Spark Chambers: Le Son et Lumière des Particules.

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OUTLINE

WHAT IS IT USED FOR?

To find the path of a charged particle from a trail of sparks.

HOW DOES IT WORK?

Apply a large HV pulse to induce spark formation.

S-C EXPERIMENTS with OPTICAL READOUT:

Two neutrinos. $\Delta I = 1/2$ Rule.

SPARK LOCALIZED by SOUND

Precision measurement of μ decay spectrum.

MODERN COUSINS: MWPC TO TPC...

Preview of the largest drift chamber.

WHAT IS A SPARK?

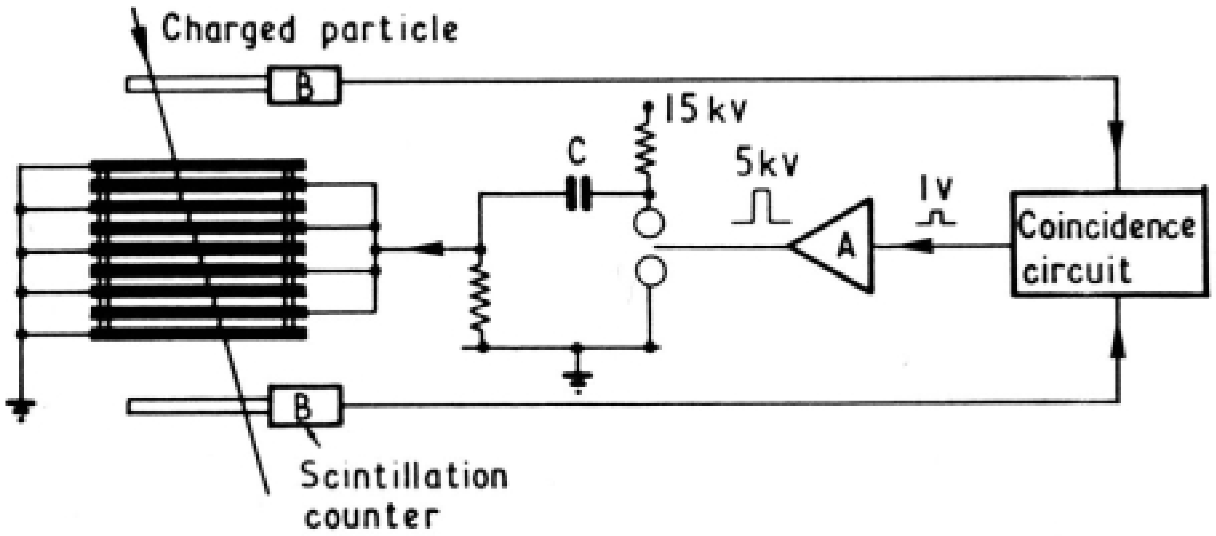
A gas discharge in a gap between two electrodes, occasioned by ionization from a passing particle.

HOW IS IT PRODUCED?

A high voltage pulse is applied, right after a particle's passage. An avalanche develops into breakdown in the gas with large conduction: a spark is formed around the initial ionization. Spark formation depends critically on the inter electrode gap and the gas amplification (at least 10^8 electrons in the head).

Many gaps are connected in parallel. The spark trail gives the particle's trajectory.

The most used gas is 70% neon, 30% helium, costing about 3p per liter in the UK some 30 years ago.

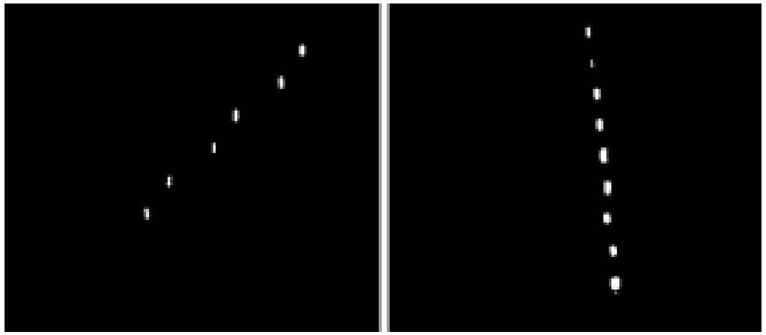


DETAILS

Spark chambers are easy to make, provided one takes elementary precautions in making the electrodes flat, extend beyond the gas volume and that the gaps are uniform in thickness

Common problems are gas tightness, so one usually resorts to a bit of over pressure and allow some continuous flow.

Proper grounding is absolutely essential to avoid spurious sparks.



Provide a good switch such that a HV pulse is applied immediately when the trigger indicates a particle's passage.

The switch closes after receiving a trigger derived from counter logic. When the switch is closed, the chamber capacitance C_{ch} is connected in parallel with the storage capacitance C_s, so the total capacitance is $C_{ch} + C_s$, and the voltage applied to the chamber is $V\,[C_{ch}/(C_{ch} + C_s)]$.

The effective HV pulse duration is determined by R,
$\tau = R(C_{ch} + C_s)$.

The requirements for the switch is that it should have low internal impedance and be able to pass a large current.

The break down delay and turn-on should be as short as 10 nsec after the trigger pulse.

It should be stable, say last for 10^5 pulses which discharge two Joules of energy.

The literature is full of recipes and meticulous mechanical drawings of how to manufacture such spark gaps in a machine shop.

We had instead, bought obsolete atomic(?) bomb trigger cubes, they were convenient, cheap, but alas, not overly reliable!!!

OPTICAL READOUT BY PHOTOGRAPH

The first method to record the sparks was by photographing the sparks, then scan, measure and calculate their positions.

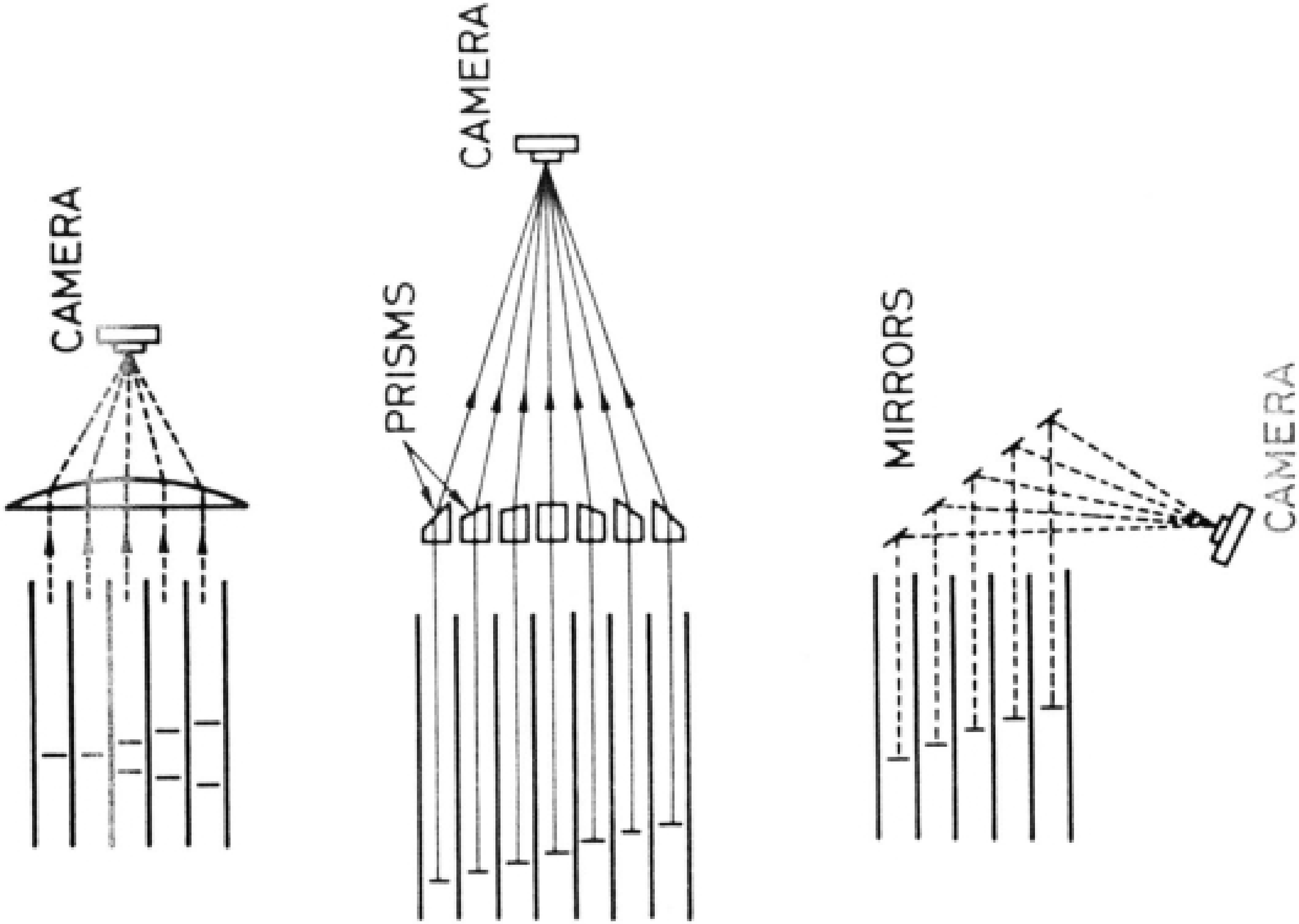
Most HEP groups usually had sophisticated bubble chamber scanning apparatus in the lab, readily usable for spark chamber pictures.

Spark chamber pictures are truly triggered and most often contain a good event.

They are usually much simpler to analyze.

However, since the electrodes are opaque, in contrast to the liquids used in bubble chambers, different optical set-ups are needed to get the images of the sparks on film.

Prisms, cylindrical (spherical) lenses, mirrors and sometimes a combination of them are used to produce a virtual image of the chamber with all gaps pointing to the camera.

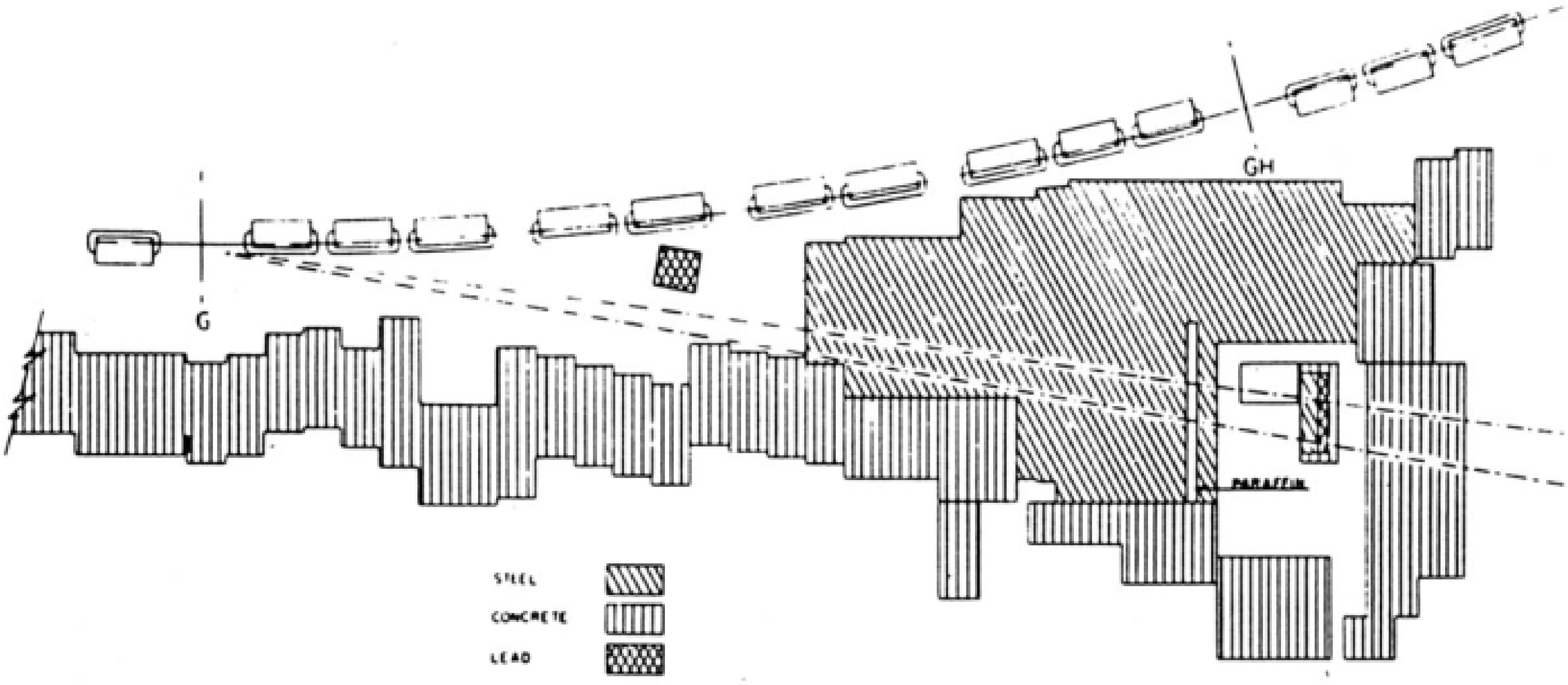


IS the ν_e different from the ν_μ ?

One of the earliest experiments which capitalizes on the spark chambers' virtues of event selectability, which in some sense, places the major responsibility of experimental design on having the appropriate beam, clean background conditions and specific triggers, is the experiment at BNL which established the existence of the ν_μ by observing muon production (but not e's) from a ν_μ beam in matter, in 1962.

An aside: an experiment, DONUT, observing τ appearance from ν_τ, has recently been published, NIMA 493 (2002) pp 45-66.

It was expected that at the AGS (or CERN PS) neutrinos from pion decay, passing through a thick shield, can produce between 0.2 to 2 events per ton of detector per day.



TEN ONE TON SPARK CHAMBERS

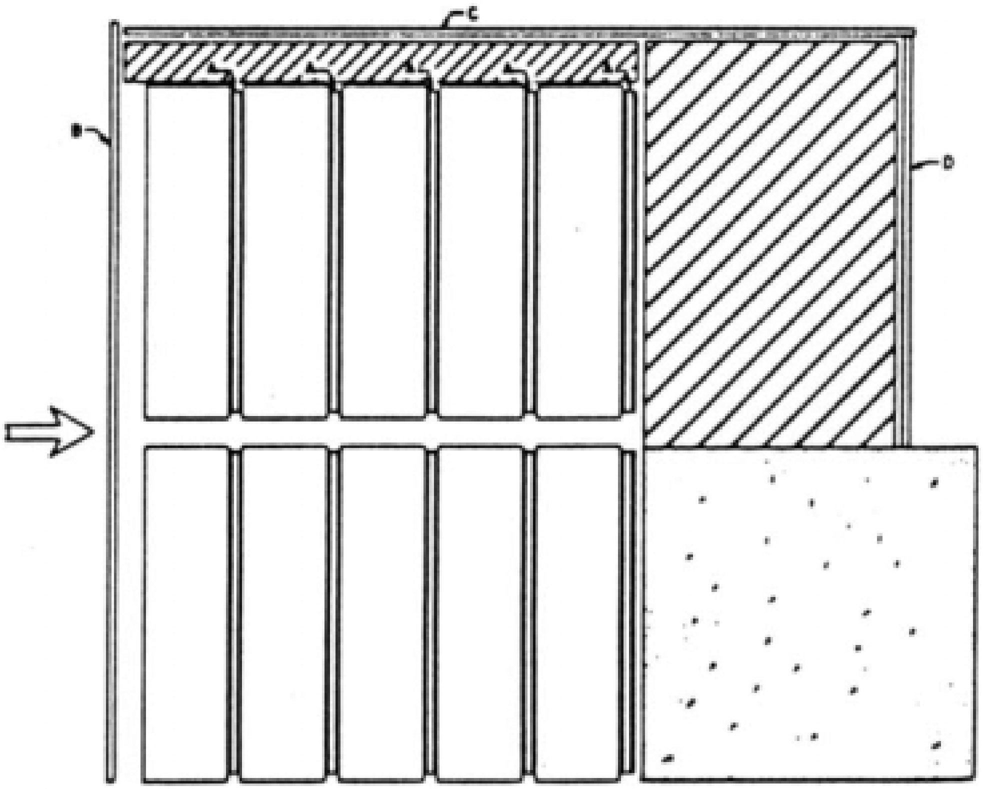
each made of 9 Al Plates, 44in x 44in x 1in, separated by 3/8 in lucite spacers, are placed behind a 13.5m thick Fe shield wall 21m from a target in the AGS ring .

The AGS beam operates with a repetition period of 1.2 sec, a fast beam deflector drives the protons onto the 3-in thick Be target for ∼20-30 μs producing pions.

The rf structure results in bursts ∼20ns wide, separated by 220 nsec

One produces a train of 30 nsec gates during which the trigger made from forty coincidence pairs (A) is accepted. Cosmic rays shield counters (B, C and D) are used in anticoincidence.

AGS has about 3x10^{11}p's per pulse, 3000 pulse/hr. Total exposure was 3.5x10^{17} protons, only 34 single high energy, greater than 300 MeV muons were found, no high energy electrons, proving ν_μ only produce muons, and there are neutrinos of two flavors.



The $\Delta I = 1/2$ RULE

Let's step back to continue the other parallel strand of historical narrative, namely to the lectures on kaons and strange particles. Recall that the kaons belong to two different isospin doublets which have opposite strangeness S:

$$K^0 = d\bar{s} \qquad \overline{K^0} = \bar{d}s$$

$$K^+ = u\bar{s} \qquad K^- = \bar{u}s$$

$$S = +1 \qquad S = -1.$$

$$C|\,K^0\,\rangle = |\,\overline{K^0}\,\rangle,\;\; S|\,K^0\,\rangle = |\,K^0\,\rangle,\;\; S|\,\overline{K^0}\,\rangle = -|\,\overline{K^0}\,\rangle$$

In order to explain why $\Gamma(K^0 \to 2\pi)$ is $\ll$ than $\Gamma(K^\pm \to \pi^\pm\pi^0)$ (by about 700), Gell-Mann and Pais in 1954 proposed an empirical rule $\Delta = 1/2$ in weak decays.

First of all we must see what I-spin values are allowed for two pions. Since they are bosons, the wave-function must be totally symmetric. For J=0, the space part of ψ is sym., therefore only $I = 0, 2$ are allowed.

For $\pi^+\pi^-$, $\pi^0\pi^0$, I_3=0, therefore both I=0 and 2 are OK. For $K^\pm$ the pions states are $\pi^\pm\pi^0$ and $I_3 = \pm 1$, *i.e.* only $I = 2$ is allowed.

Non leptonic weak interactions are due to the product of the hadronic weak current with itself. The current is the sum of two term:

$$J^{\text{hadr}} = (du) + (su)$$

The first term contributes to ΔS=0, $\Delta\vec{I}$=1 and the second to ΔS=1, $\Delta\vec{I}$=1/2.

$K \to 2\pi$ decays are due to

$$J^{\text{had}\dagger} J^{\text{hadr}} = \ldots (du)^\dagger (su) \ldots$$

and the I-spin selection rule is ΔI=1/2, 3/2.

K^0 decays can go by ΔI=1/2, 3/2 while for $K^\pm$ only ΔI=3/2 contributes.

Not only a ΔI=1/2 dominance explains the suppression of $K^\pm$ decays, it also agrees with $\pi^+\pi^-/\pi^0\pi^0 \sim 2$ in K^0 decay,

it also explains why $p\pi^-/n\pi^0 \sim 2$ in Λ decay, etc.

To express this rule quantitatively, including final state interaction we define

$$A(K^0 \to 2\pi, I) = A_I e^{i\delta_I}$$

where δ_I are the $\pi\pi$ scattering phase shifts in the I=0, 2 states.

Also recall that $|\,K_1\,\rangle \equiv (|\,K^0\,\rangle + |\,\overline{K}^0\,\rangle)/\sqrt{2}$

To get the result project $|\,K, S, I_3, I_3\,\rangle$ onto $|\,0,0\,\rangle$, $|\,2,0\,\rangle$ and $|\,2,1\,\rangle$ (S, called sometimes spurion has spin 1/2 and 3/2 and stands for the I-spin property of the interaction. The I_3 are obvious).

Do the same for the 2 pion states. Finally you get:

$$\langle \pi^+\pi^- | K_1 \rangle = \sqrt{\frac{2}{3}} A_0 e^{i\delta_0} + \sqrt{\frac{1}{3}} A_2 e^{i\delta_2}$$

$$\langle \pi^0\pi^0 | K_1 \rangle = \sqrt{\frac{1}{3}} A_0 e^{i\delta_0} - \sqrt{\frac{2}{3}} A_2 e^{i\delta_2}$$

$$\langle \pi^+\pi^0 | K^+ \rangle = \frac{1}{2}\sqrt{3} A_2 e^{i\delta_2}$$

$$\frac{\Gamma(K_1 \to \pi^+\pi^-)}{\Gamma(K_1 \to \pi^0\pi^0)} = \frac{\rho_\pm}{\rho_{00}} \left[2 + 6\sqrt{2}\frac{A_2}{A_0}\cos(\delta_2 - \delta_0) \right]$$

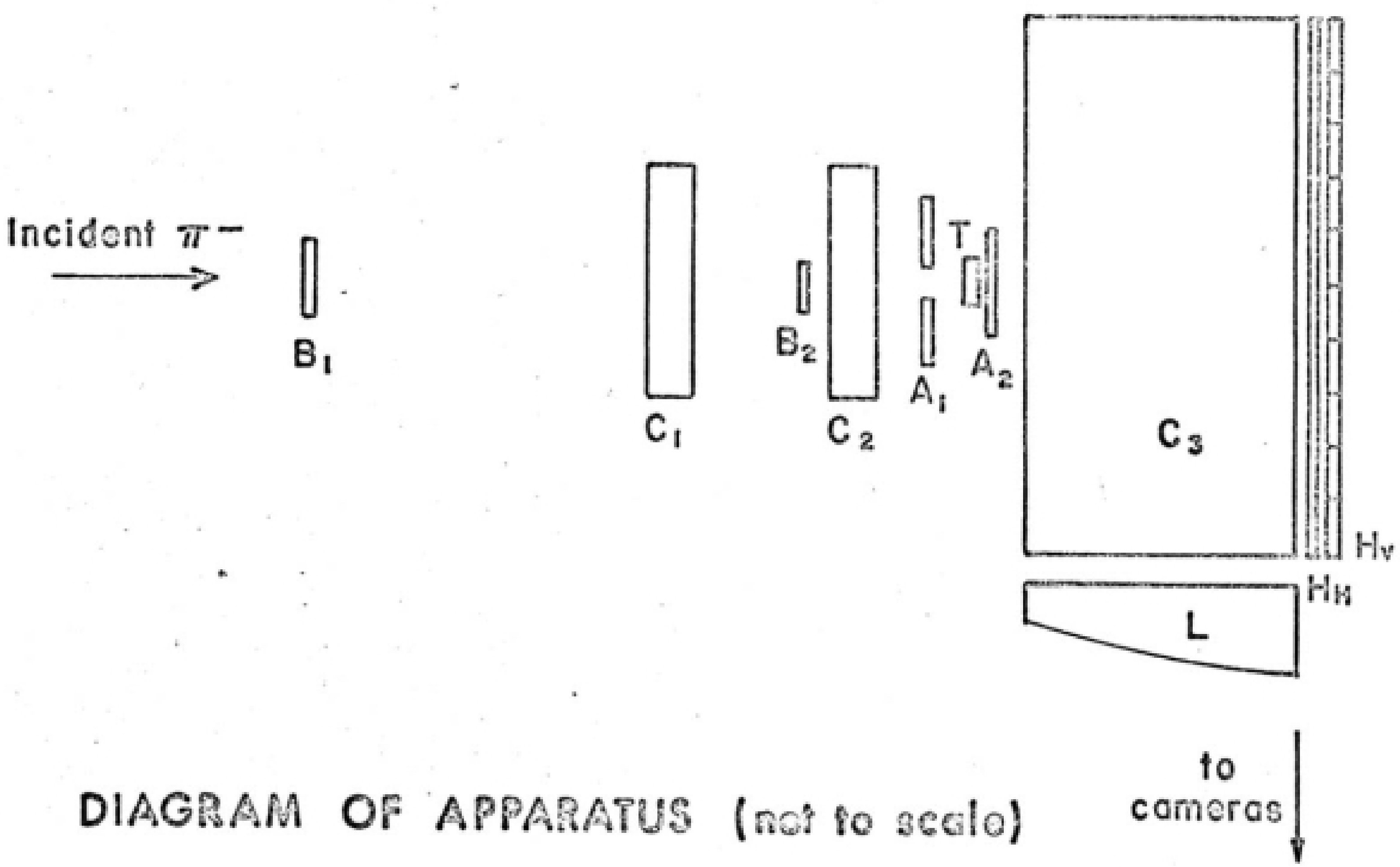
$$\frac{\Gamma(K^+ \to \pi^+\pi^0)}{\Gamma(K_1 \to 2\pi)} = \frac{3}{4}\left(\frac{A_2}{A_0}\right)^2$$

Since the K has isospin 1/2, the isospin change in the transition to two pions can also be 5/2. The amplitude for a change ΔI can be related to the amplitudes A_I to find the two pions in a final state of isospin I.

$e^{i\delta_0}A_0 = a_{1/2}/\sqrt{2}$,
$e^{i\delta_2}A_2 = (a_{3/2} + a_{5/2})/\sqrt{2}$,
$e^{i\delta_2}A_+ = \sqrt{3/4}a_{3/2} - \sqrt{1/3}a_{5/2}$

The departure from the $\Delta I = 1/2$ rule in kaon non leptonic decay is experimentally done through measuring the ratio R, the rate of $K_1 \to \pi^+\pi^-$ over $K_1 \to \pi^0\pi^0$, and then seeing how much it differs from 2, after taking into account the em corrections.

One of the first measurements of R which accounts correctly for systematic uncertainties, with high statics, was performed in an optical spark chamber in 1972 at the PPA.



We used a 1 GeV π^- beam hitting a polyethelene target which produced ΛK pairs in associated production. $\pi^- p \to \Lambda K$, triggering on the proton from the decay $\Lambda \to \pi p$, the energy was chosen to be at the peak of Λ production while being below the threshold for ΣK production.

The trigger is based on the disappearance of the beam π^- and the appearance of a three times mimimum charged track (the decay proton) which passing through a 1" by 1" element of a 10x10 hodoscope, $H_V \times H_H$.

A 40 layer very thin spark Al (X_0=0.06) chamber C_3 filled with Neon (doped with 2/10000 part of Freon), operating at 9KV high voltage, was placed between the target and in front of the hodoscope.

A large cylindrical lens made the entire depth range of the chamber visible to two cameras with 15 degree stereo. Chamber and hodoscope were both immersed in a highly homogeneous 14 KG field. 162,000 pictures were taken which recorded the decay products. Upon subsequent analyses, yield the decay vertex, momenta, and energy were reconstructed. 65,000 Lambda decays were analyzed, yielding 16,000 $K^0 \to \pi^+\pi^-$ decays, resulting in R = 2.165 $\pm$ 0.098. Note that this is a 5% error experiment. We had to wait 30 years before improving it by about an order of magnitude.

The experiment also proved that $a_{5/2}$ is smaller than $a_{3/2}$

SONIC CHAMBERS: THE MUON DECAY SPECTRUM

From the first day of studying muon decays, one noted that the positron is not monochromatic, that its end point indicates the production of two massless particles, specifically, a $\bar{\nu}_\mu$ and a ν_e.

Neglecting the electron mass and introducing $x = E/(2M_\mu)$, the electron spectrum is given, for a $V-A$ coupling, by:

$$\mathrm{d}\Gamma = \frac{G^2 M_\mu^5}{96\pi^3} x^2 (3 - 2x)\mathrm{d}x$$

and, integrating over the spectrum,

$$\Gamma = \frac{G^2 M_\mu^5}{192\pi^3}. \tag{1}$$

Accurate measurements of the muon lifetime allow one to determine the Fermi coupling constant G. One must however include radiative corrections. (1) then becomes:

$$\Gamma = \frac{G^2 M_\mu^5}{192\pi^3}(1 - \frac{\alpha}{2\pi}(\pi^2 - 25/4))$$

Moreover, a detailed measurement of the shape of the spectrum gives us the weak coupling, *i.e.* whether it is (V-A), (V+A) or a combination of both.

If we allow both, the muon decay spectrum is:

$$\mathrm{d}\Gamma = 12\Gamma[(1-x) - \frac{2}{9}\rho(3-4x)]x^2 \qquad (2)$$

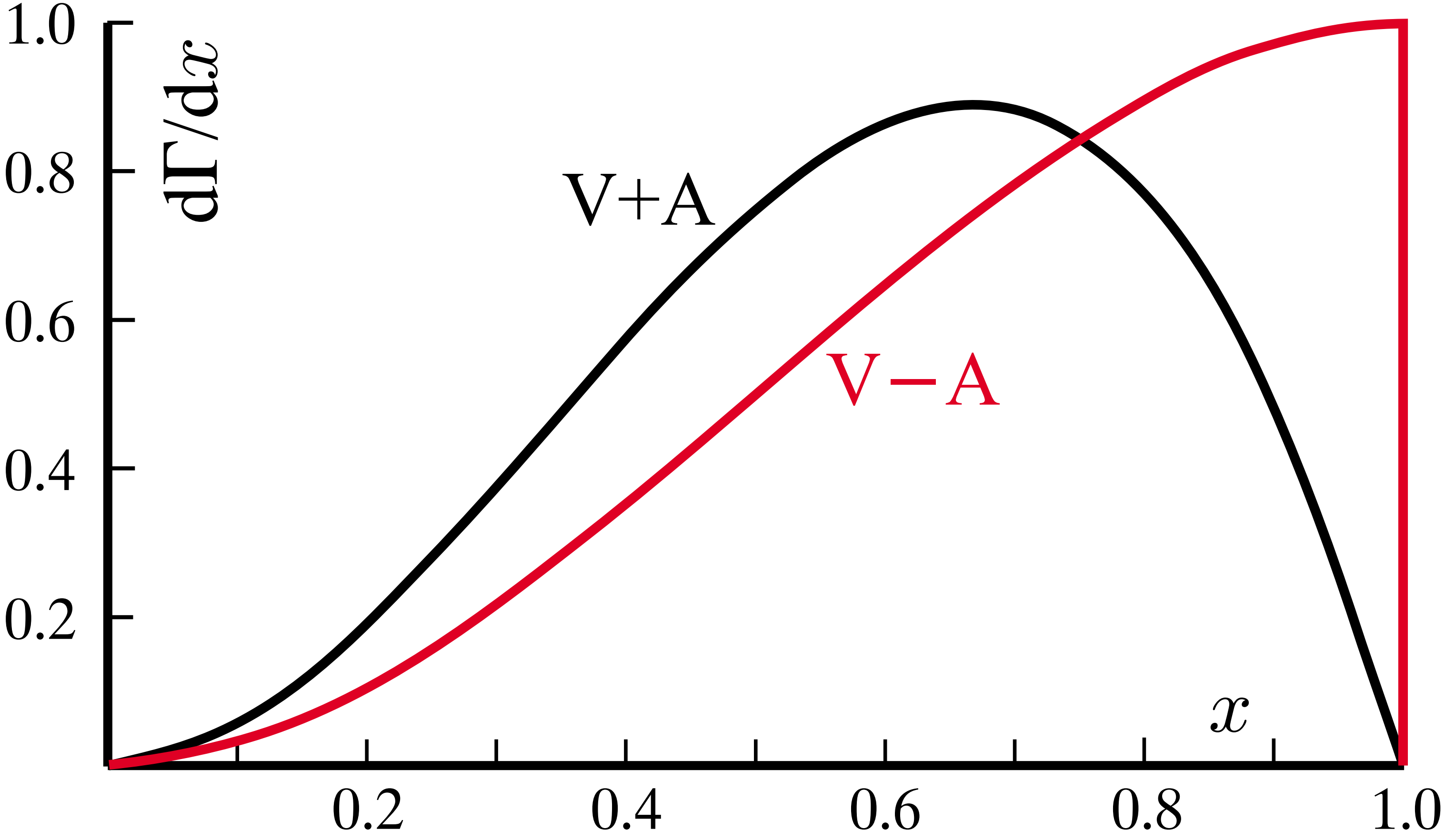
where $\rho = 0.75$ for pure V-A.

$$\mathrm{d}\Gamma = \frac{G^2 M_\mu^5}{96\pi^3} x^2 (3-2x)\mathrm{d}x$$

For pure V+A interaction, $\rho = 0$ and

$$\mathrm{d}\Gamma = \frac{G^2 M_\mu^5}{96\pi^3} 6x^2 (1-x)\mathrm{d}x$$

The two spectra, with correct relative normalization, are shown here:



The history of the rho value determination between 1952 through 1964 is funny: while the claimed accuracy improved by almost an order of magnitude, from 28% to 2.4% the central value vacillated merrily many std. dev., from 0.48 to 0.751.

We decided that we wished to do an experiment which could stand the test of time for say, at least a couple of decades, to an accuracy of 10^{-3}. IT STILL STANDS

What are the requirements?

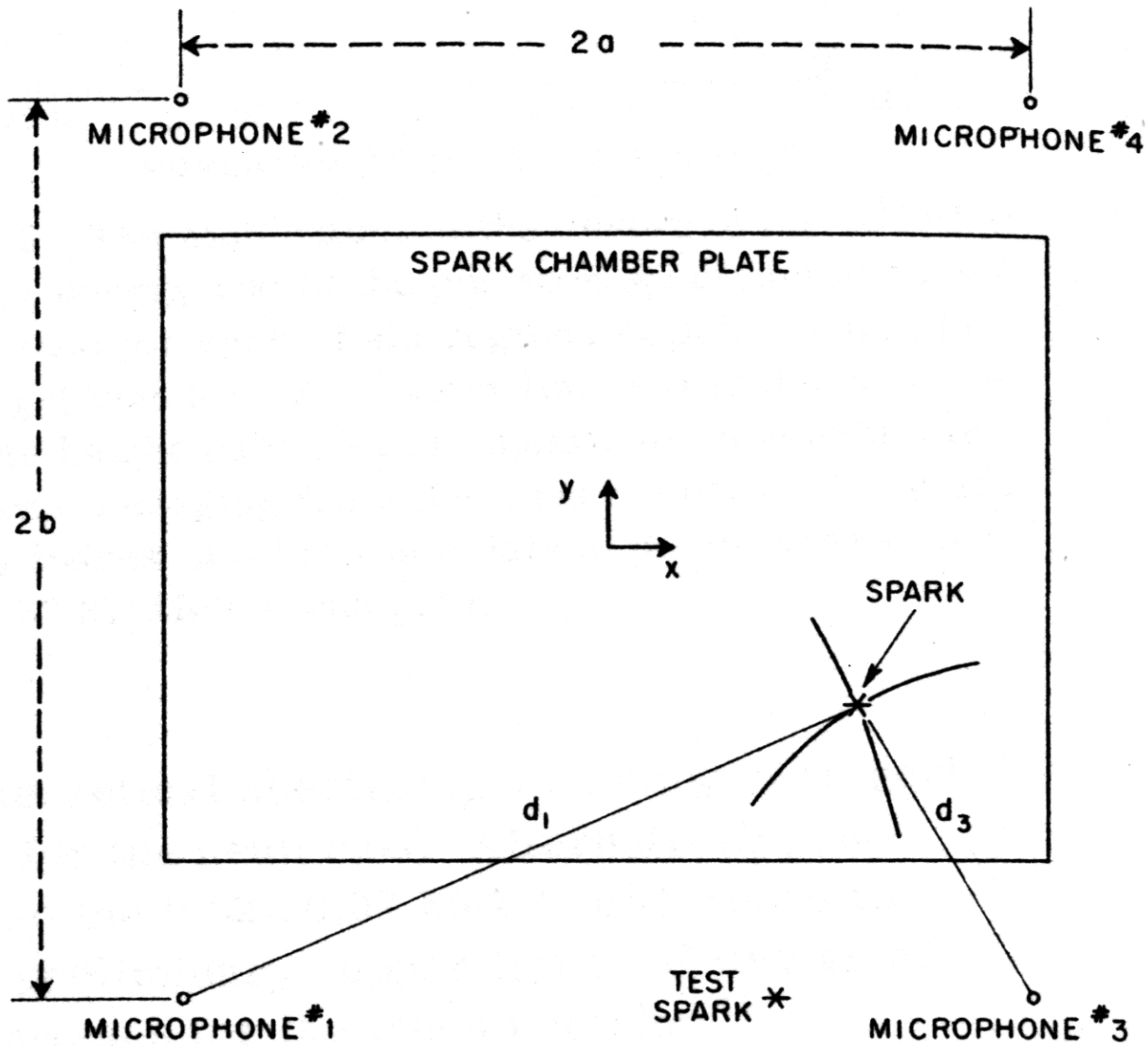
1. The experiment must be capable of analyzing about 10 million events. Optical chambers out, use sonic chambers: measure time delay of sound arrival (with microphones), digitize it and write it to tape.

$$d = V_{\text{snd}} t + K_{1\text{cm}}$$

$$t_p = 300 + \frac{K + R_d}{V}$$

$$x = \frac{V^2}{4a}[(t_1 + t_p)^2 - (t_3 + t_p)^2]$$

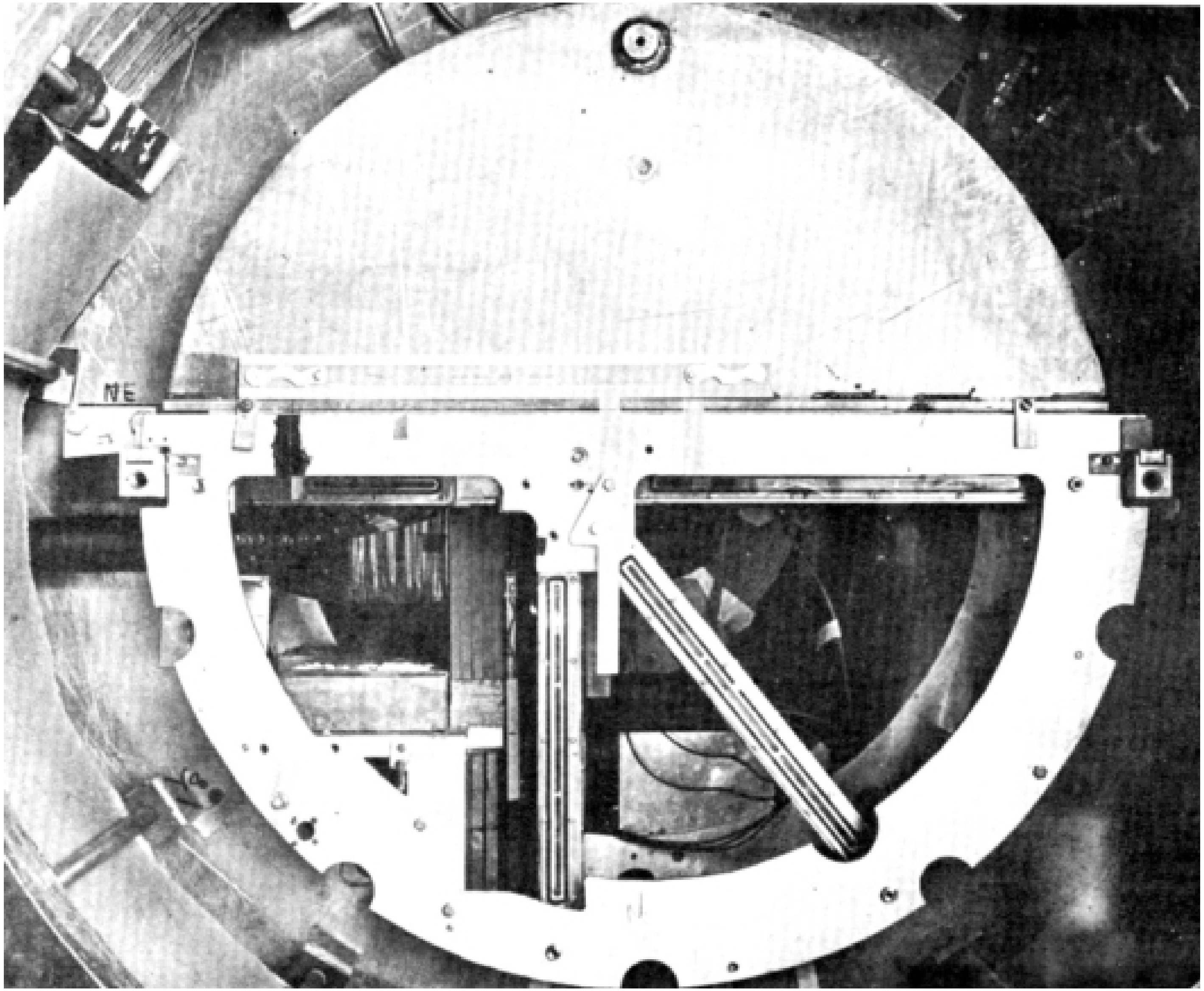
$$y = \frac{V^2}{4b}[(t_1 + t_p)^2 - (t_2 + t_p)^2]$$



2. Momentum resolution should be 1% or better, momentum measurement must be free of systematic errors to 1/10000. need special trick, 180° spectrometer.

3. Momentum acceptance magnet must be large enough so no more than four, five magnetic setting are necessary to cover the whole spectrum. super well shimmed, beefed up with extra coils 36” cloud chamber magnet.

Solid angle selection must be momentum independent.very large magnetic volume, electrons travel in vacuum, greater than 180° bending.



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is
tex

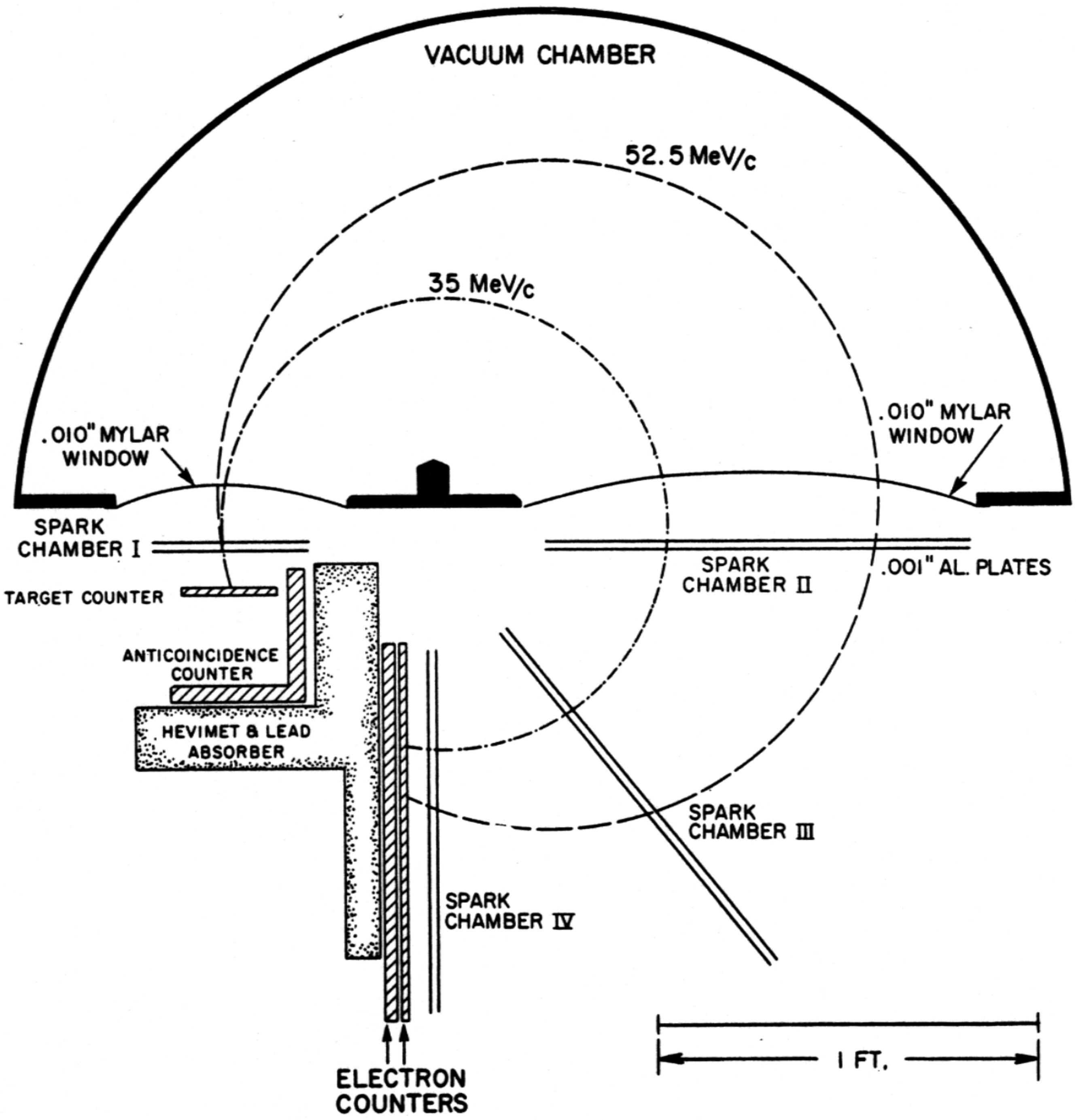
A π^+ beam is incident along the field and is stopped in a 3 mm thick target counter whose pulse height is recorded.

The trigger is a stopping π followed by an emerging positron curving through the four spark sonic chambers.

The momentum is essentially given by the separation of the sparks along the line through chambers I and II, correcting for angle.

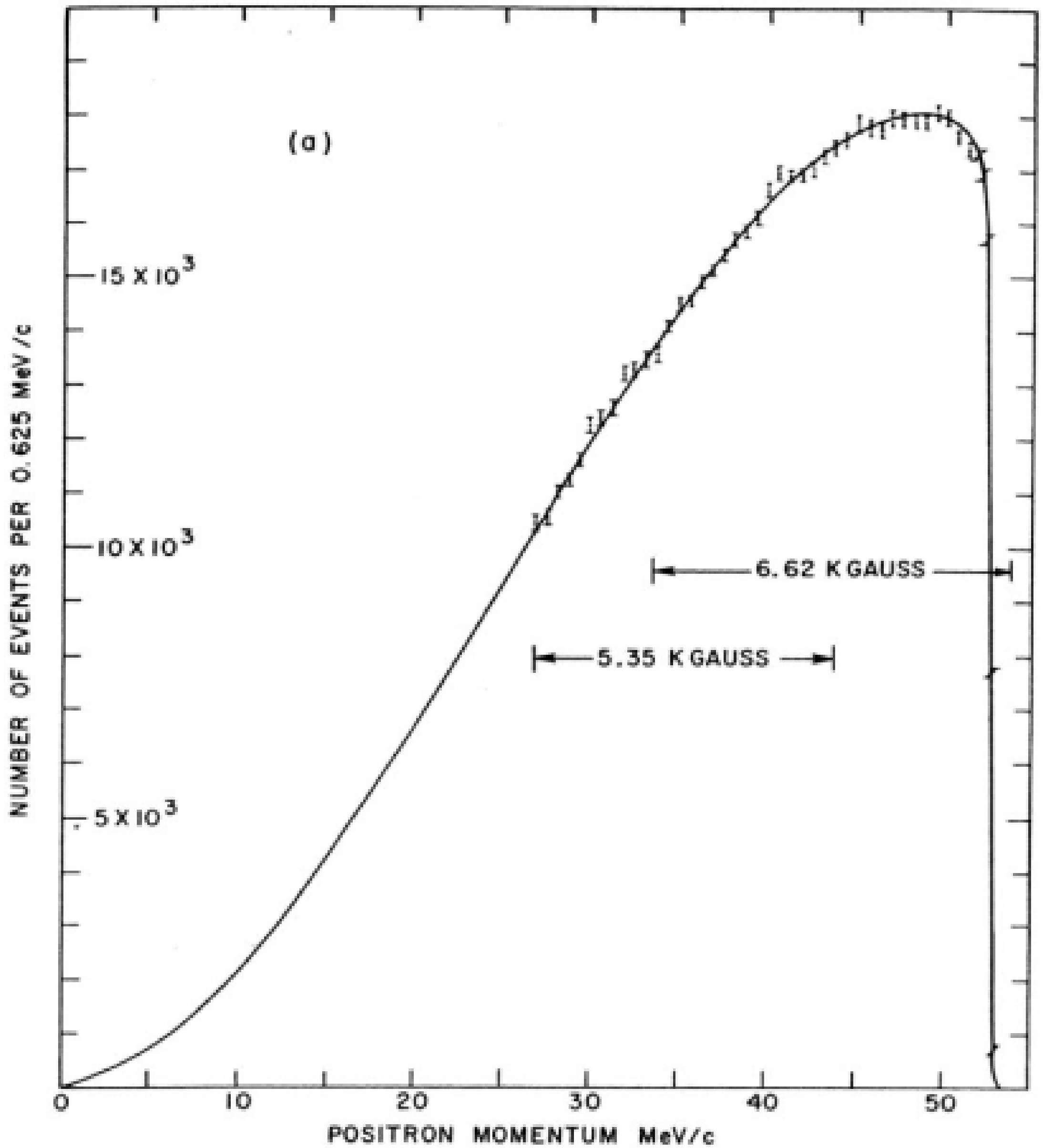
Chamber III measures the angle, chamber IV excludes tracks which have scattered

1.3 $\times 10^7$ events, at six different field settings were analyzed. After suitable radiative corrections, the most precise ρ value was obtained, as well as the ν_μ mass limited to be less than $6 m_e$.


VACUUM CHAMBER
52.5 MeV/c
35 MeV/c
.010" MYLAR WINDOW
.010" MYLAR WINDOW
SPARK CHAMBER I
TARGET COUNTER
SPARK CHAMBER II
.001" AL. PLATES
ANTICOINCIDENCE COUNTER
HEVIMET & LEAD ABSORBER
SPARK CHAMBER III
SPARK CHAMBER IV
ELECTRON COUNTERS
1 FT.

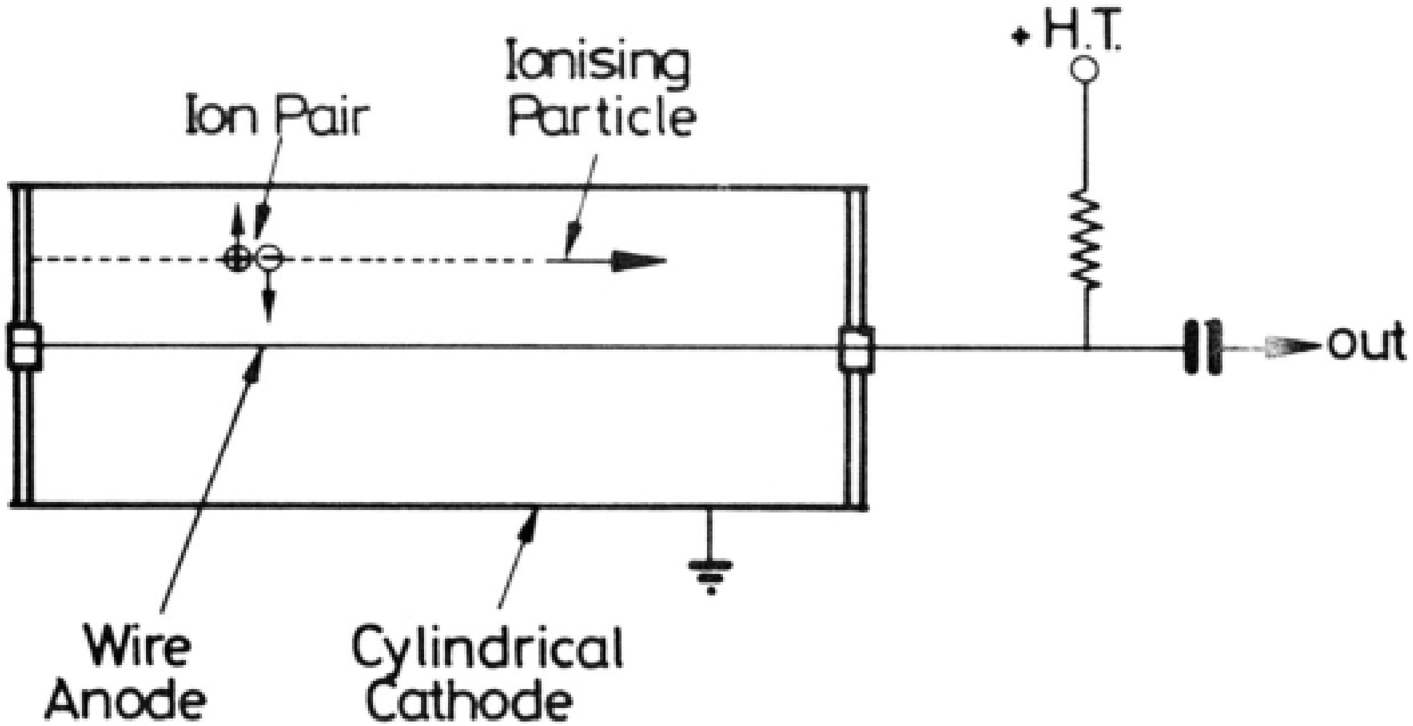
this is tex

MUON DECAY SPECTRUM, $\rho = 0.7503 \pm 0.0026$, PRL **14**, 449, (1965). PDG-2002: 0.7518±0.0026



MODERN COUSINS: MWPC, DRIFT CHAMBER, TPC · (not discussed here)

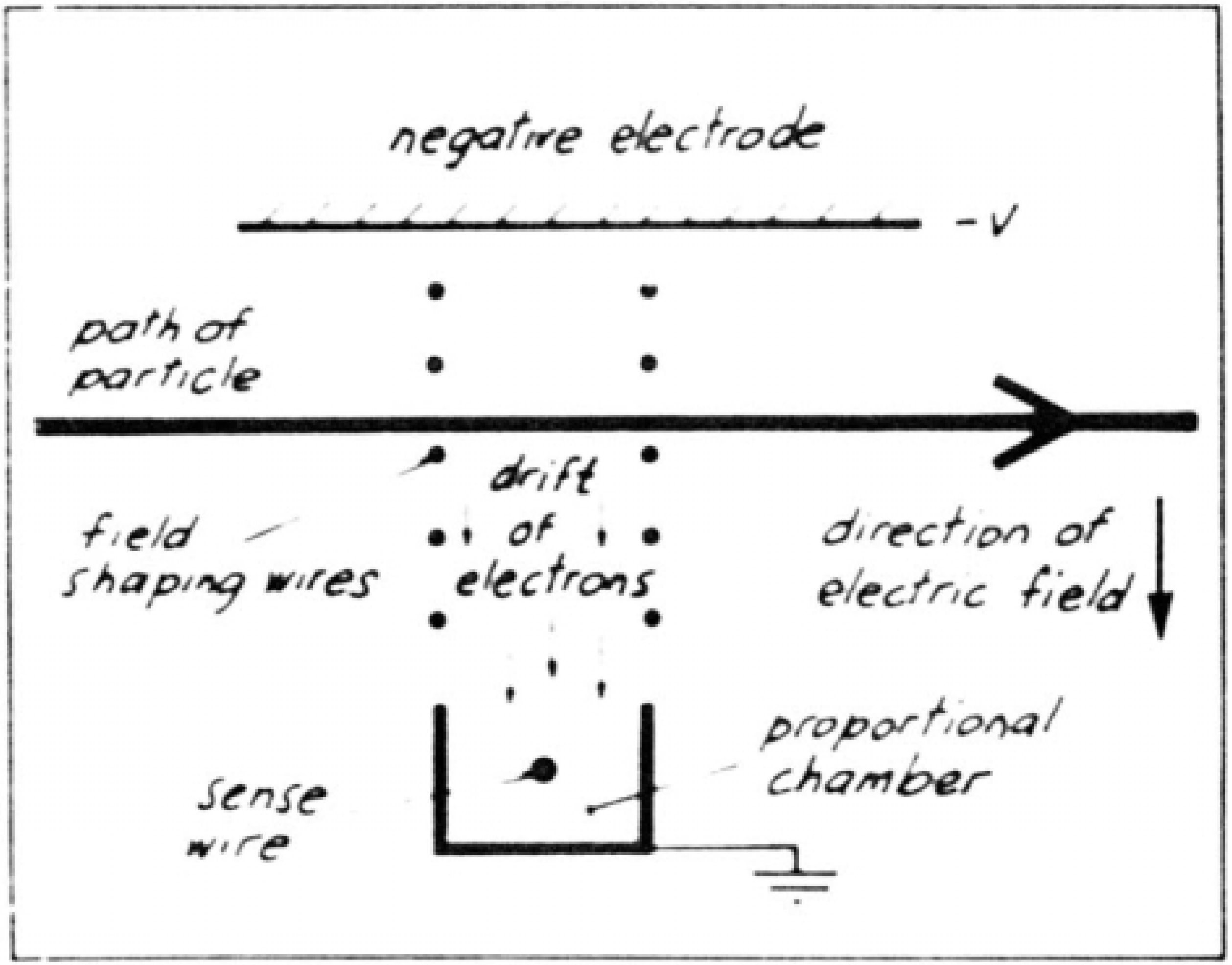
PROPORTIONAL WIRE CHAMBER OPERATING PRINCIPLE



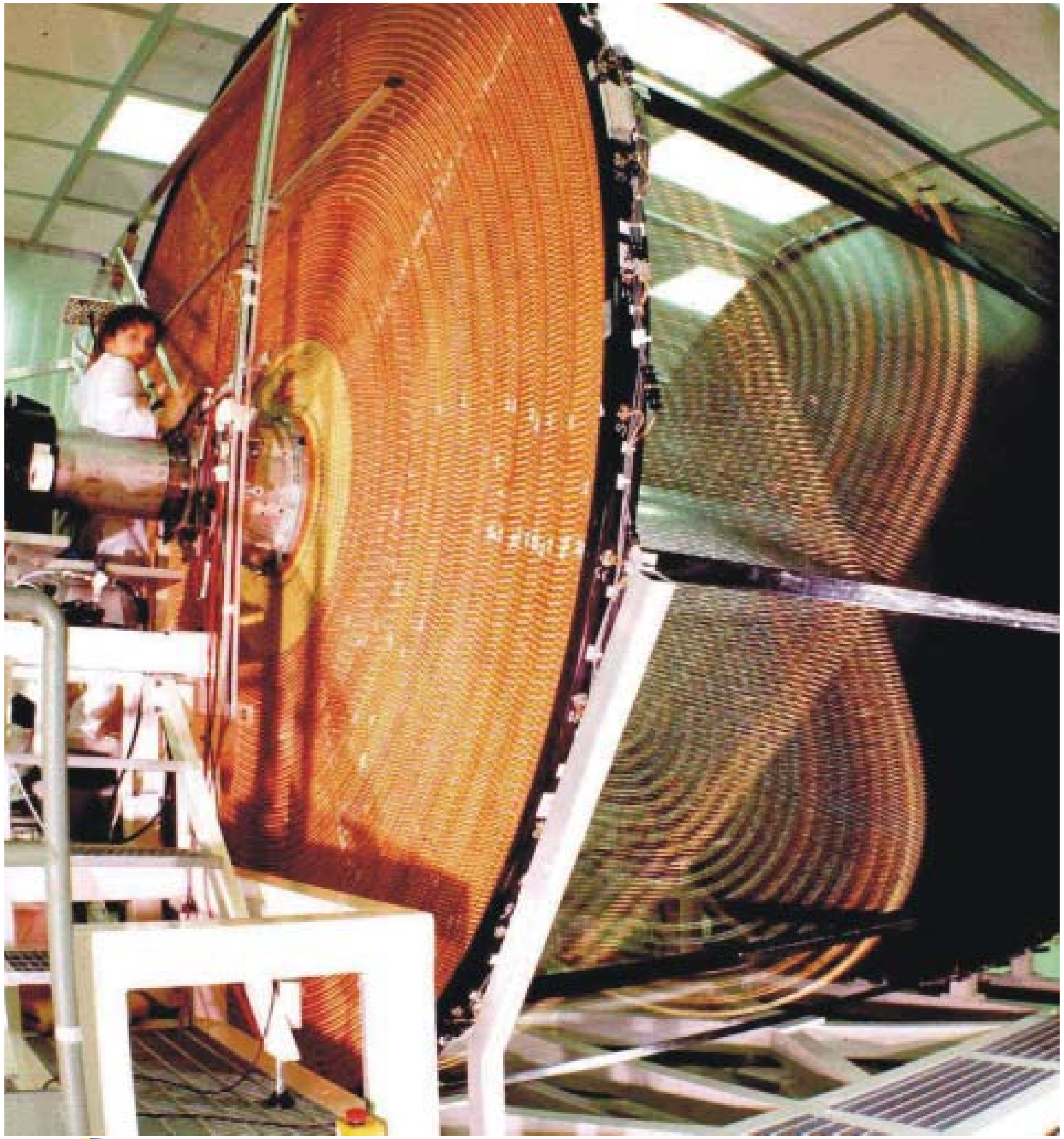
Put many together, get MWPC.

Drift Chamber Cell Operating Principle

uniform electric field in chamber such that ionization electrons drift with constant average velocity towards the proportional chamber. Measure drift time from t_0 to sense wire to obtain track position.



A MODERN GIANT, THE KLOE CHAMBER



52,000 wires - Al + W.

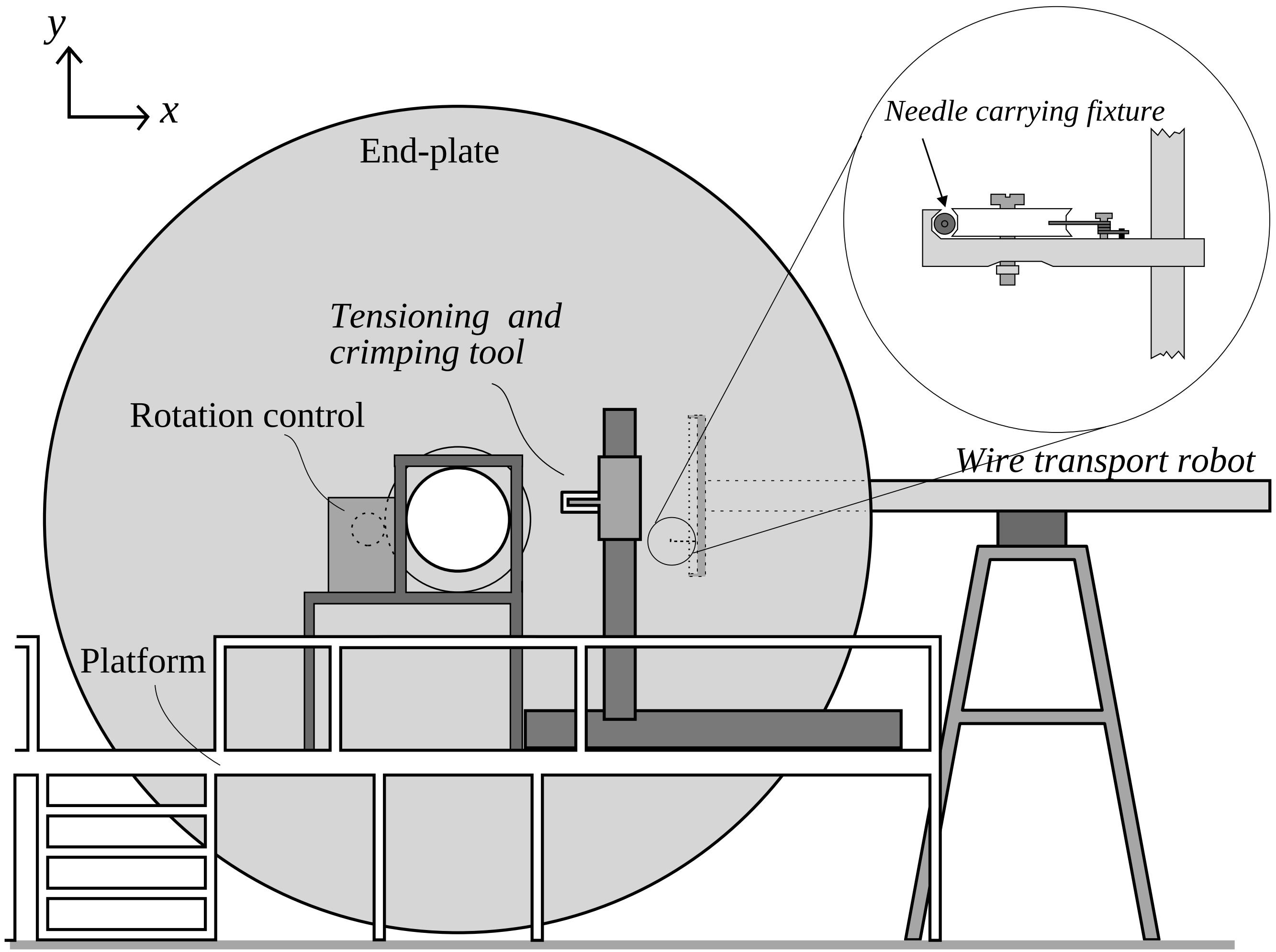
All C-fiber construction.

Spherical end-plates tensioned while stringing.

He + 10% iso-C_4H_{10}+ water 0.5%.

Wire tension measured electrostatically.

New techniques were invented to build such objects, for. ex. how to string the thousands of wires? The KLOE solution was later used also to build the BABAR Chamber



The KLOE Chamber is inside its calorimeter which provides the trigger and thus the t_0 for the tracks in the drift chamber.

One of KLOE's first physics results is an improvement in the measurement of ratio of the two pion decay rates we'd previously discussed' as shown in the next two transparencies.

So I think the ionization chamber saga, of which I've mentioned a small part of which I'd been personally involved, is a continuing and beautiful one which will go on for a very long time.

R, 2001

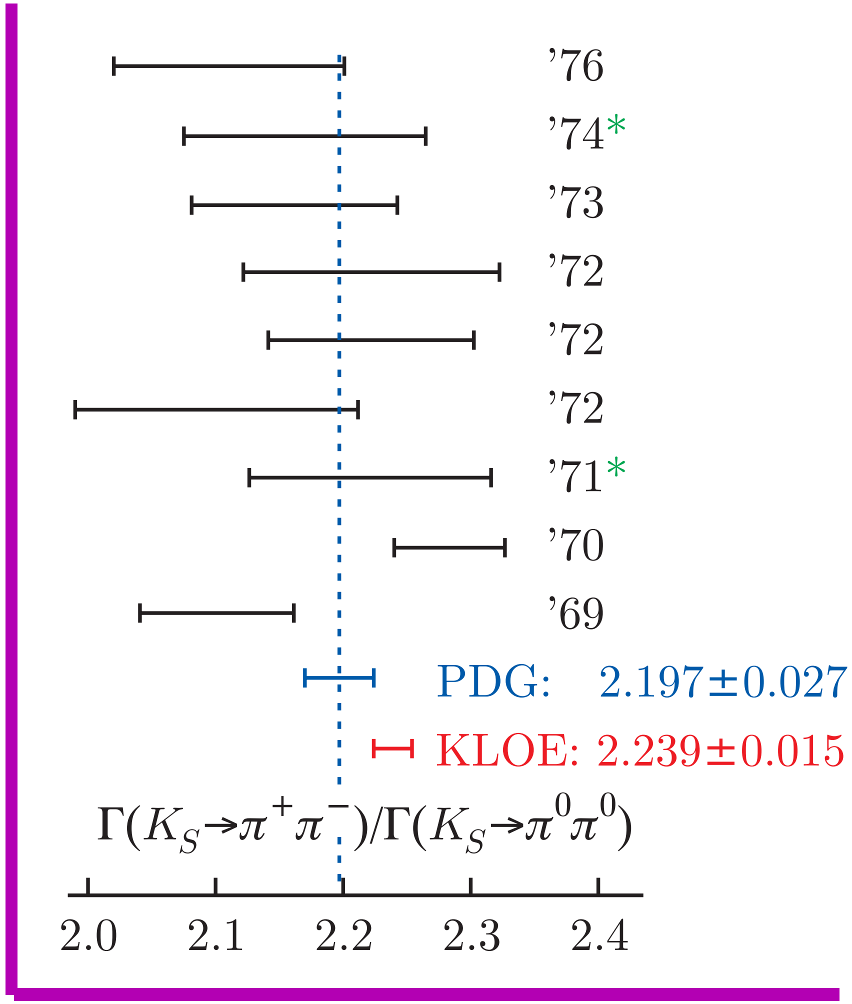
Trigger eff >96.5%

Overall accept. ~57%

ALL FROM DATA ⇓

Systematic errors

Source	Error, %
Tracking	0.2
Cluster count	0.5
Trigger	0.06
Cosmic-r. veto	0.35
Tagging	0.4
Total	0.76



$R = 2.239 \pm 0.003(\text{stat.}) \pm 0.015(\text{syst.})$

KLOE includes all $K_S \to \pi^+\pi^-\gamma$, others inc. unknown fraction.

$\delta_2 - \delta_1$ 2001

From old data:

$$A_2/A_0 = 0.045$$

$$\delta_0 - \delta_2 = 56.7^\circ \pm 3.8^\circ$$

inconsistent with

- measurement: $45.2^\circ \pm 1.3^\circ \pm 1.5^\circ$
- $\mathcal{O}(p^2)$ χpt value $45^\circ \pm 6^\circ$
- the phase of ϵ_K,

The KLOE value gives

$$\delta_0 - \delta_2 = 48^\circ \pm 3^\circ$$

in much better agreement. Radiative correction MUST be included. (Ecker)