Counter Experiments

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1. Why counters (and electronics)
2. Early cosmic ray experiments
   (a) Mesotron lifetime
   (b) The Muon
3. Evolution of the fast coincidence
4. Experiments at the Nevis Cyclotron
   (a) $\mu \not\to e\gamma$
   (b) The muon helicity

While the visual impact of Wilson chamber nuclear emulsions and bubble chambers were enormously important in the beginning of elementary particle physics, there was always the necessity of dealing with large samples of events of the same kind.

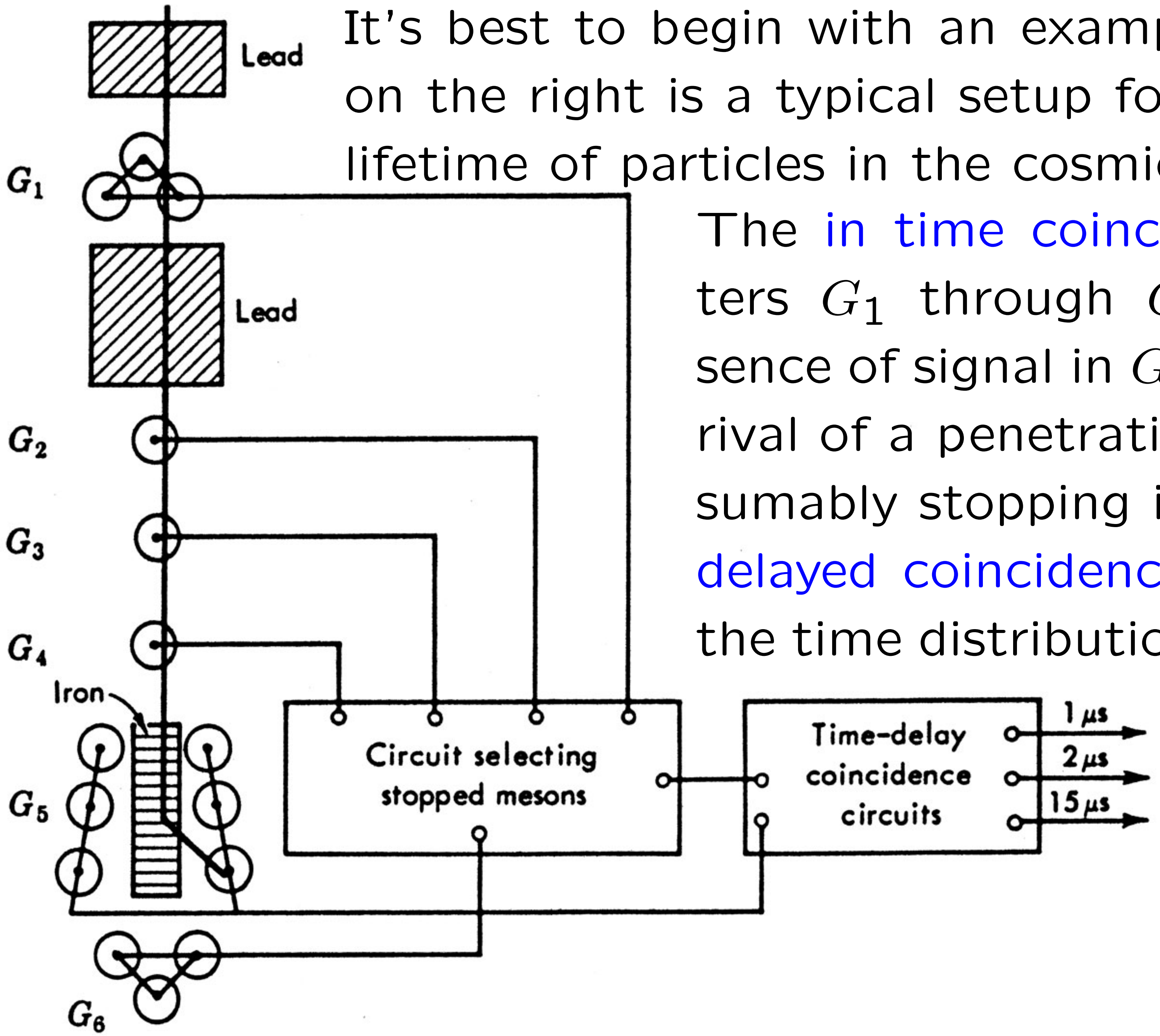
Typical example are the measurement of a particle lifetime, of a decay spectrum or an angular distribution in a scattering experiment. For an accuracy at the 10^{-2} level one needs typically 10^4 events, today we can reach 10^{-5}: $\tau_\mu=(2.19703 \pm 0.00004) \times 10^{-6}$ s.

Visual techniques then become useless, you cannot commit the labor of hundreds of people for hundreds of years to examining and measuring billion of pictures!!

Use of counters requires however electronics. In general we need to amplify tiny signals best defined by giving the number of electrons

While means for counting particles were early developed few more steps were necessary, foremost the possibility of detecting some happenings in temporal coincidence. They first coincidences were observed by Bothe by electromechanical means. Rossi first introduced in 1930, the use of thermoionic valves or vacuum tubes: triodes or pentodes if anybody ever heard about them.

Together with the Geiger-Müller counter, the Rossi coincidence was used in the 30's and 40's to study cosmic rays, em shower, measuring the muon lifetime to $\sim$1% accuracy and to prove the special properties of the muon.



It's best to begin with an example. The sketch on the right is a typical setup for measuring the lifetime of particles in the cosmic radiation.

The in time coincidence of counters G_1 through G_4 and the absence of signal in G_6 signals the arrival of a penetrating particle, presumably stopping in the iron. The delayed coincidences with G_6 give the time distribution of the decays.

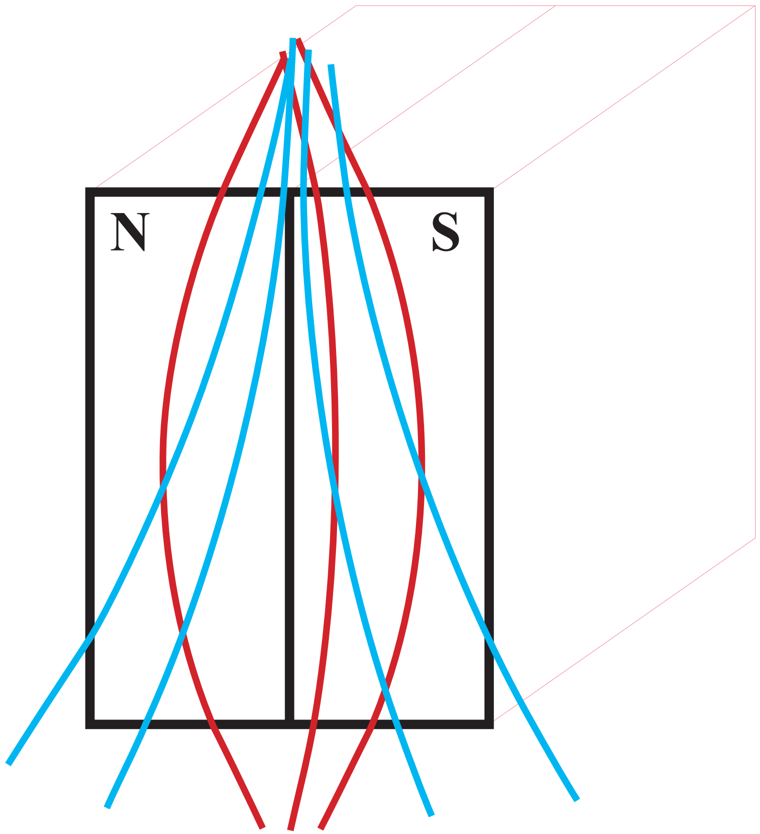
In 1937 Anderson and Neddermeyer proved the existence of a particle of mass $\gg m_e$, it did not radiate in a 1 cm platinum plate. Street and Stevenson measured $130\times m_e$. It could have been Yukawa's mesotron, expected mass $\sim 1/r_p\sim$200 MeV (m_μ=105 MeV). The mass is now 105.658357 MeV.

In 1947 Conversi, Pancini and Piccioni observed that the lifetime of negative muons stopped in carbon equals that of positive muons. A definitive proof that the muon is not Yukawa's mesotron.

During the last war years the Rome group had developed a method to select positive and negative muons in the cosmic radiation at sea level. This was done with the so-called magnetic lenses.

The magnetic lens

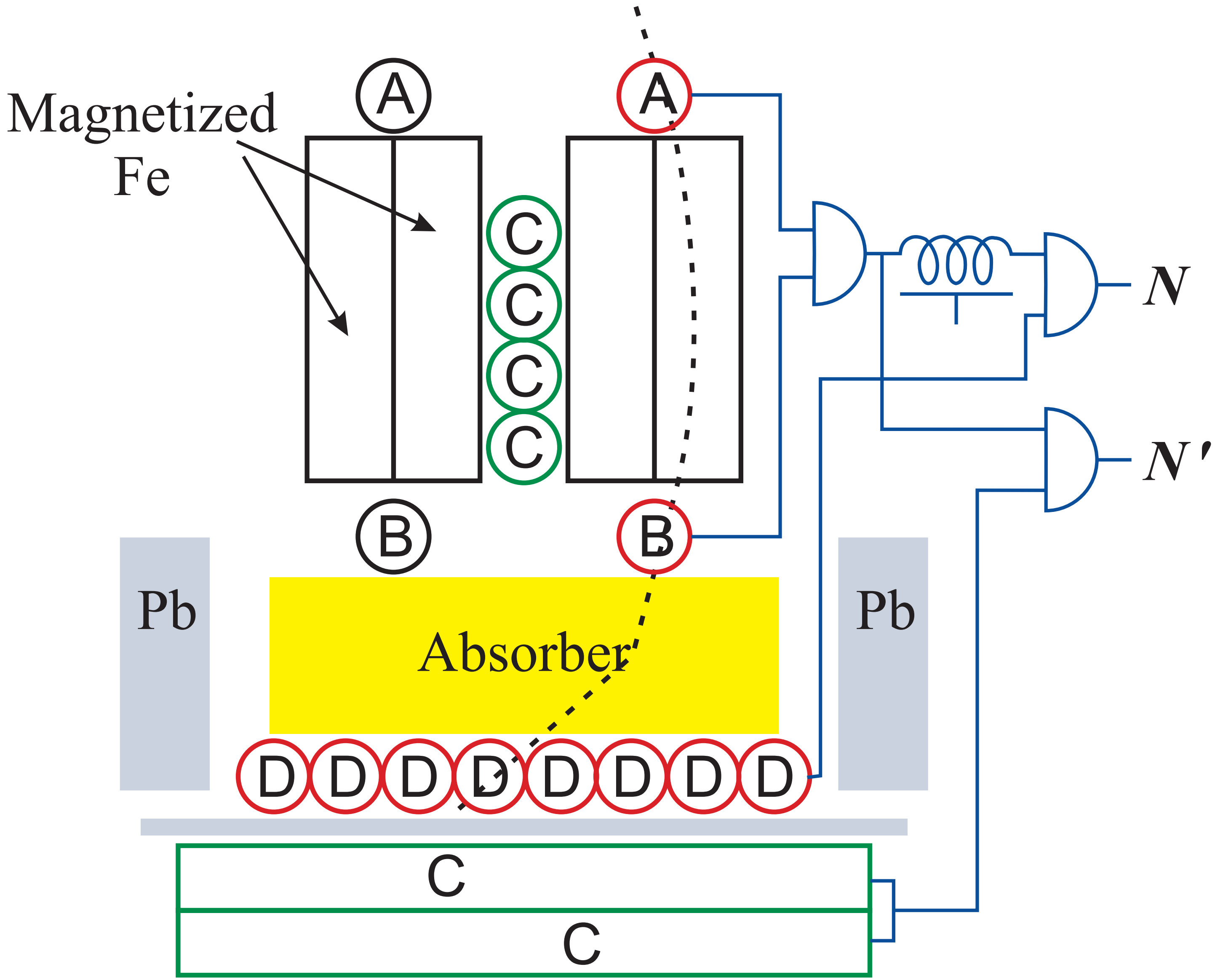
Two Fe blocks, magnetized with a current in opposite directions, have a focussing effect on particles of one sign and defocussing on the opposite sign.
First tried by Rossi in early 30's to find sign of Cosmic Rays!



The Conversi Pancini Piccioni experiment

A late signal from the D counters in coincidence with the A and B counters delayed, signals the arrival of a positive (negative) muon which stops in the absorber and then decays into an electron.

A·B·D gives a background count.



So what?

The muon lifetime in vacuum is 2.2 μs, measured since the early days. This immediately tells us that the decay is due to the weak interaction.

The Yukawa mesotrons have however strong interaction with nucleons. This means that a mesotron interacts with a nucleon with a reaction rate of $\sim 3 \times 10^{23}$ per second (s^{-1}).

When muons come at rest in matter, ($<$10 ps), positive muons can only decay as in vacuum while negative muons will bind in hydrogen-like structures. In condensed matter, thermal muons bind into S-wave orbits also in very short times. Mostly by Stark effect.

For muons in a $1S$ states we estimate the overlap integral as just the ratio of the nucleus radius to the Bohr radius, cubed.

If you do not remember the Bohr radius, begin writing the energy:

$$E = V + T = -\frac{\alpha}{r} + p^2/2m_e.$$

Quantize the system by the uncertainty principle, $p = 1/r$ ($\hbar$=c=1) and find the minimum energy:

$$\frac{\mathrm{d}}{\mathrm{d}p}(-\alpha p + p^2/2m_e) = -\alpha + p/m_e = 0$$

giving $p = m_e\alpha$ from which the Bohr radius $a_\infty = 1/(m_e\alpha)$, in natural units.

Reintroducing $\hbar$ and c we find a (maybe??) more familiar expression $a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2$ in SI units, $a_\infty = \hbar^2/m_e e^2$ in cgs units. $a_\infty \sim 5 \times 10^{-8}$ cm.

In natural units the Rydberg constant is $\alpha^2 m_e/2$ or $R_\infty = 510\ 999$ eV$/(2 \times 137.036^2) = 13.605\ldots$eV.

The Bohr radius is R_{Bhor}=$1/(m_r Z\alpha)$=$2.8 \times 10^{-11}/Z$ cm and the overlap integral

$$\frac{A(1.4 \times 10^{-13})^3 Z^3}{(1.9 \times 10^{-11})^3} = 1.2 \times 10^{-7} Z^3 A.$$

Even for hydrogen the absorption rate for Yukawa mesons is

$$\Gamma_{\text{abs., Yukawa}} = 3 \times 10^{23} \times 1.2 \times 10^{-7} \sim 3 \times 10^{16}\ \text{s}^{-1}$$

or 10^8 times larger then the decay rate.

Very grossly, taking the reaction rate for $\mu^- + N \to N' + \nu_e$ as $1/\tau_\mu$~10^6/s, the weak μ^- absorbtion rate is

$$\Gamma_{\text{weak}} \sim 0.12 \times Z^3 A \sim 0.24 \times Z^4\ \text{s}^{-1}.$$

For carbon, $Z = 6$ and Γ_{weak}~300, which is much smaller than the decay rate of the muon. Positive and negative muons equally decay when stopped in carbon.

However, for $Z = (10^6/.24)^{1/4} \sim 45$, the weak capture rate becomes significant. Conversi et al. did observe that for negative muons stopping in Fe, Z=26, the free decay is almost not present.

The estimates above are of course very crude. The $Z^3 A$ dependence of the capture rate has been however verified (later) by measuring $\tau_\mu = 1/(\Gamma(dec) + \Gamma(cap))$ in different materials.

From the observation of Conversi *et al.* the muon was born. The names π, μ are due to the Bristol nuclear emulsion group of Lattes, Occhialini and Powell. The muon is a basic constituent of the so called standard model and as best as we can tell an elementary particle. The π-meson is the Yukawa mesotron.

Evolution of counters and electronics

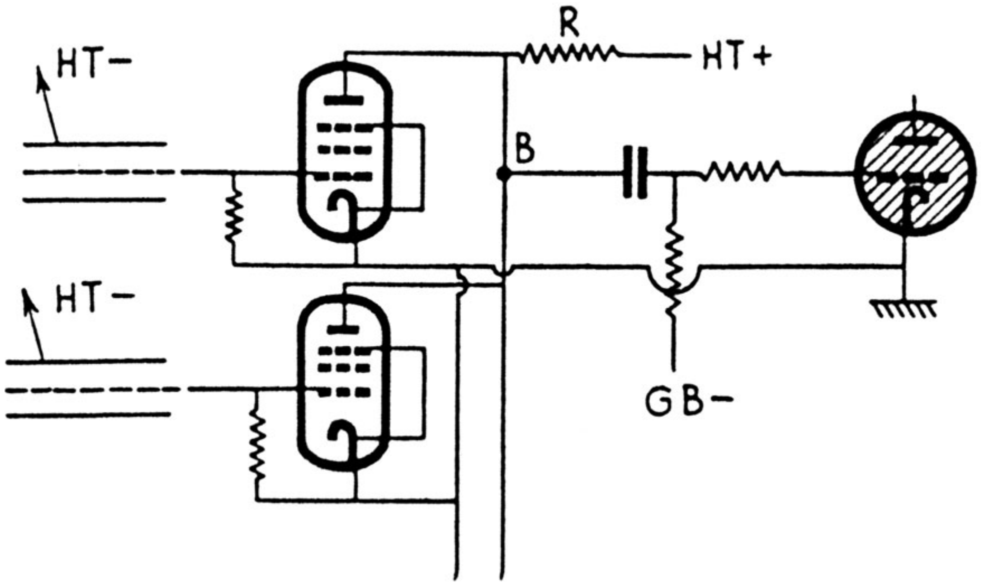
Geiger-Müller dominated the early days but had one basic limitation. Coincidence resolving time is limited to the μs level. This is not really a failing of the G-M tube but but is due to the (drift) time elapsed before the initial ionization reaches the multiplication region near the central wire.

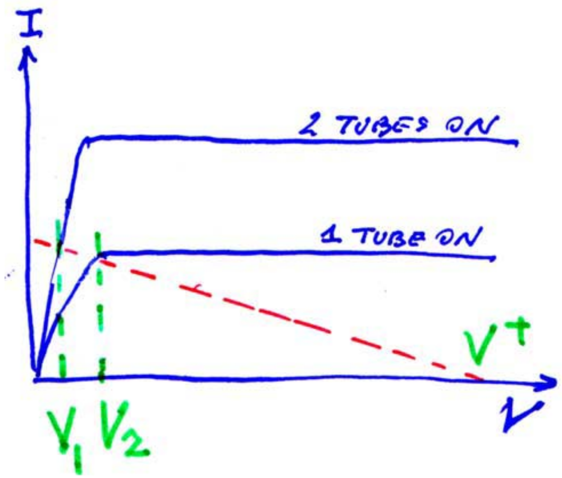
GM counters with 100 ns or less resolving time can be built. They go under different names, streamer tubes, etc. and are sometimes used.

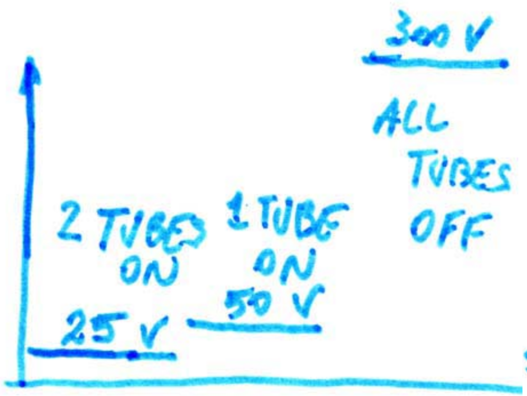
This slow drift is used today for measuring position to $\sim$1/10 mm accuracy in the drift chamber.

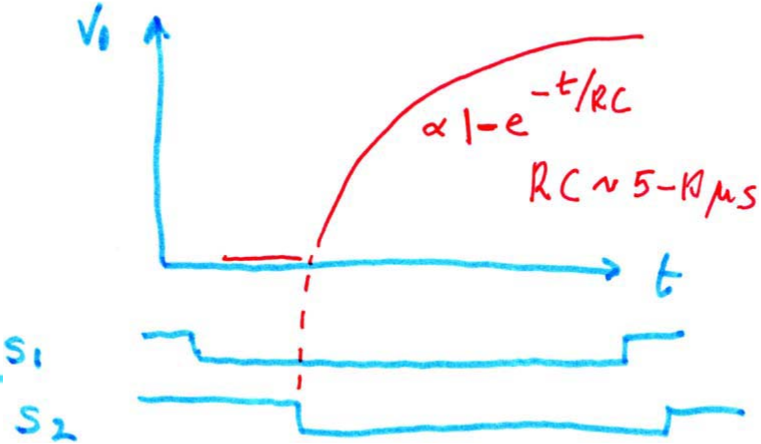
Basic electronics

GM counters were used for two decades with the Rossi coincidence. The Rossi coincidence has a resolving time of $\sim$1 μs - RC$\sim$10 μs. The shaded tube is a gas discharge tube or thyratron.





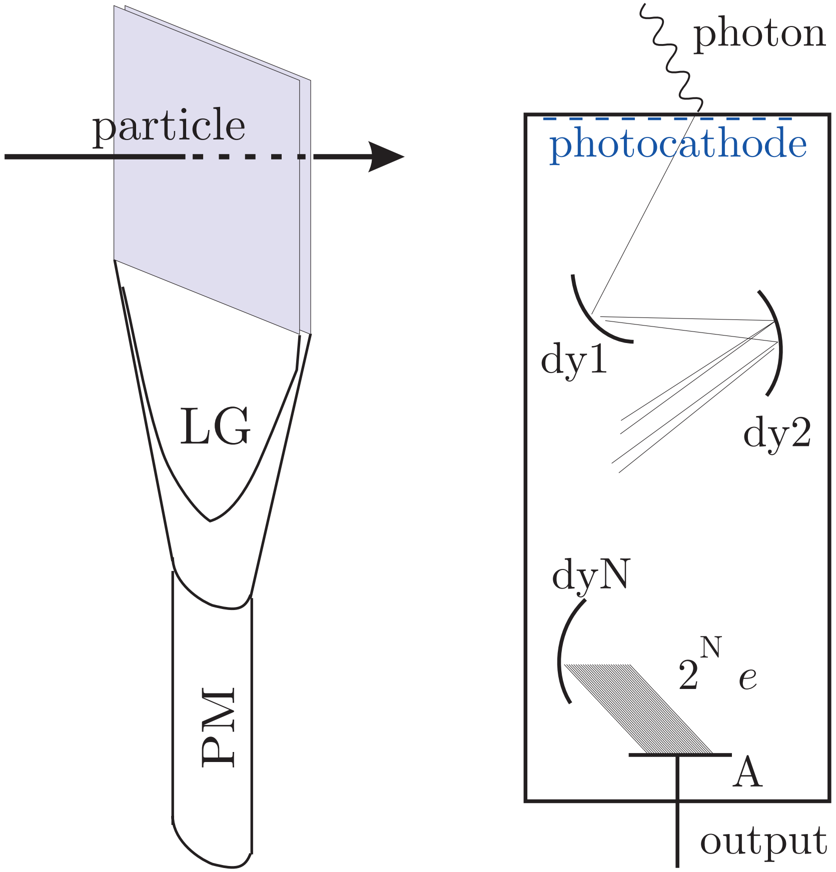




At accelerators the GM counter has been replaced by scintillator and photomultipliers. Typical fast scintillator has the following characteristics: 1. Bulk material plastic, density $\sim$1 gr/cm^3; light output $\leq$10,000 blue photons per MeV of energy loss, rise and fall time around 1 ns.

10,000 photons are a large number. Only a few % can be guided to a photocathode where the photons extract electrons, photoelectric effect, efficiency $<$30%.

It is easy to obtain a signal of 100 *p-e*'s from a min. ion. particle crossing a 2 mm thick plastic scintillator viewed through a long light guide. Since a photomultiplier is a noise-less amplifier ($kT \ll \hbar\omega$), it is "easy" to have efficient counters with time resolution $\ll$1 ns, 50 ps being possible.

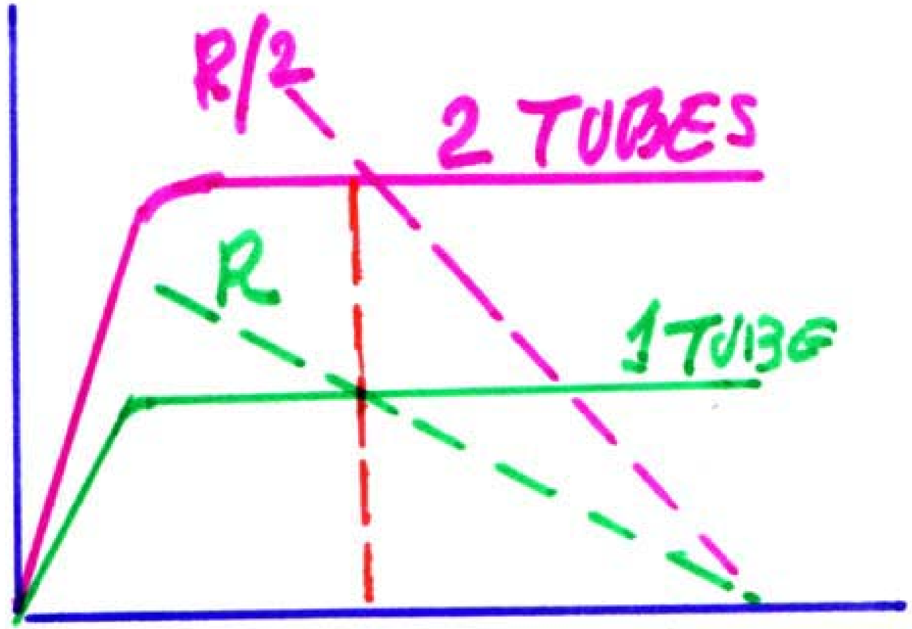


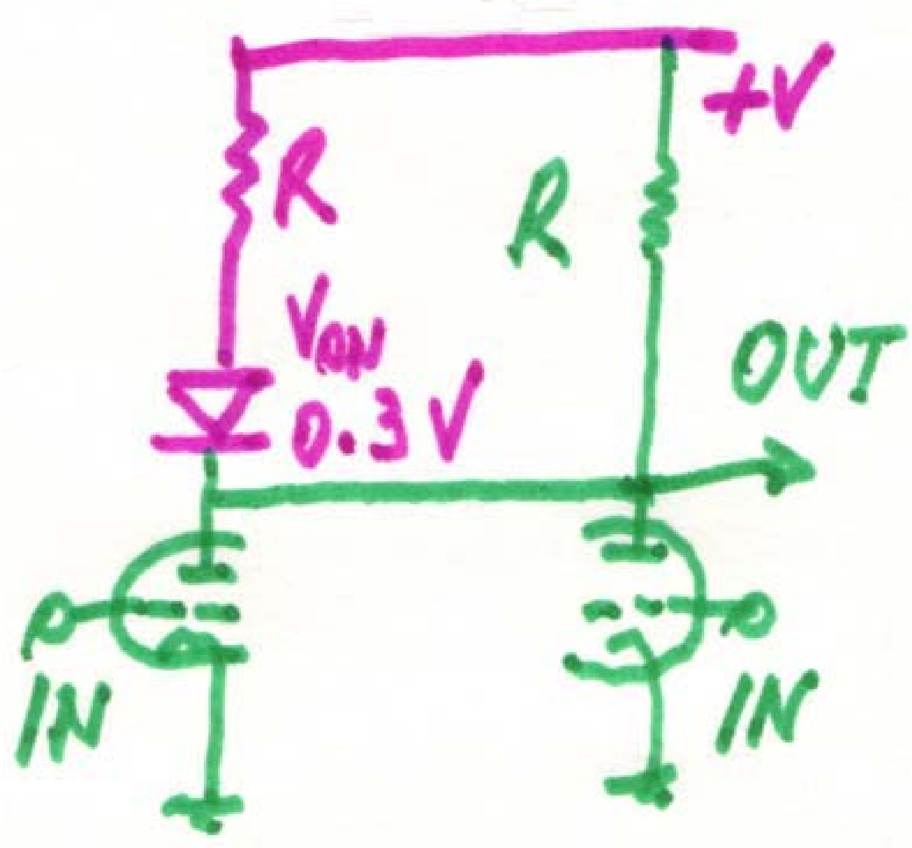
Photocathode and electron multiplier are enclosed in a glass envelope, under high vacuum.

The counter at left is typical of 1950-80 and even today is seen in test beams.

Plastic scintillator can be machined or molded to any shape.

Scintillation counters became available in the early '50's and their use became universal, especially after R. Garwin introduced current switching with his coincidence circuit.





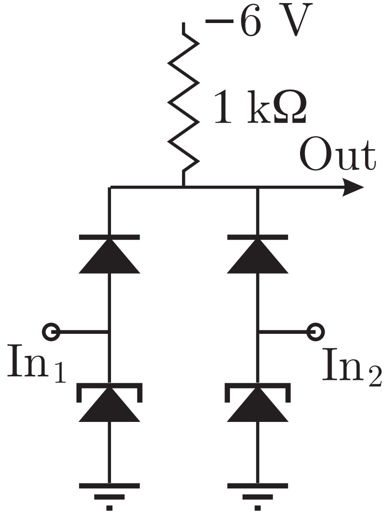
There is another important difference between the GM counter and fast scintillation counters.

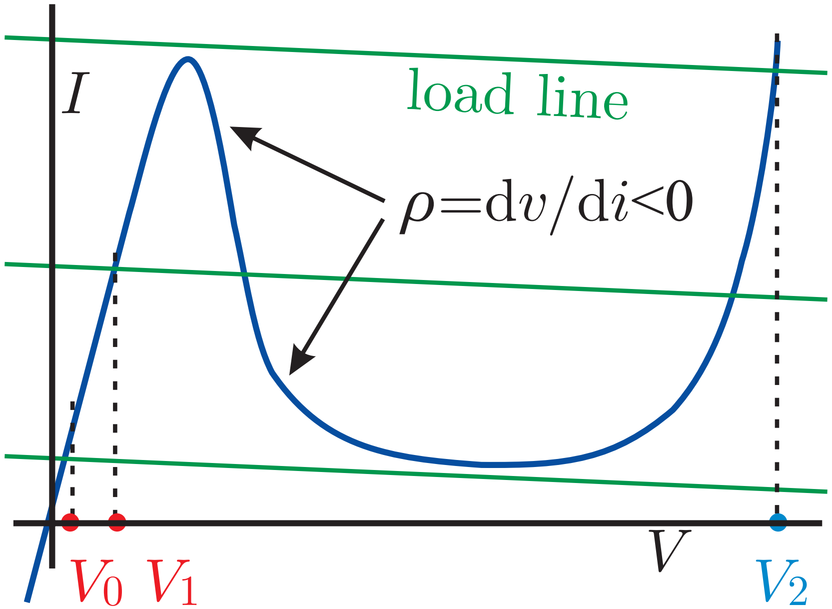
The first produces a large signal through a saturated gain mechanism, the signal amplitude is constant. Both scintillation and the photomultiplier tube (PM, photube) are linear and the final signal is proportional to the initial energy loss in the scintillator.

This is in general more information, but it is often necessary to accept only signals larger than a threshold, or signals in an interval: $S_{min} < S < S_{max}$.

By the end of the '50's solid state devices are fully available. Ultimately they did change experimental particle physics.

In '61 I invented a solid state coincidence, using just 4 diodes, two of which are so called tunnel diodes, since QM tunnelling leads to conduction in the usually forbidden condition. This results in a two terminal device with negative resistance. My coincidence has turn-on times of $<$100 ps, in practice it is faster than most detector signals. Its simplicity is still unsurpassed since it provides also a threshold discrimination on each input.





I_1	I_2	Out
0	0	0.55 V
0	1	0.57
1	0	0.57
1	1	1.0

$\mu \not\to e\gamma$

Since the early days of studying the muon, it was somewhat of a mystery why the decay $\mu \to e\gamma$ was not dominant. It is principle an EM processes, *i.e.* very much faster then 10^6 decays/s.

If however we insist on lepton number conservation, the decay is due to radiative correction to the WI and it occurs via emission and re-absorption of a neutrino. Introduction of the intermediate vector boson W, allows calculating:

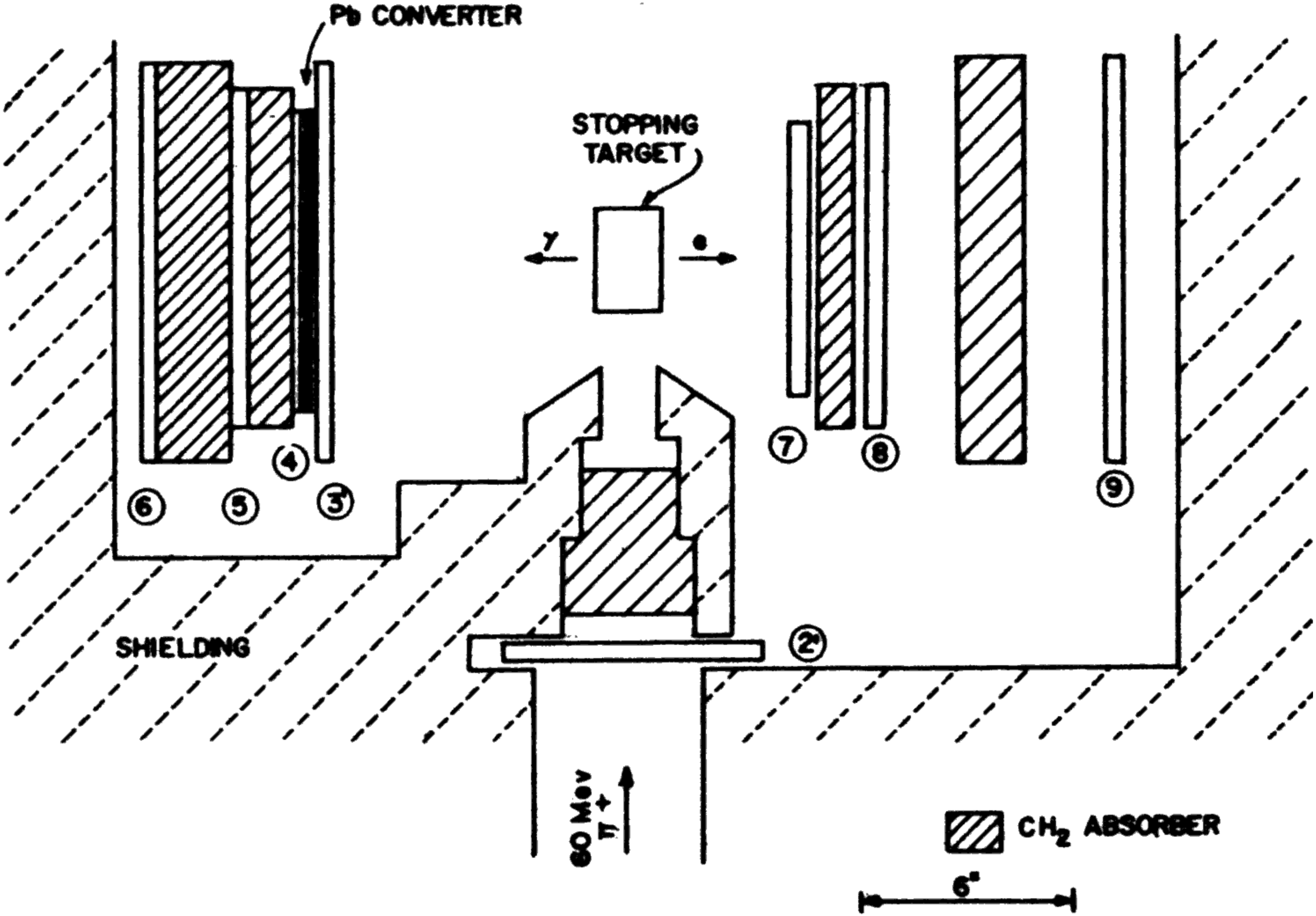
$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\overline{\nu})} = 10^{-3}.$$

In 1959 (Nevis Cyclotron, JL, PRL **2** 357 (1959)) it was found:

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\overline{\nu})} < 10^{-6}$$

leading to the hypothesis that $\nu_\mu \neq \nu_e$ and requiring the simultaneous conservation of 2 lepton numbers L_ν and L_e.

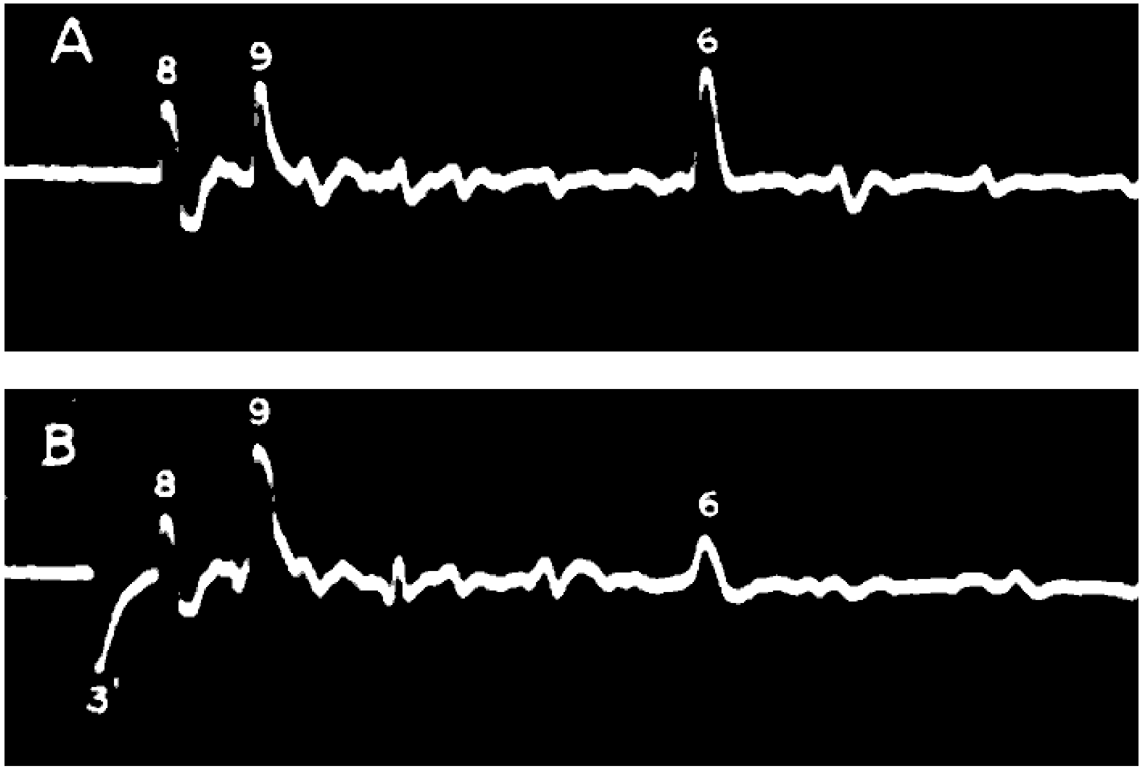
The set-up selects back-to-back e and γ of high energy, ~53 MeV, requiring that they cross considerable amount of absorber.
The γ is identified by no signal in the "anti-counter" 3.
The event candidates are displayed on a scope trace, which are then visually inspected.



Pb CONVERTER
STOPPING TARGET
γ
e
7
8
9
6
5
4
3'
2'
SHIELDING
60 Mev π+
CH2 ABSORBER
6"

this
is
tex

8 and 9=e 6 and no 3=γ



3 proves that the particle on the left is not a γ

Event A is a radiative decay $\mu \to e\gamma\nu\nu$ observed with a lower energy threshold (remove absorber on γ arm).
Event B is an accidental coincidence.

The muon neutrino helicity

Soon after the discovery of parity violation a large electron polarization $\langle\vec{\sigma}\cdot p_e\rangle \sim -1(\beta)$ was observed, also proving $\not{R}$. The negative helicity of the electron could be due to a $\bar{e}\gamma_\mu(1-\gamma_5)\nu$ or a $\bar{e}(1+\gamma_5)\nu$ coupling (V,A or S,T). The observed helicity of the neutrino in β-decay, -1, together with other results, confirms the $V-A$ interaction of Feynman and Gell-Mann and of Marshak and Sudarshan.

The emerging evidence that there is an independent conservation of electrons and muons and their associated neutrino, or just that $\nu_e \neq \nu_\mu$ begs for a measurement of the ν_μ helicity.

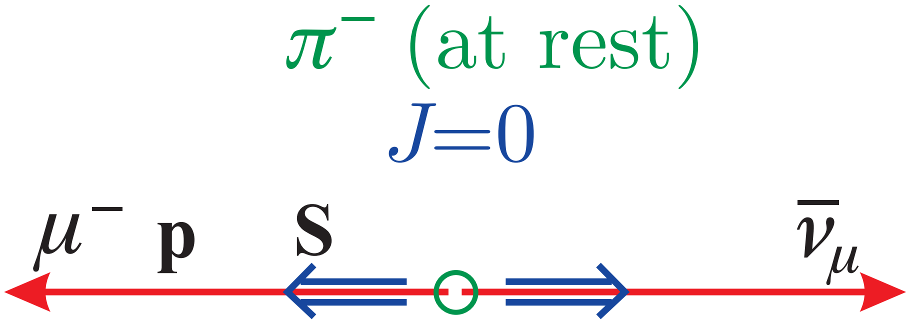
Of course one does not measure the neutrino polarization – but, by angular momentum conservation, the neutrino helicity can be connected to the polarization of photons in β capture or the muon helicity in

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

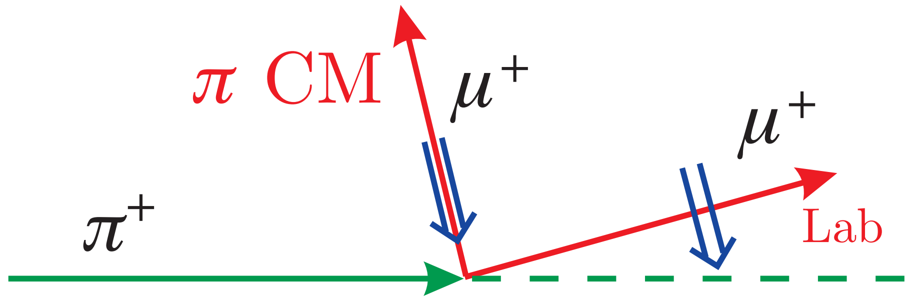
One cannot use muon decay to get the muon polarization without getting into a vicious circle. The muon polarization can be measured by Mott scattering, for transverse polarization, or Moller scattering for longitudinal.

1. $\mathcal{H}(\mu^-) = \mathcal{H}(\overline{\nu}) = \pm 1$
2. Longitudinal polarization into transverse polarization
3. Use Mott scattering to find spin orientation

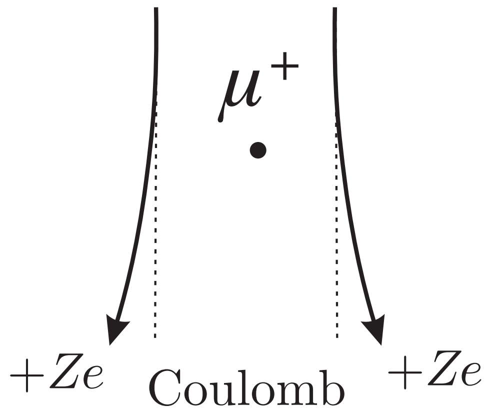
1. $\mathcal{H}(\mu^-) = \mathcal{H}(\overline{\nu})$



2. Rotate $\vec{\sigma}$

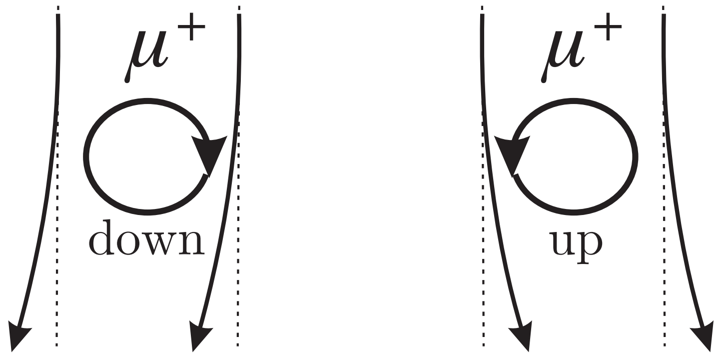


Mott - Coulomb



Coulomb
left-right
symmetric

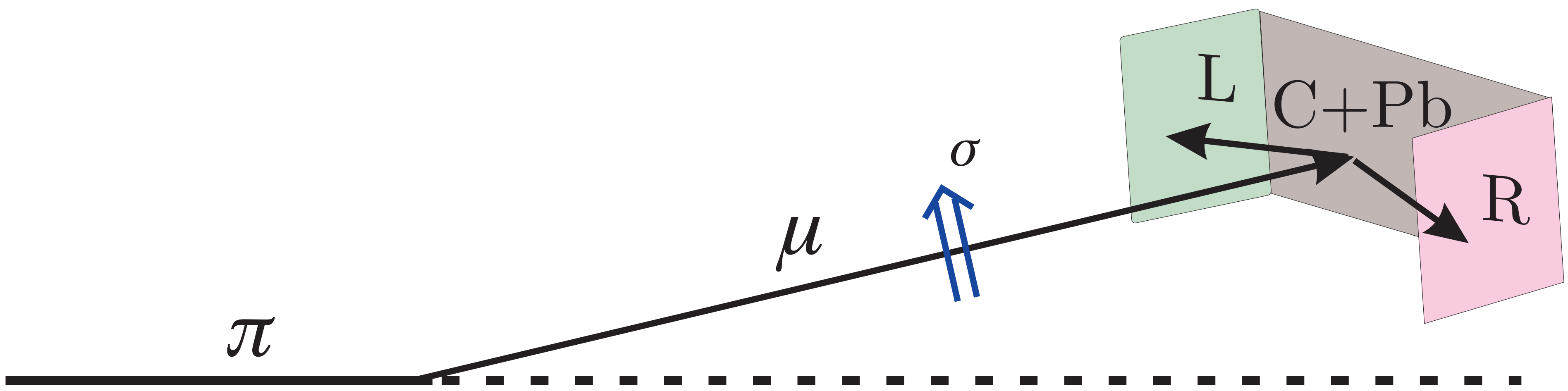
Mott - Spin



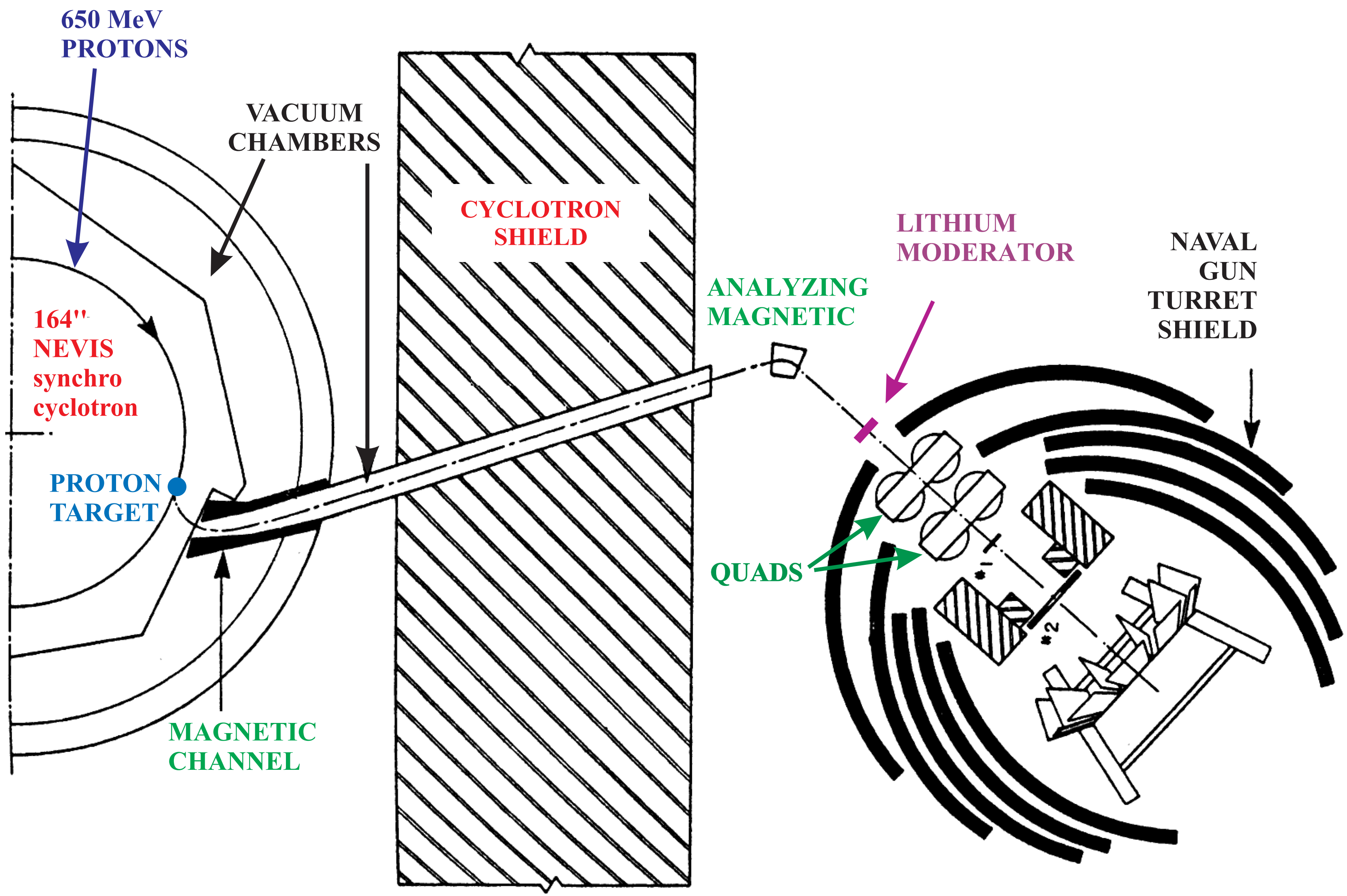
Magnetic moment
spin up favors right
spin down favors left

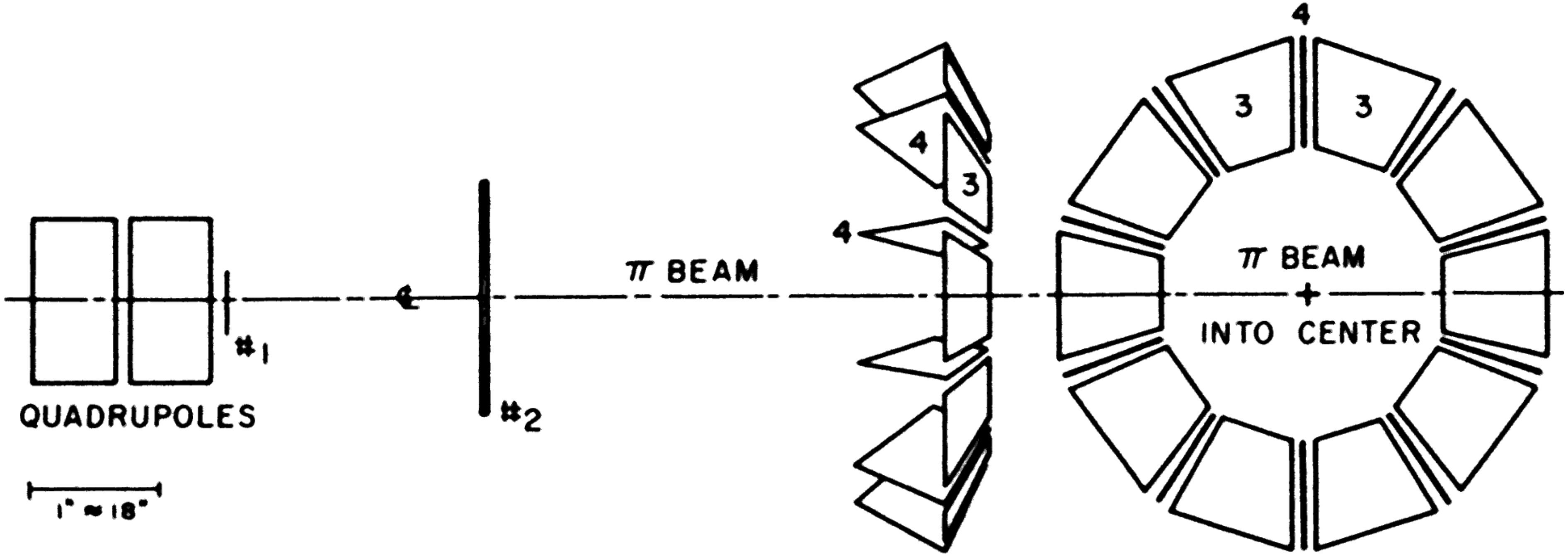
The basic arrangement

Measure left-right asymmetry of back-scattered negative muons. Gives maximum asymmmetry.



T_π=43 MeV


650 MeV
PROTONS
VACUUM
CHAMBERS
CYCLOTRON
SHIELD
LITHIUM
MODERATOR
NAVAL
GUN
TURRET
SHIELD
ANALYZING
MAGNETIC
164"
NEVIS
synchro
cyclotron
PROTON
TARGET
QUADS
MAGNETIC
CHANNEL



1. Incident muon: $1 \cdot \overline{2} \cdot 3 = C_1$
2. Backscattered muon: $C_1 \cdot 4(4') = C_2$
3. Confirm Muon $C_2(\text{Del}) \cdot 4$

Remove asymmetries: Each 4 counter appears as left and right for 2 adjacent 3 counters; electronics chain for $(1 \cdot \overline{2} \cdot 3) \cdot 4$ switched around; rotate entire set-up around nominal beam axis.

Expected Mott scattering asymmetry over geometry

$$A = (L - R)/(L + R) = \pm 0.09 \text{ for } P_y = \mp 1$$

L-R counts in 100 hours: $L = 515$, $R - 618$, corresponding to

$$A = -0.09 \pm 0.031 \quad \text{PRL } \mathbf{7} \text{ 23 (1961)}$$

$$P(\text{obs. -0.09, true val. } +0.1) = 10^{-7}$$

Therefore the μ^- helicity is positive and so is that of the anti-neutrino. The muon-neutrino has negative helicity like the electron-neutrino. All leptons appear to have the same helicity.

The μ^- helicity in pion decay is positive because of angular momentum conservation and the muon is very slow and $1/2(1-\gamma_5)u$ has both negative and positive helicity for $E - m < m$.

$\mu \not\to e\gamma$ - Again, 20 years later

The absence of mixing of $(\nu_e\ e^-)$ with $(\nu_\mu\ \mu^-)$ compared to $(u\ \ d)$ and $(c\ \ s)$ is guaranteed if the neutrino have zero mass. This is not so, but the limits on the neutrino masses ensure that $\mu \to e\gamma$ remains unmeasurably small. There are however other mechanisms and I refer you to Marciano's lectures.

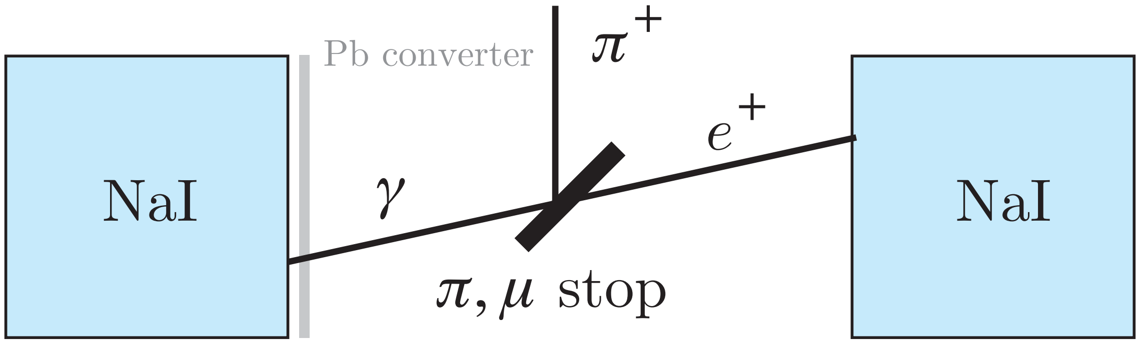
Historically, the upper limit for $\Gamma(\mu \to e\gamma)/\Gamma(\mu \to e\nu\overline{\nu})$ was lowered to 2.2×10^{-8} in 1964 at the Chicago Cyclotron.

In the late 70's, rumors spread out to the effect that the decay was observed. This led to a spate of predictions, mostly (15 of them) in '77, in the range 10^{-8} to 10^{-26}.

Most of them could be abandoned today. Supersymmetry was not yet in fashion.

Anyway, in 1978 we set up an experiment at the old venerable, partly renewed Nevis Cyclotron aiming to reach 10^{-10}. The experiment is an example of very extensive use of electronics in order to extract digital information from the apparatus in the form of final physical results.

The entire analysis was done by hardware, in real time as compared to past, present and future experiments which, beginning about that time, extract and store data for off-line analysis.

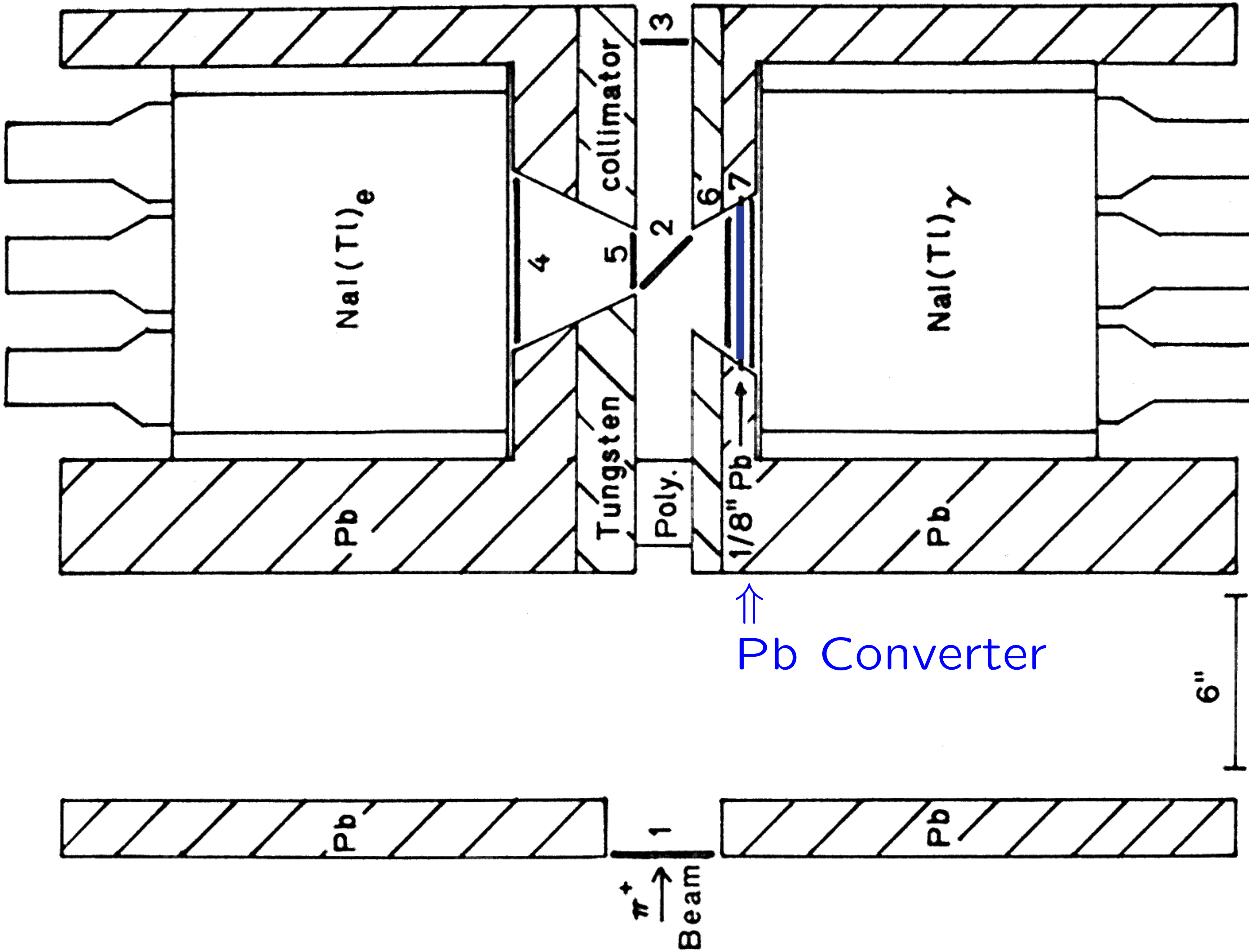


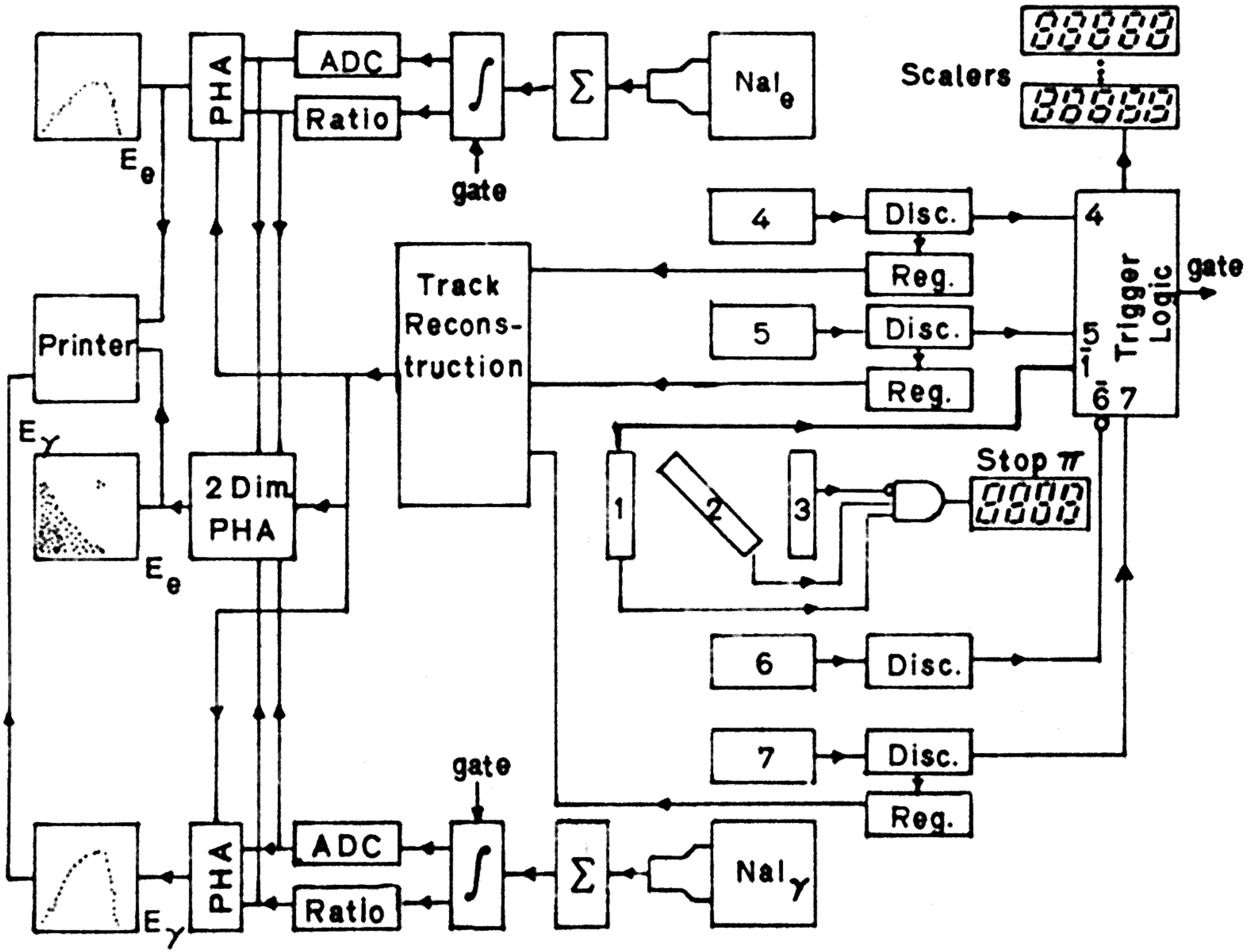
$\mu \to e\gamma$ SIGNAL. Collinear, $E = M(\mu)/2$, e and γ.

$\mu \to e\nu\nu$ BCKGND 1. $E < M(\mu)/2$ e plus random coincidence.

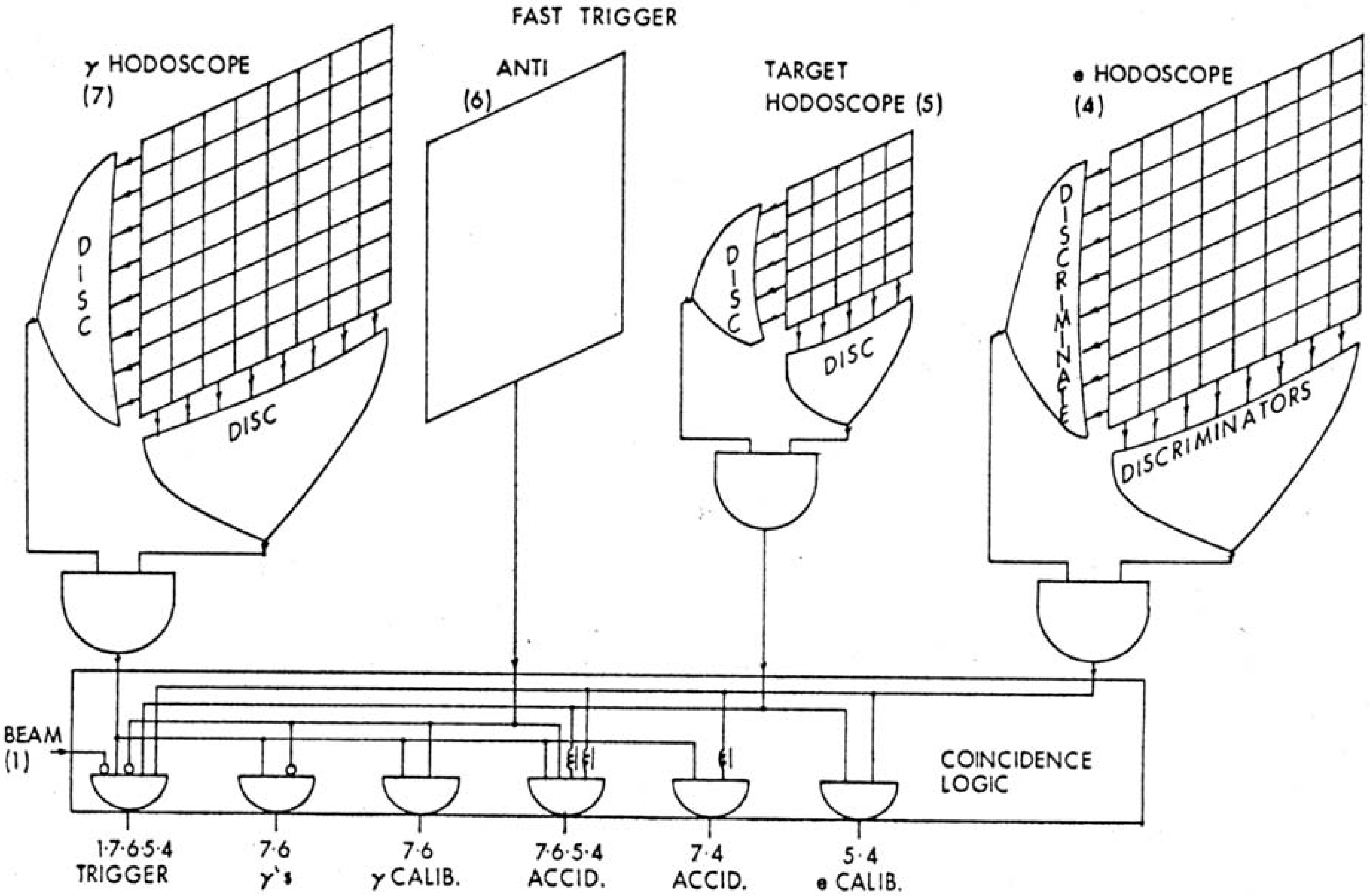
$\mu \to e\gamma\nu\nu$ BCKGND 2. Non collinear, $E < M(\mu)/2$, e and γ.

1. Measure $E(\gamma)$ and E(e) in NaI crystals.
2. Determine collinearity. γ shower initiates in thin converter.
3. Determine contemporaneity.
4. Examine $>10^{10}$ decays, *i.e.* collect $>10^{11}$ muons.
5. Ensure cyclotron delivers adequate beam...

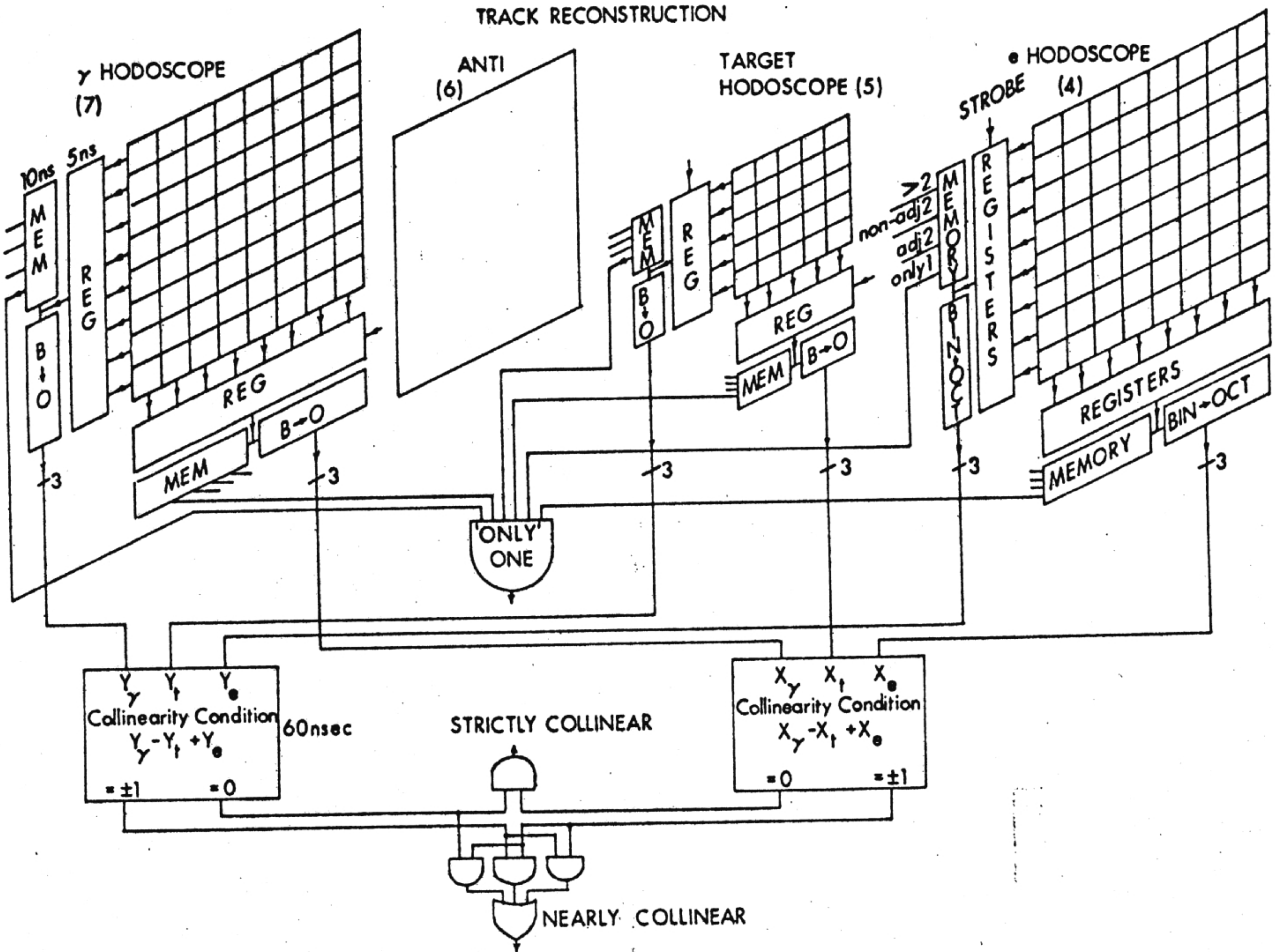

collimator
Tungsten
Poly.
1/8" Pb
NaI(Tl)$_e$
NaI(Tl)$_\gamma$
Pb
6"
π^+ Beam
Pb Converter


Scalers
PHA
ADC
Ratio
gate
Σ
NaI_e
E_e
4
Disc.
Reg.
Track Recons- truction
5
Trigger Logic
gate
Printer
E_γ
2 Dim PHA
1
2
3
Stop π
E_e
6
7
gate
NaI_γ
E_γ

TRIGGER

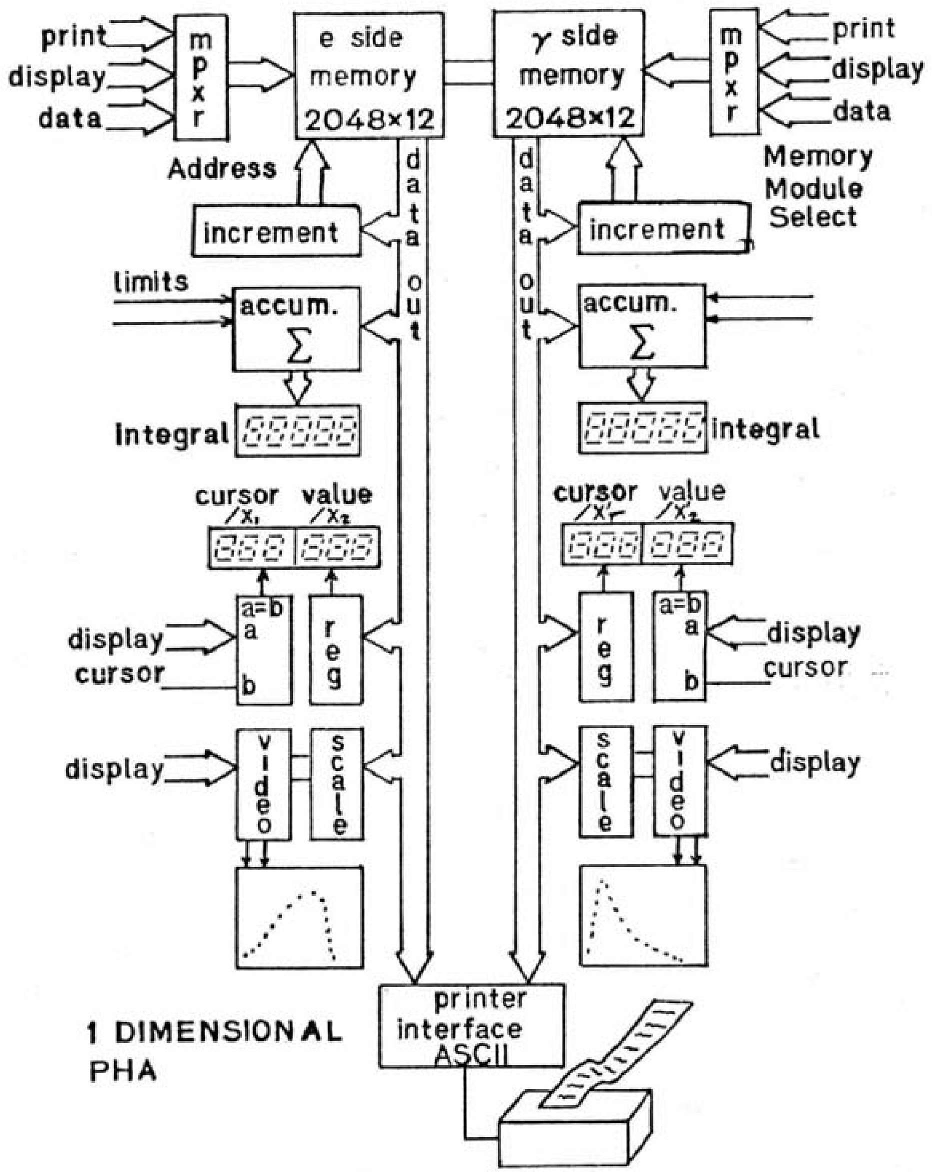


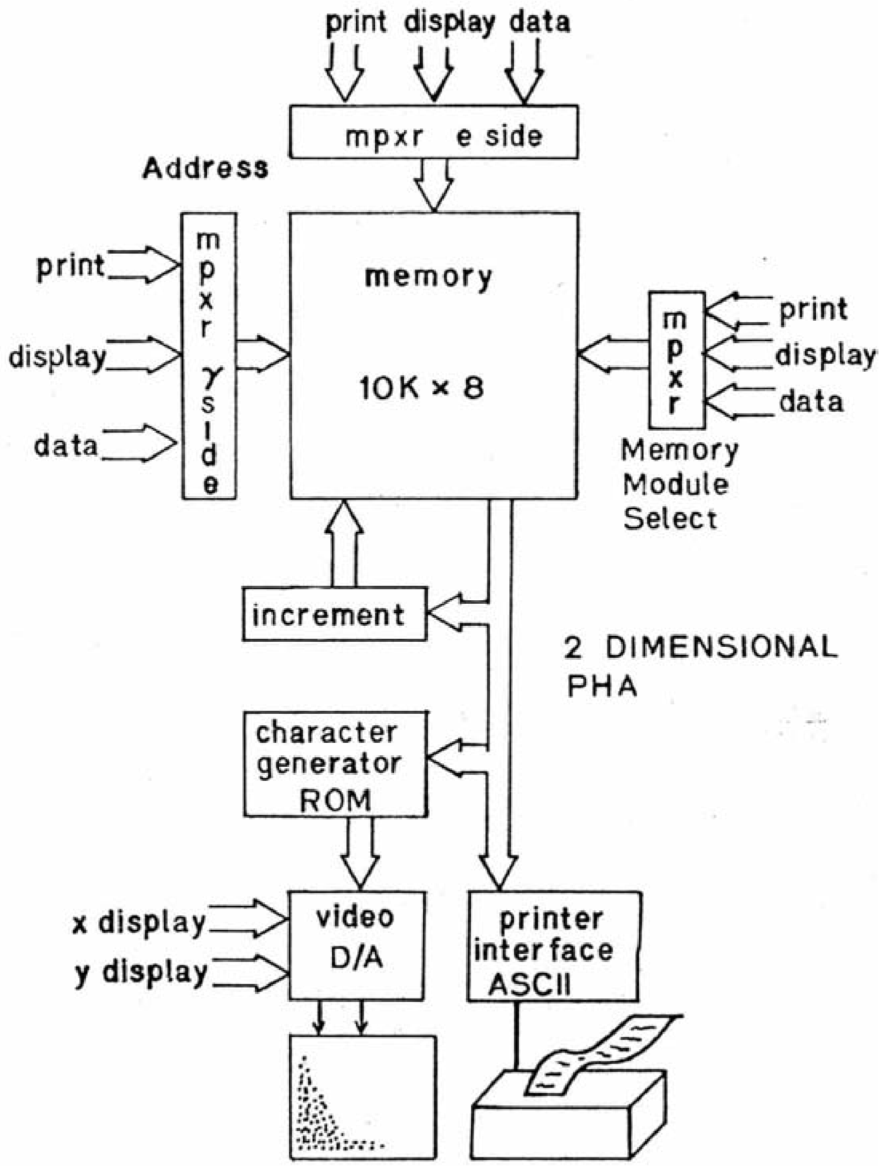
this is tex



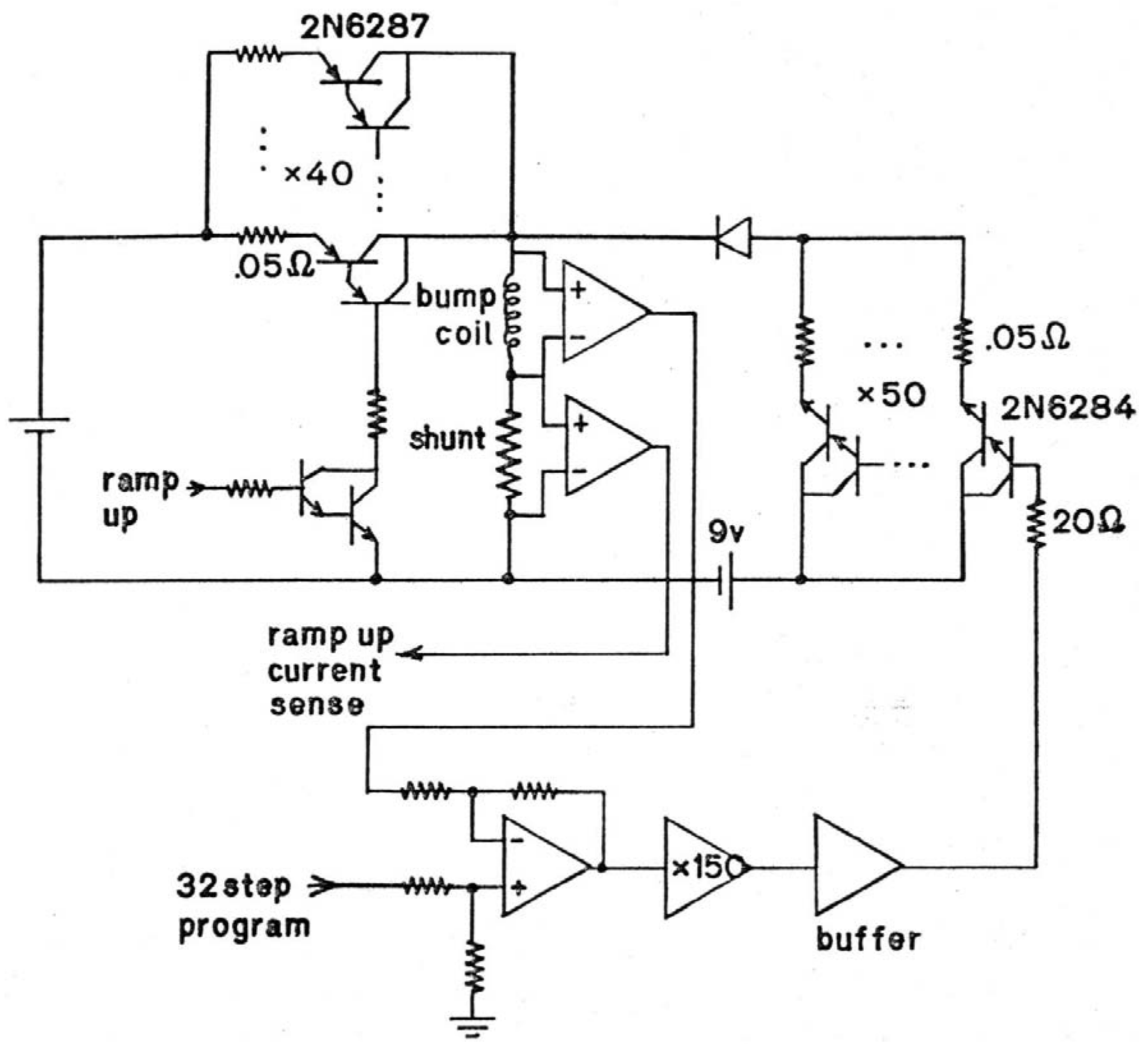
TRACK RECONSTRUCTION
γ HODOSCOPE (7)
ANTI (6)
TARGET HODOSCOPE (5)
e HODOSCOPE (4)
STROBE
10ns
5ns
MEM
REG
B→O
MEMORY
REGISTERS
BIN→OCT
>2
non-adj2
adj2
only1
3
'ONLY' ONE
Collinearity Condition
60nsec
STRICTLY COLLINEAR
NEARLY COLLINEAR

Producing histograms





A 100 kW HIFI amplifier

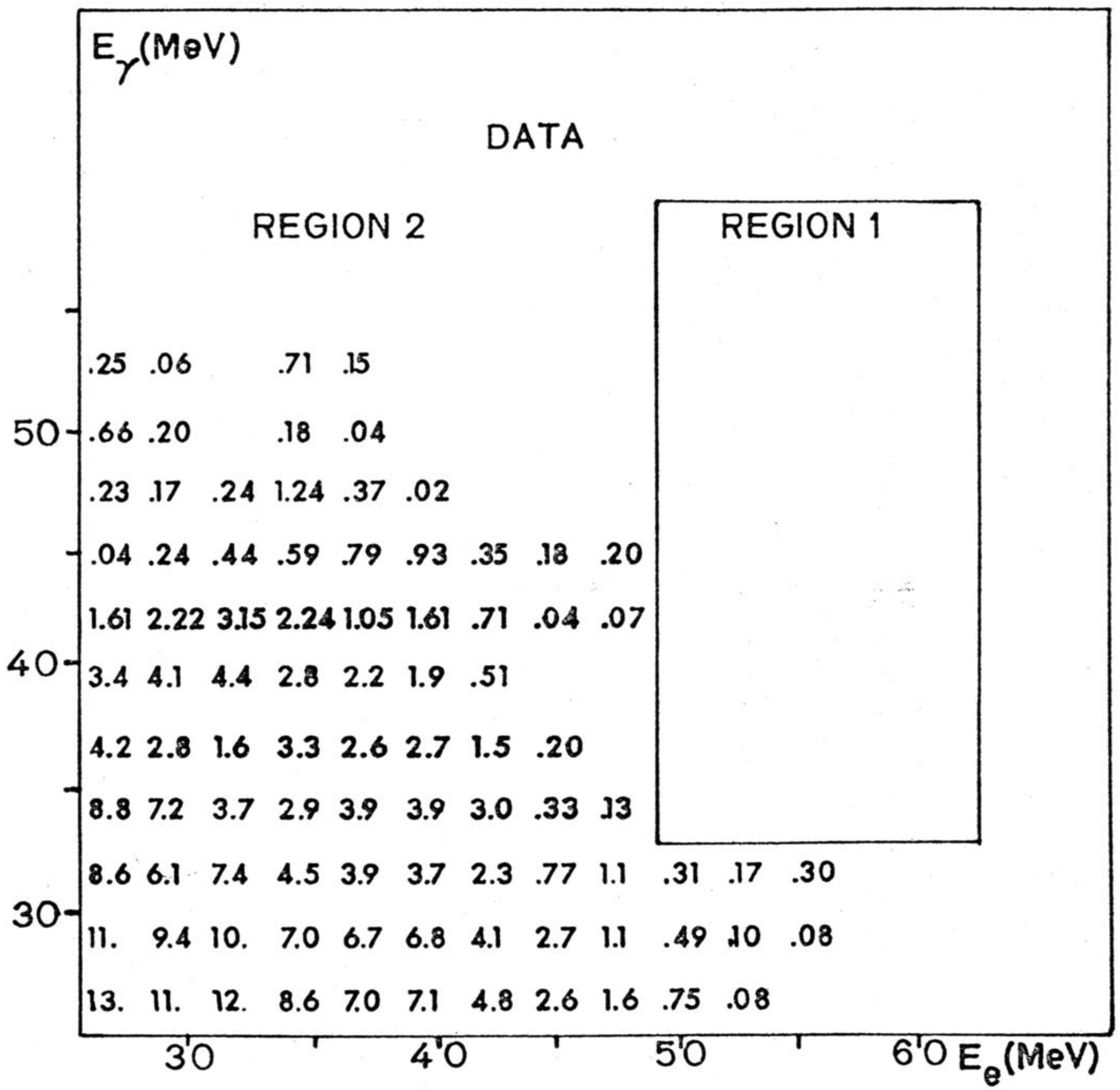


BUMP COIL DRIVE POWER SUPPLY

Those were the last days that physicists still worked on machine and experiment.

To improve, by almost 1000-fold, the duty cycle we built a super HIFI amp, water cooled no less.

No $\mu \to e\gamma$ found



We got to a limit of $<2\times10^{-9}$ without finding a single candidate for $\mu \to e\gamma$ decay.

We could have easily reached the goal of 10^{-10}.

The Nevis cyclotron was however retired after 30 years of honorable service.

Today it is hard to “see” a coincidence in an experiment.

Modern trigger systems, for instance, consist of manipulations of large amounts of information through vast logic arrays, equivalent to hundreds or tens of thousand coincidences.

We then measure time intervals between signals, with digital output, *i.e.* as numbers.

Computers, running a complicated set of program, further manipulate the event information. Or, more likely, builds up distributions which are then again manipulated to obtain a (hopefully) relevant result.

That’s the way today, still coincidence were used for well over fifty years. The concept remains valid today.