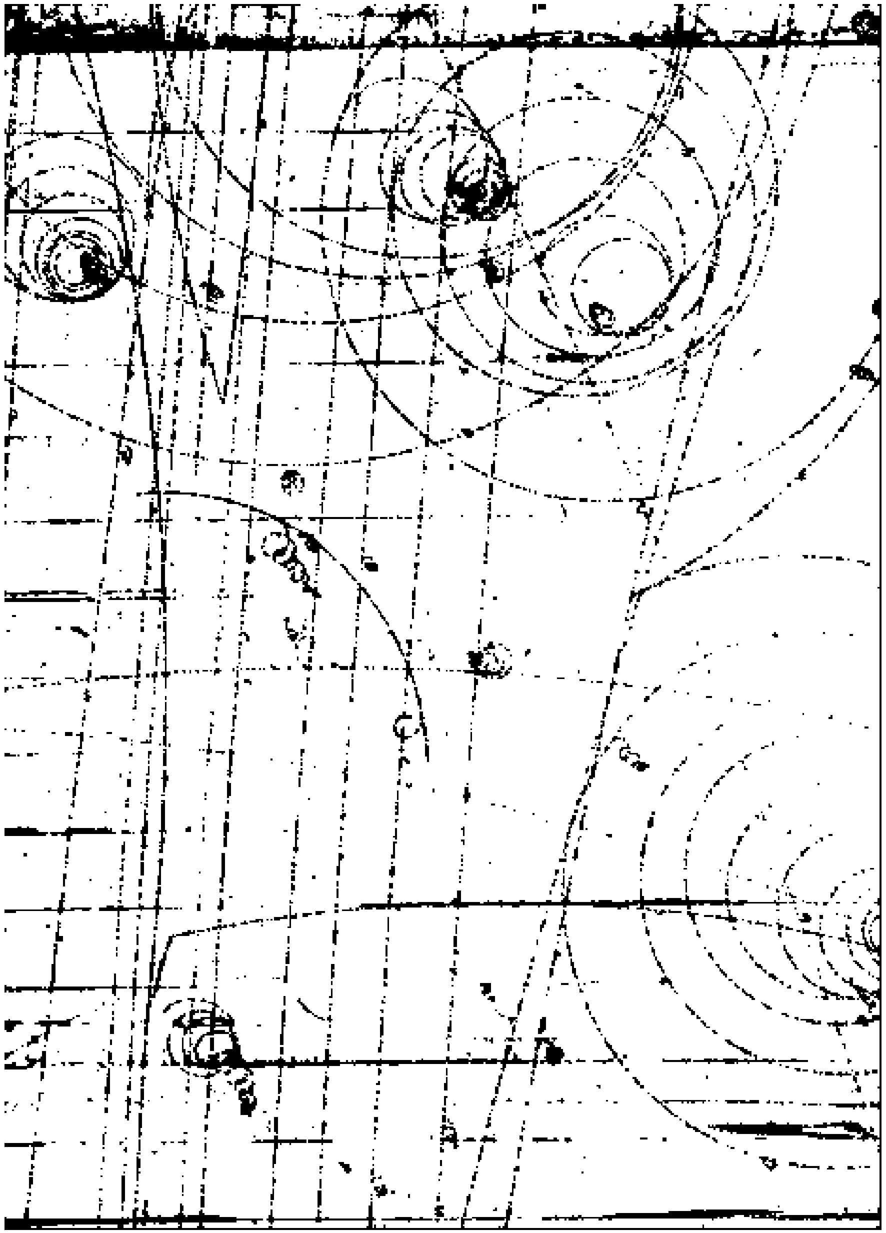
More New Particles

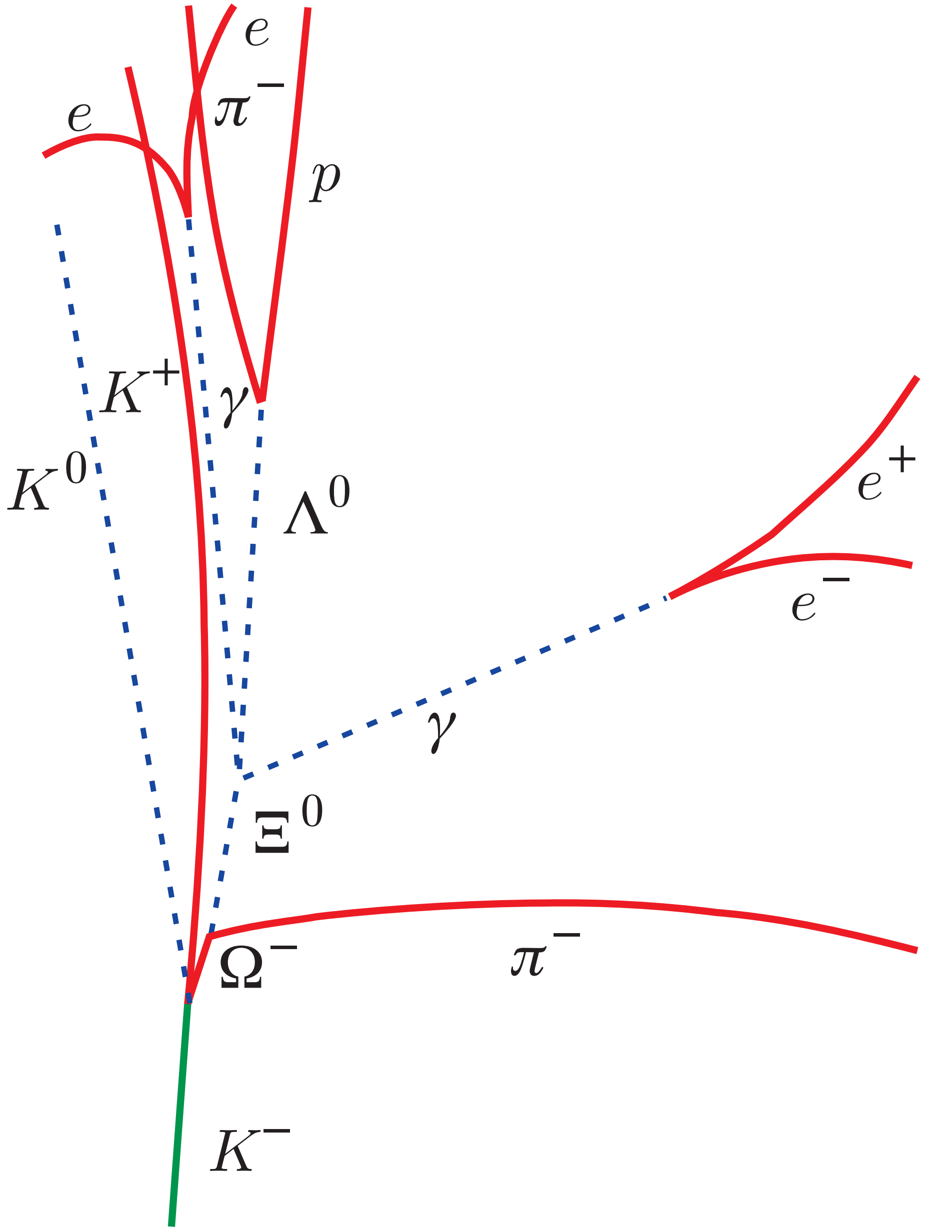
The story continues with the Gell-mann-Ne'eman "8-fold way", today $SU(3)_{\text{flavor}}$.
The completion of the spin 3/2 baryon decuplet requires the existence of a $Q = -1$, $S = -3$ baryon, named Ω^-. Moreover the mass is predicted to be 1670 Mev. Expected decays are: $\Omega^- \to \Lambda \overline{K}^0$ and $\Omega^- \to \Xi\pi$.
Found in H_2 with K^-.

NS very lucky



Ω^-, BNL 80" H_2, '64





Neutral currents, 1973

A truly unexpected, by most, discovery was made in the giant Gargamelle chamber filled with 18 tons of freon, built by Lagarrigue and co., at Saclay. The chamber was 1.85 m dia and 4.85 m long - 12 m^3, working in a 2 T field. It used 8 cameras and was followed by a muon identifier.

Two new type of neutrino interactions were observed:

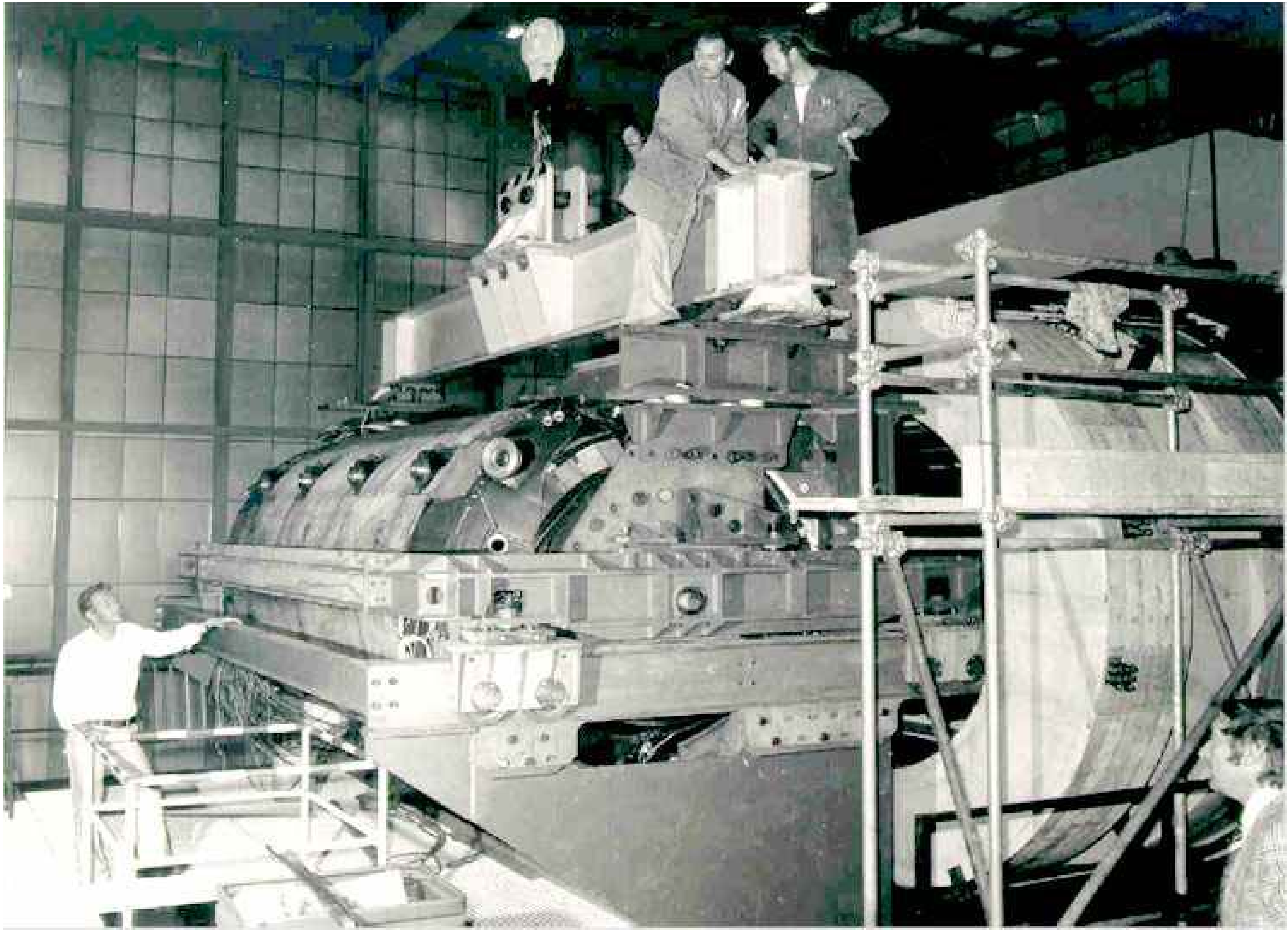
1. Interactions without production of muon
2. Production of a single electron

The '73 CERN discovery of "neutral currents" in neutrino interactions was born among raging controversy and nail-biting doubt. For the first time, neutral currents had been seen, against the overwhelming prejudices of most phsy-cists.

In 1973 CERN had yet to reach full scientific maturity. European physicists were not used to making major discoveries at their accelerators and were sometimes hesitant to swim against powerful currents of opinion. The discovery enabled CERN to attain research maturity.

From CERN Courier, Nov 98, Twenty-five years of neutral currents, by Gordon Fraser.

In the end it was conclusively proved that the signal was there and a new chapter in physics was begun. Neutral weak currents, expected in the unified electroweak interaction had been found.



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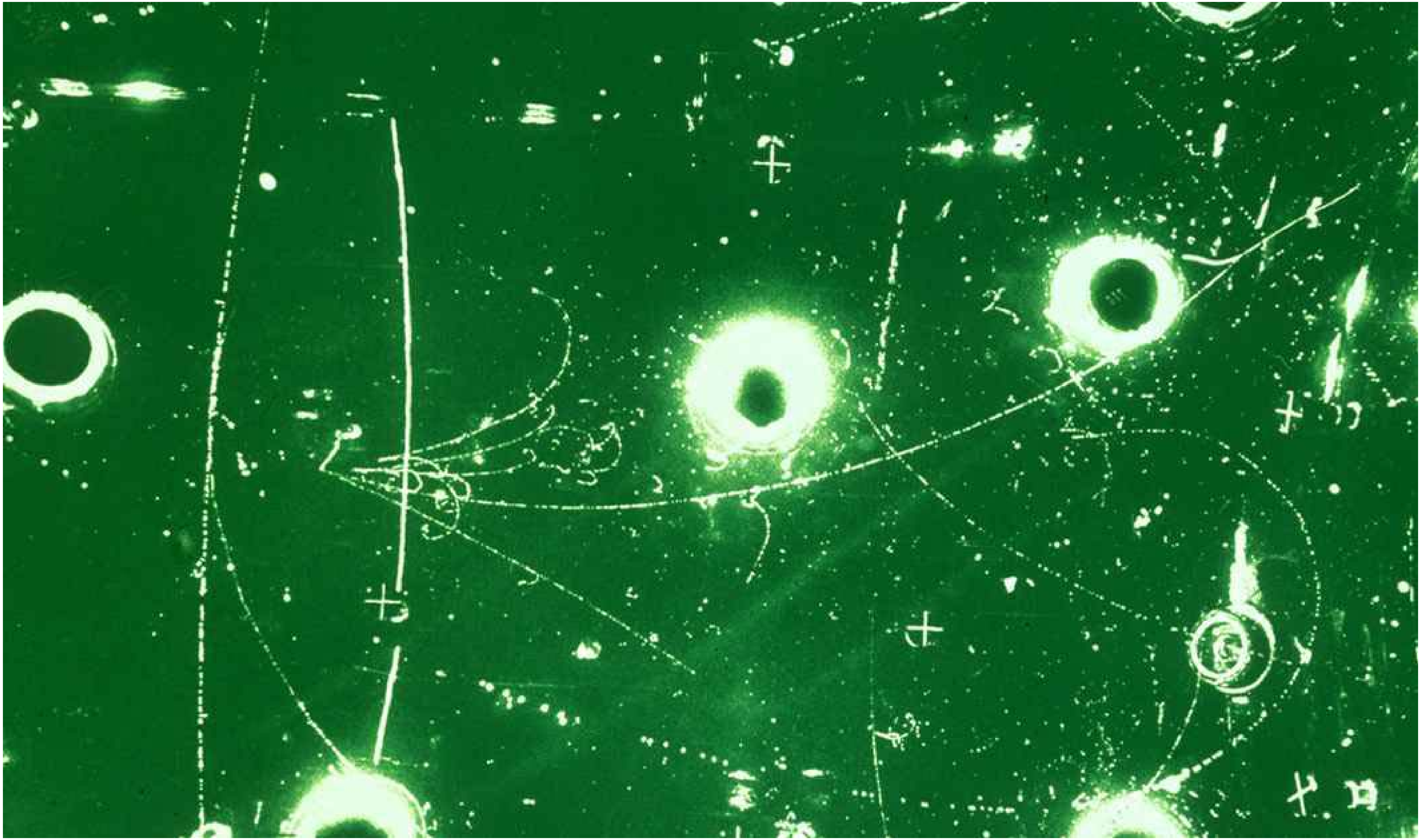


The discovery was in strong disagreement with previous BEBC limits and early Fermilab results from conventional neutrino set-ups.

The Gargamelle discovery gave a tremendous push to a new industry: neutrino experiments in bubble chambers. BC are not best suited to this kind of physics, the major drawback being the impossibility of triggering the chamber.

The fantastic power of a visual technique of superior spatial resolution together with excellent momentum measuring accuracy and hermeticity were however of tremendous help to neutrino physics and also in the understanding of the charm coupling, V_{cs}.

From 6 inches to 15 feet

The first chamber to produce physics was $6''$ or 15 cm in diameter and used propane. The last, at Fermilab, was $15'$ or 450 cm diameter and was operated with H_2, D_2 and H_2-Ne mixtures. Many technical innovations were necessary. The shape of the chamber changed from tub-like, with windows getting bigger and unsafe to an almost spherical volume viewed through small windows with super wide-angle lenses.

The whole chamber inner wall is lined with Scotch-lite an almost perfect retroreflector.

Gross distortion due to the optics was removed by the computer.

The Monster chambers

BNL 7 foot chamber

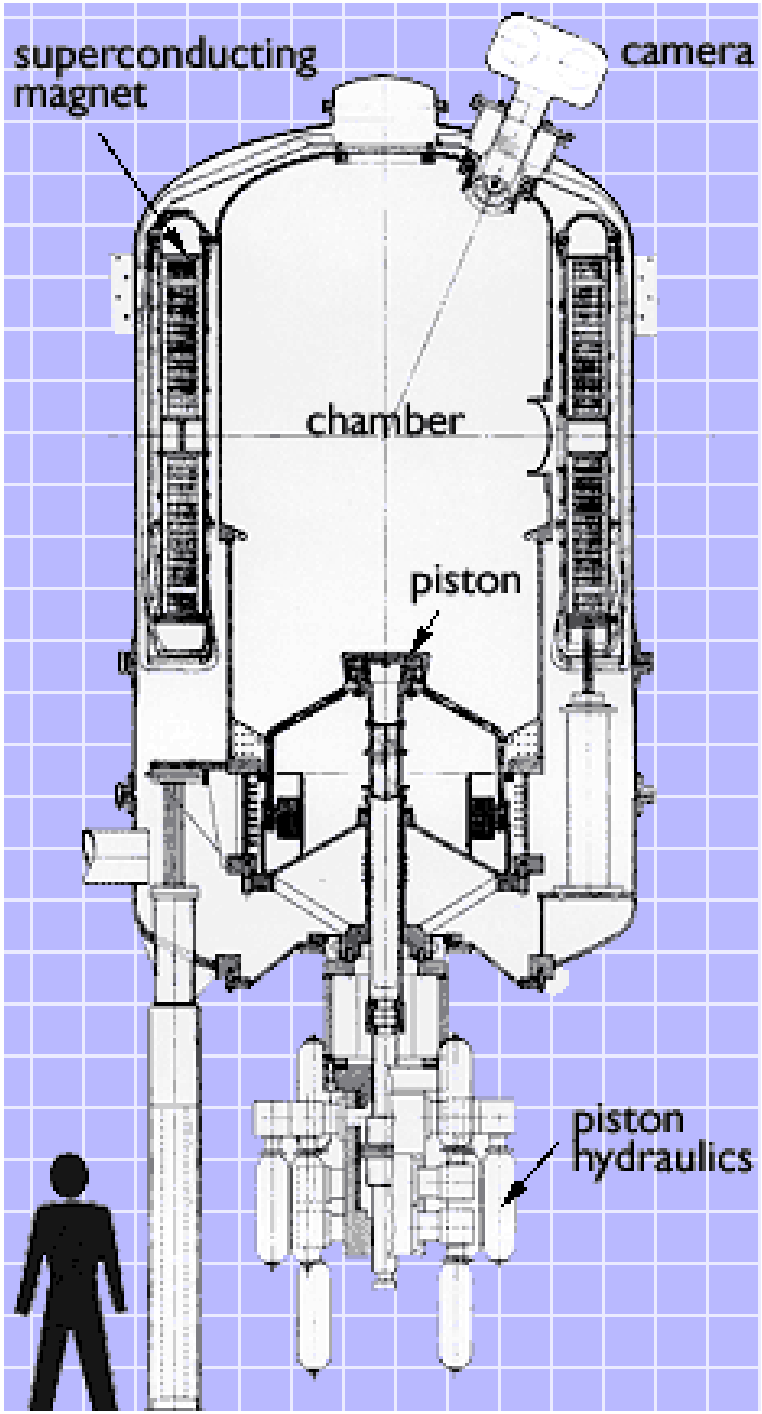
also

CERN BEBC, 35 m^3

ANL, 12 foot

FNAL 15 foot

They finally led to the extinction of the species



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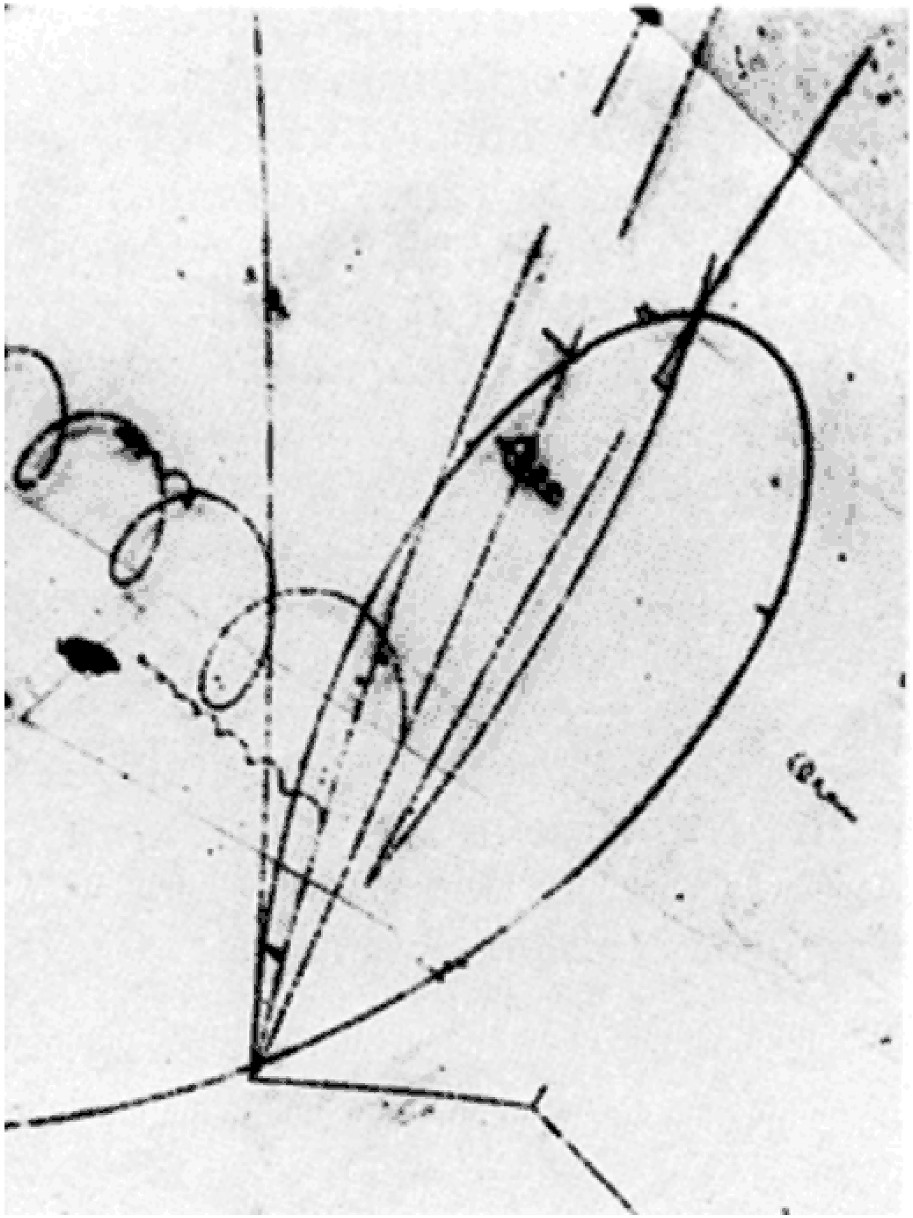
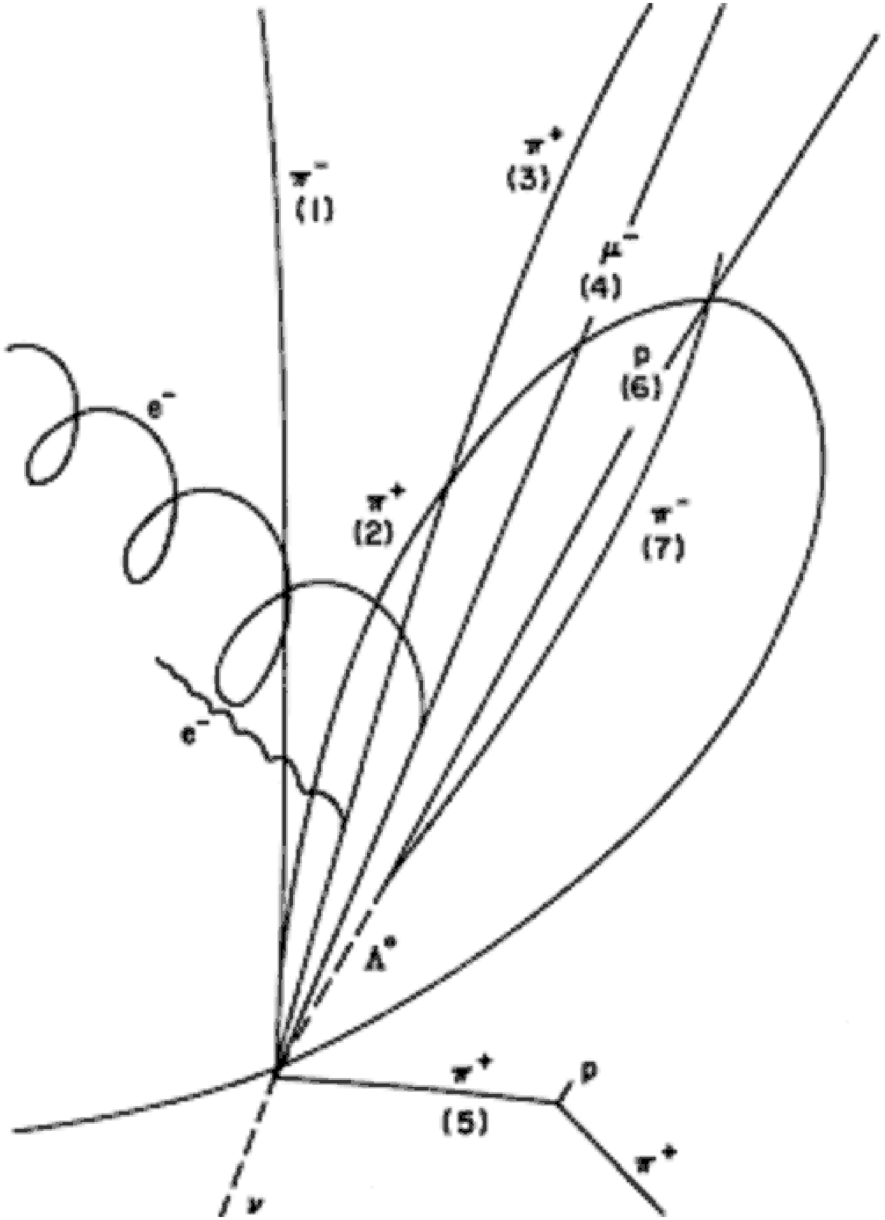
Charmed baryon, BNL

$\nu p \to \mu^- \Sigma_c^{++}$; $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$; $\Lambda_c^+ \to \Lambda^0 \pi^+ \pi^+ \pi^-$; $\Lambda^0 \to p\pi^-$





The collaborations

Soon BC work became somewhat routine. Large numbers of scanners and measurer were needed. Pictures would be distributed to many small groups who only needed a modest investment in a few, even 1 or 2, projector and measuring tables.

"Bubble chamber experiments brought physicists from almost all over the world closer together. The participants generally did not have the technical knowledge to run the chamber, since most of the chambers were considered facilities, operated by their designers at the accelerator laboratories.

Data could be exchanged either by recordings on magnetic tapes or over the telephone line. Collaboration meetings were held, bringing experimenters together at various places."

From G.G. Harigel, CERN

Not much different from LEP, TeV-I or the future colliders.

No scanners and measurers

Since the mid 60s attempts were made to eliminate scanning (the search for the event) and measuring.

The principle is simple. "Digitize" the image and feed all data to a computer. Pattern recognition software joins bubble into tracks, tracks into events and also choose the right ones. While doing all that, the program also computes the momenta of the particles and by kinematics confirms the event class. THAT'S ALL.

Well it did not quite work. But it did get close in a few cases. And the large collaborations could provide the labor much more simply.

Oddities

The first rapid cycle, 10 expansion/s, bubble chamber was operating at the Frascati synchrotron in 1959. The record is 50 Hz and a field of 11 T. Another 30 Hz chamber was used to study charm. It could record 15 μm bubbles and collected some 800 charm decay events.

Tiny chambers used holography for super high accuracy. When holography was proposed for the 15 foot chamber it was rejected. The BC era was coming to an end.

There where even chambers inside chambers. . .

The advent of the collider unquestionably doomed the bubble chamber. It was not however the only reason. The wide ranging contributions to physics are due to the study of relatively abundant processes. Even the study of weak decays, never better than the few % accuracy, succeeded because of abundant production.

One cannot otherwise study rare processes without intense beams, sophisticated triggers and detectors capable of very rapid response. A BC is an integrating instrument and cannot deal with even only 1000 events/s.

Nobody ever succeeded in triggering a BC, though many tried. The best was to trigger the flash, but no big deal.

Ca. 1980. The BC also disappears from particle physics, replaced by the general purpose collider detector.

The future is in the hands of the super-large collaborations of the super-detectors at the new super-colliders.

But they will never have one event to show that proves all!

RIP