

Extremely useful resource

Particle Physics. One Hundred
Years of Discovery

Ezhela

in CERN library

pts. to all discovery
papers

W
Z
O
Y

First Resource

Particle Data Group PDG

<http://pdg.lbl.gov>

Look at each best measurement

eg. muon mass 105.658389 ± 0.000034

how is it measured?

value document technique change comment

best MARIAM '82 PRL 49, 993

look it up in library

→ hyperfine Zeeman transition in groundstate
of muonium !!!!!



$$J = \frac{1}{2}$$

μ MASS

The mass is known more precisely in u (atomic mass units) than in MeV (see the footnote to COHEN 87). The conversion from u to MeV, $1 u = 931.49432 \pm 0.00078$ MeV, involves the relatively poorly known electronic charge.

Where m_{μ}/m_e was measured, we have used the 1986 CODATA value for $m_e = 0.510998946 \pm 0.00000015$ MeV.

VALUE (MeV)	DOCUMENT ID	TECH	CHG	COMMENT
105.658389 ± 0.000034	¹ COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
105.65841 ± 0.00033	² BELTRAMI	86	SPEC	- Muonic atoms
105.658432 ± 0.000064	³ KLEMP	82	CNTR	+ Incl. in MARIAM 82
105.658386 ± 0.000044	⁴ MARIAM	82	CNTR	+
105.65856 ± 0.00015	⁵ CASPERSON	77	CNTR	+
105.65836 ± 0.00026	⁶ CROWE	72	CNTR	
105.65865 ± 0.00044	⁷ CRANE	71	CNTR	

¹ The mass is known more precisely in u : $m = 0.113428913 \pm 0.000000017 u$. COHEN 87 makes use of the other entries below.

² BELTRAMI 86 gives $m_{\mu}/m_e = 206.76830(64)$.

³ KLEMP 82 gives $m_{\mu}/m_e = 206.76835(31)$.

⁴ MARIAM 82 gives $m_{\mu}/m_e = 206.768259(62)$.

⁵ CASPERSON 77 gives $m_{\mu}/m_e = 206.76859(29)$.

⁶ CROWE 72 gives $m_{\mu}/m_e = 206.7682(5)$.

⁷ CRANE 71 gives $m_{\mu}/m_e = 206.76878(85)$.

μ MEAN LIFE τ

Measurements with an error $> 0.001 \times 10^{-6}$ s have been omitted.

VALUE (10^{-6} s)	DOCUMENT ID	TECH	CHG
2.19703 ± 0.00004	OUR AVERAGE		
2.197078 ± 0.000073	BARDIN	84	CNTR +
2.197025 ± 0.000155	BARDIN	84	CNTR -
2.19695 ± 0.00006	GIOVANETTI	84	CNTR +
2.19717 ± 0.00008	BALANDIN	74	CNTR +
2.1973 ± 0.0003	DUCIOS	73	CNTR +

$\tau_{\mu^+}/\tau_{\mu^-}$ MEAN LIFE RATIO

A test of CPT invariance.

VALUE	DOCUMENT ID	TECH	COMMENT
1.000004 ± 0.000076	BARDIN	84	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.0008 ± 0.0010	BAILEY	79	CNTR Storage ring
1.000 ± 0.001	MEYER	63	CNTR Mean life μ^+ / μ^-

$$(\tau_{\mu^+} - \tau_{\mu^-}) / \tau_{\text{average}}$$

A test of CPT invariance. Calculated from the mean-life ratio, above.

VALUE	DOCUMENT ID
$(2 \pm 8) \times 10^{-6}$	OUR EVALUATION

μ MAGNETIC MOMENT ANOMALY

$$\mu_{\mu} / (e\hbar/2m_{\mu}) - 1 = (g_{\mu} - 2) / 2$$

For reviews of theory and experiments, see HUGHES 88, KINOSHITA 84, COMB-LLY 81, FARLEY 79, and CALMET 77.

VALUE (units 10^{-6})	DOCUMENT ID	TECH	CHG	COMMENT
1165.9230 ± 0.0064	COHEN	87	RVUF	1996 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1165.910 ± 0.011	^R BAILEY	79	CNTR	Storage ring
1165.937 ± 0.017	^S BAILEY	79	CNTR	Storage ring
1165.923 ± 0.0085	^A BAILEY	79	CNTR +	Storage ring
1165.922 ± 0.009	^S BAILEY	77	CNTR ±	Storage ring
1166.16 ± 0.31	BAILEY	68	CNTR ±	Storage rings
1162.0 ± 5.0	CHAMPAK	62	CNTR +	

^S BAILEY 79 is final result. Includes BAILEY 77 data. We use μ/p magnetic moment ratio = 3.1833452 and recalculate the BAILEY 79 values. Third BAILEY 79 result is first two combined.

$$(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}}$$

A test of CPT invariance.

VALUE (units 10^{-8})	DOCUMENT ID
-2.4 ± 1.6	BAILEY 79



$$J = \frac{1}{2}$$

Not in general a mass eigenstate. See note on neutrinos in the ν_e section above.

ν_{μ} MASS

Applies to ν_2 , the primary mass eigenstate in ν_{μ} . Would also apply to any other ν_j which mixes strongly in ν_{μ} and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for $j \geq 3$, given the ν_e mass limit above.) Results based upon an obsolete pion mass are no longer shown; they were in any case less restrictive than ASSAMAGAN 96

VALUE (MeV)	CLS	REFERENCE NO	TECN	COMMENT
<0.10	90	¹ PDG	99 SPEC	$m^2 = -0.003 \pm 0.023$
<0.17	90	² ASSAMAGAN 96	SPEC	$m^2 = -0.016 \pm 0.023$
* * * We do not use the following data for averages, fits, limits, etc. * * *				
<0.15		³ DOLGOV	95 COSM	Nucleosynthesis
<0.48		⁴ ENQVIST	93 COSM	Nucleosynthesis
<0.003		^{5,6} MAYLE	93 ASTR	SN 1987A cooling
<0.025-0.030		^{6,7} BURROWS	92 ASTR	SN 1987A cooling
<0.3		⁸ FULLER	91 COSM	Nucleosynthesis
<0.42		⁸ LAM	91 COSM	Nucleosynthesis
<0.028-0.15		⁹ NATALF	91 ASTR	SN 1987A
<0.028		⁶ GANDHI	90 ASTR	SN 1987A
<0.014		^{6,10} GRIFOLS	90B ASTR	SN 1987A
<0.06		^{6,11} GAFMERS	89	SN 1987A
<0.50	90	¹² ANDERHUB	82 SPEC	$m^2 = -0.14 \pm 0.20$
<0.65	90	CLARK	74 ASPK	$K_{\mu 3}$ decay

¹ PDG 99 result is based on OUR AVERAGE for the π^{\pm} mass and the ASSAMAGAN 96 value for the muon momentum for the π^+ decay at rest. The limit is calculated using the unified classical analysis of HELLMANN 98 for a Gaussian distribution near a physical boundary. WARNING: since m^2 is calculated from the differences of large numbers, it and the corresponding limits are extraordinarily sensitive to small changes in the pion mass, the decay muon momentum, and their errors. For example, the limits obtained using the JECKELMANN 94, LENZ 98, and the weighted averages are 0.15, 0.79, and 0.19 MeV, respectively.

² ASSAMAGAN 96 measurement of p_{μ} from $\pi^+ \rightarrow u^+ \nu_{\mu}$ at rest combined with JECKELMANN 94 Solution B pion mass yields $m^2 = -0.016 \pm 0.023$ with corresponding Bayesian limit listed above. If Solution A is used, $m^2 = -0.143 \pm 0.024$ MeV². Replaces ASSAMAGAN 94.

³ DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below T_{QCD} for wrong-helicity Dirac neutrinos (ENQVIST 93, FULLER 91) to set more stringent limits.

⁴ ENQVIST 93 bases limit on the fact that thermalized wrong-helicity Dirac neutrinos would speed up expansion of early universe, thus reducing the primordial abundance. FULLER 91 exploits the same mechanism but in the older calculation obtains a larger production rate for these states, and hence a lower limit. Neutrino lifetime assumed to exceed nucleosynthesis time, ~ 1 s.

- ⁵ MAYLL 93 recalculated cooling rate enhancement by escape of wrong helicity Dirac neutrinos using the Livermore Supernova Explosion Code, obtains more restrictive result than the "very conservative" BURROWS 92 limit because of higher core temperature.
- ⁶ These would be an increased cooling rate if Dirac neutrino mass is included; this does not apply for Majorana neutrinos. Limit is on $\sqrt{m^2_{\nu_\mu} + m^2_{\nu_\tau}}$, and error becomes very large if ν_τ is nonrelativistic, which occurs near the lab limit of 31 MeV. RAJPOOT 93 notes that limit could be evaded with new physics.
- ⁷ BURROWS 92 limit for Dirac neutrinos only.
- ⁸ Assumes neutrino lifetime > 1 s. For Dirac neutrinos only. See also ENQVIST 93.
- ⁹ NATALF 91 published result multiplied by $\sqrt{8}\sqrt{4}$ at the advice of the author.
- ¹⁰ GRWOLS 90B estimated error is a factor of 3.
- ¹¹ GAEMERS 89 published result (< 0.03) corrected via the GANDHI 91 erratum.
- ¹² ANDRIHUB 82 kinematics is insensitive to the pion mass.

$$m_{\nu_2} - m_{\nu_3}$$

Test of CPT for a Dirac neutrino. (Not a very strong test.)

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
* * * We do not use the following data for averages, fits, limits, etc. * * *				
< 0.45	90	CLARK	74	ASPK $K_{\mu 3}$ decay

ν_2 (MEAN LIFE) / MASS

These limits often apply to ν_τ (ν_3) also.

VALUE (s/eV)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
> 15.4	90		¹³ KRAKAUER	91	CNTR $\nu_\mu, \bar{\nu}_\mu$ at LAMPF
* * * We do not use the following data for averages, fits, limits, etc. * * *					
> 7.8×10^{15}			¹⁴ BILLER	98	ASTR $m_\nu = 0.05-1$ eV
none $10^{-12} - 5 \times 10^4$			^{15,16} RIUDMAN	92	ASTR $m_\nu < 50$ eV
> 6.3×10^{15}			¹⁷ DODDIFSON	97	ASTR $m_\nu = 1-300$ keV
> 1.7×10^{15}			^{16,18} CHUPP	89	ASIR $m_\nu < 20$ eV
> 3.3×10^{14}			¹⁶ KOH R	89	ASTR $m_\nu < 20$ eV
> 0.11	90	0	^{19,20} VONFEILIT...	88	ASTR
			²¹ FRANK	81	CNTR $\nu\bar{\nu}$ LAMPF
			²² HENKY	81	ASTR $m_\nu = 16-20$ eV
			²³ KIMBLE	81	ASTR $m_\nu = 10-100$ eV
			²⁴ REPHAELI	81	ASTR $m_\nu = 30-150$ eV
			²⁵ DERUJULA	80	ASTR $m_\nu = 10-100$ eV
> 2×10^{21}			²⁶ STECKER	80	ASTR $m_\nu = 10-100$ eV
> 1.0×10^{-2}	90	0	²¹ BLIETSCHAU	78	HLBC ν_μ , CERN GGM
> 1.7×10^{-2}	90	0	²¹ BLIETSCHAU	78	HLBC $\bar{\nu}_\mu$, CERN GGM
> 2.2×10^{-3}	90	0	²¹ BARNES	77	DBC ν , ANI 17-ft
> 3×10^{-3}	90	0	²¹ BELLOTTI	76	HLBC ν , CERN GGM
> 1.3×10^{-2}	90	1	²¹ BELLOTTI	76	HLBC $\bar{\nu}$, CERN GGM

¹³ KRAKAUER 91 quotes the limit $\tau/m_{\nu_1} > (0.15a^2 + 21.65a + 26.3)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta$

- $= (1/2)(1 + \alpha \cos\theta)$ The parameter $\alpha \neq 0$ for a Majorana neutrino, but can vary from -1 to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $\alpha = -1$).
- 14 BILLER 98 use the observed TeV γ -ray spectra to set limits on the mean life of a radiatively decaying neutrino between 0.05 and 1 eV. Curve shows $\tau_\nu/B_\gamma > 0.15 \times 10^{21}$ s at 0.05 eV, $> 1.7 \times 10^{21}$ s at 0.17 eV, $> 3 \times 10^{21}$ s at 1 eV, where B_γ is the branching ratio to photons.
- 15 BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.
- 16 Nonobservation of γ 's in coincidence with ν 's from SN 1987A. Results should be divided by the $\tau_\nu \rightarrow \gamma X$ branching ratio.
- 17 DODELSON 92 range is for wrong helicity keV mass Dirac ν 's from the core of neutron star in SN 1987A decaying to ν 's that would have interacted in KAM2 or IMB detectors.
- 18 CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.
- 19 Model-dependent theoretical analysis of SN 1987A neutrinos.
- 20 Limit applies to ν_τ also.
- 21 These experiments look for $\nu_\mu \rightarrow \nu_e \gamma$ or $\bar{\nu}_\mu \rightarrow \bar{\nu}_e \gamma$.
- 22 HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.
- 23 KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}-10^{23}$ s.
- 24 REPHAËLI 81 consider ν decay γ effect on neutral H in early universe; based on M31 HI concludes $\tau > 10^{24}$ s.
- 25 DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.
- 26 STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

$(v - c) / c$ ($v \equiv \nu_2$ VELOCITY)

Expected to be zero for massless neutrino, but also tests whether photons and neutrinos have the same limiting velocity in vacuum.

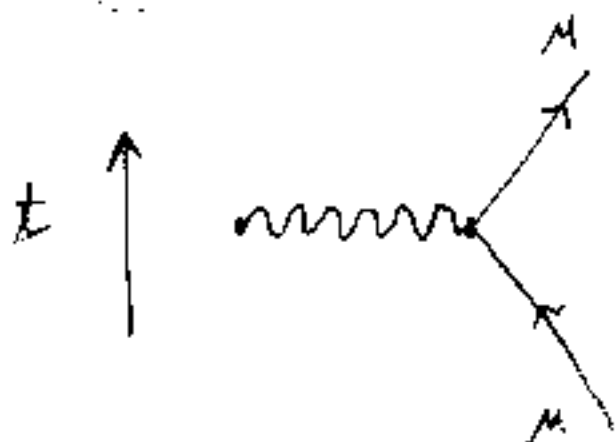
VALUE (units 10^{-4})	CL%	EVTs	DOCUMENT ID	TECN	CIG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.4	95	9800	KALBI LLISCH 79	SPLC		
< 2.0	99	11	ALSPECTOR 76	SPFC	0	> 5 GeV ν
< 4.0	99	26	ALSPECTOR 76	SPFC	0	< 5 GeV ν

ν_2 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard $SU(2) \times U(1)$ electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu \approx 3eG_F m_\nu / (8\pi^2 \sqrt{2}) = (3.7 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_{\nu_2} < 0.17$ MeV, it follows that for the extended standard electroweak theory, $\mu(\nu_2) < 0.61 \times 10^{-13} \mu_B$.

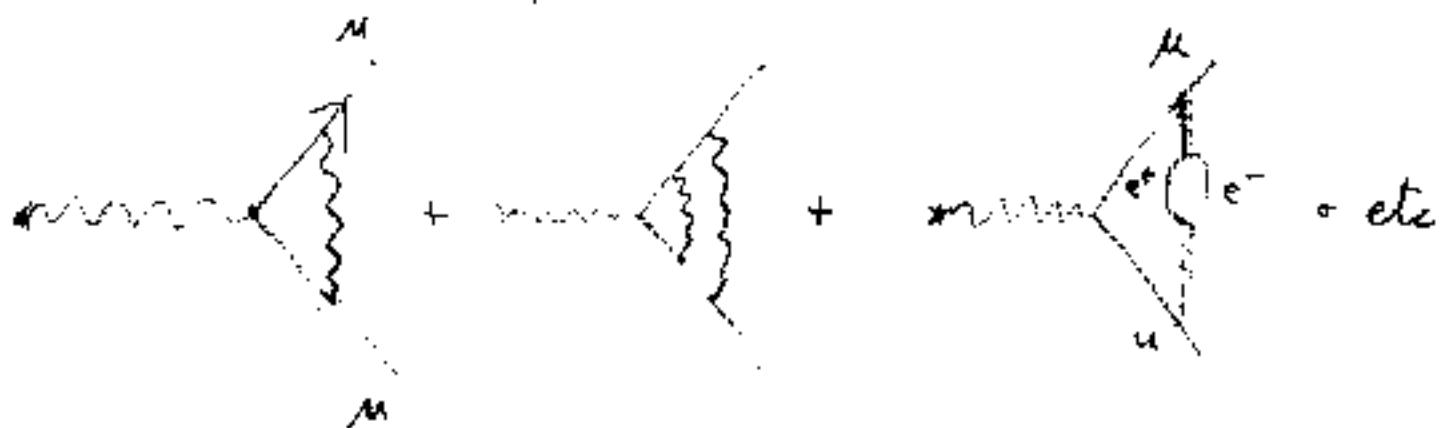
VALUE ($10^{-10} \mu_B$)	CL%	DOCUMENT ID	TECN	COMMENT
< 8.5	90	ATKINS	90	CNTR $\nu_\mu e \rightarrow \nu_\mu e$
< 7.4	90	27 KRAKAUER	90	CNTR LAMPPE ($\nu_\mu, \bar{\nu}_\mu$) e elast.

Muon magnetic moment



photon couples to the magnetic moment

Compare e to μ ?
 Is there new physics in μ ?



electromagnetic + weak + strong corrections



Dirac elementary particles

$$\vec{M} = \frac{qe}{2mc} |\vec{S}|$$

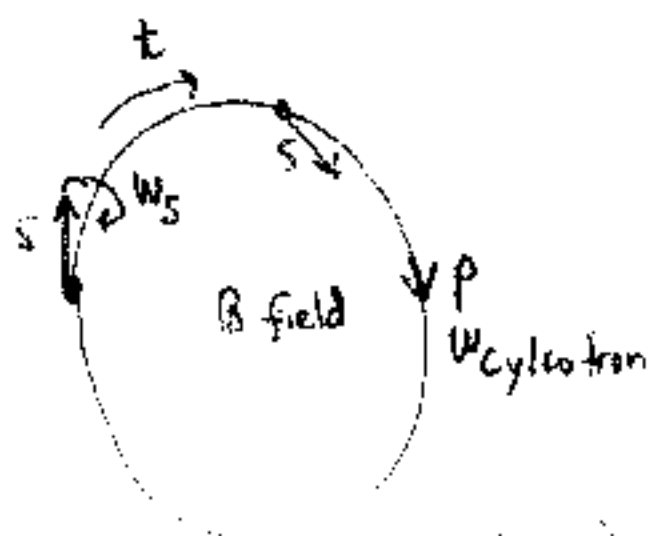
\swarrow spin
 \nwarrow g-factor

Anomalous contribution

$$g = \frac{4-2}{2}$$

Measure this precisely

Make muon storage ring



particle goes around w/ freq. ω_c
 spin precesses w/ freq. ω_s

$$\omega_c = \frac{eB}{\gamma mc}$$

lab frame

$$\omega_s = \frac{eB}{m\gamma} \left[1 + \left(\frac{g-2}{2} \right) \gamma \right]$$

Then muon decays

$$\vec{M} \rightarrow \vec{e} \vec{r} \vec{p} \vec{M}$$

$$\phi = (\omega_s - \omega_c) t$$

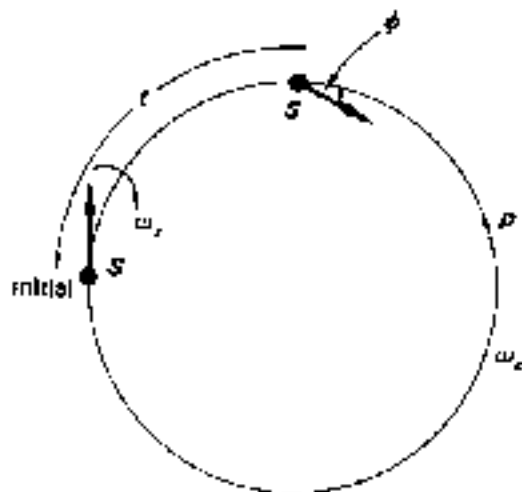
And more

magnetic moment:

Dirac pt. particle

$$\mu = \frac{ge}{2m} |\mathbf{S}|$$

← spin



$$\omega_c - \text{cyclotron} = \frac{eB}{mc} \text{ frequency}$$

$$\omega_s - \text{precession} = \frac{geB}{2mc} \text{ frequency}$$

Fig. 5.2 For a particle of $g \neq 2$ in a uniform magnetic field, the spin vector s , initially aligned with the momentum p , will "lead" by a phase angle ϕ at later times—see Eq. (5.7).

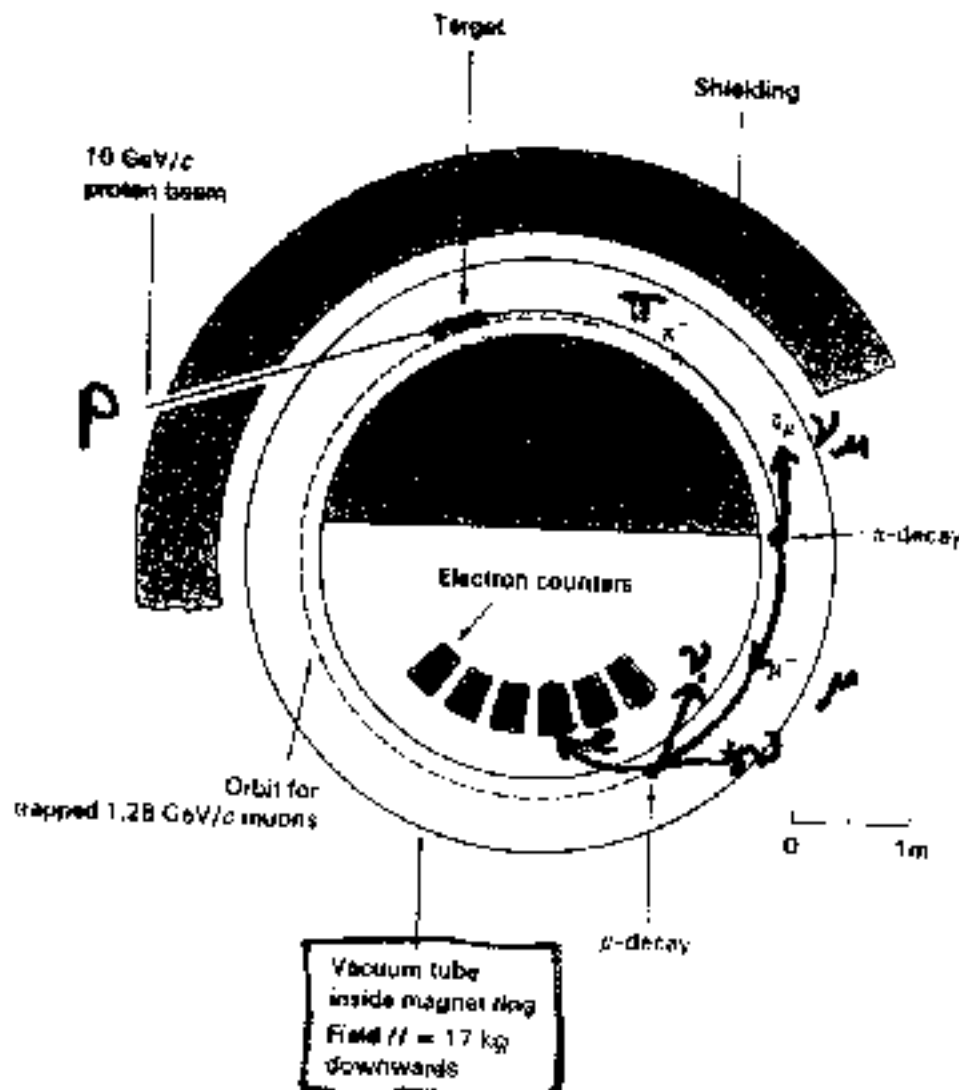


Fig. 5.3

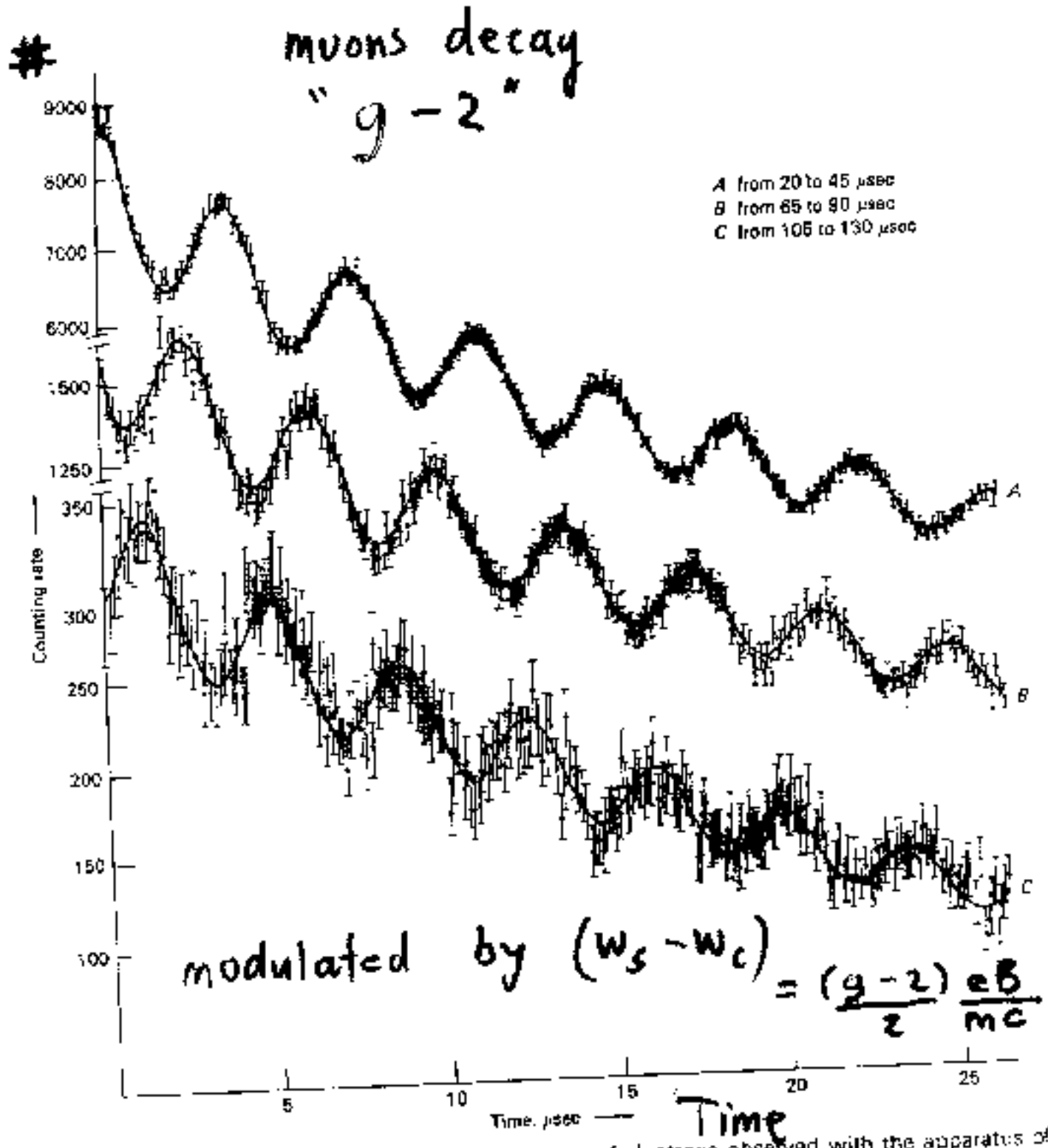


Fig. 5.5 Time dependence of the counting rate of electrons observed with the apparatus of Fig 5.3. The general exponential decrease corresponds to a lifetime $\tau = 26 \mu\text{sec}$ in the laboratory system. The rate is modulated by the frequency $(\omega_s - \omega_c)$, which measures $(g - 2)$.

period of the anomalous moment $2\pi/(\omega_s - \omega_c)$ is about $3.7 \mu\text{sec}$, so that, by following out over some thirty

This year, new $g-2$ @ Brookhaven Lab

$$a_{\mu^+} = \frac{g-2}{2} = 11\,659\,202 \pm 14 \pm 6 \times 10^{-10}$$

1.3 parts/million

a_e measured to 4 parts/billion

but a_{μ} more sensitive to new physics

because $\left(\frac{m_{\mu}}{m_e}\right)^2 \approx 40,000$.

For example: QED only,

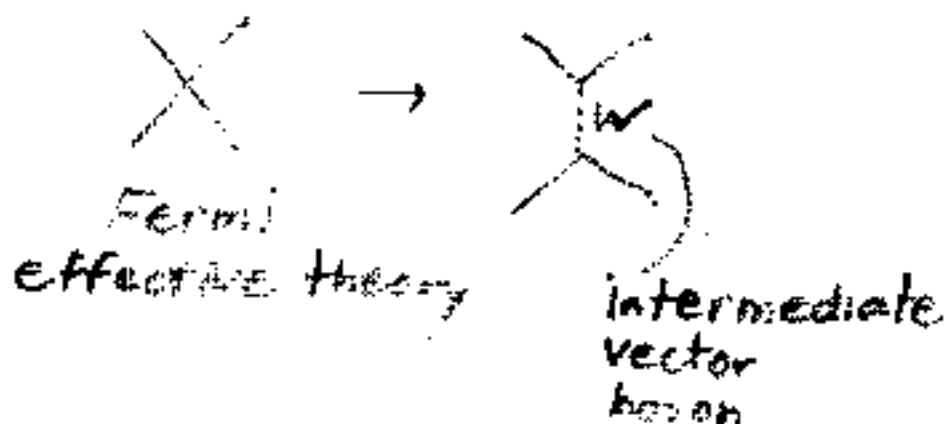
$$a_e = 0.5 \frac{d}{\pi} - 0.32848 \left(\frac{d}{\pi}\right)^2 + 1.19 \left(\frac{d}{\pi}\right)^3 + \dots$$

$$a_{\mu} = 0.5 \frac{d}{\pi} + 0.76578 \left(\frac{d}{\pi}\right)^2 + 24.45 \left(\frac{d}{\pi}\right)^3 + \dots$$

TWO NEUTRINOS?

PONTECORVO puzzles over e, μ

SCHWARZ wants to see Fermi break down



Both thought of ν beams.

We knew $\text{Rate}(\mu \rightarrow e \gamma) \sim 0$, but if only one kind of ν , then



Make ν beam: π beam

$\pi \rightarrow \mu \nu$ ($K \rightarrow \mu \nu$)

($\pi \rightarrow e \nu$ small).

μ or e ?



Muon and electron signatures

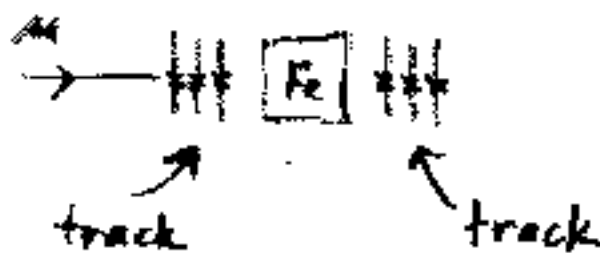
- electron showers in matter



loses energy early and often

- muons ionize but penetrate through steel

identify muons



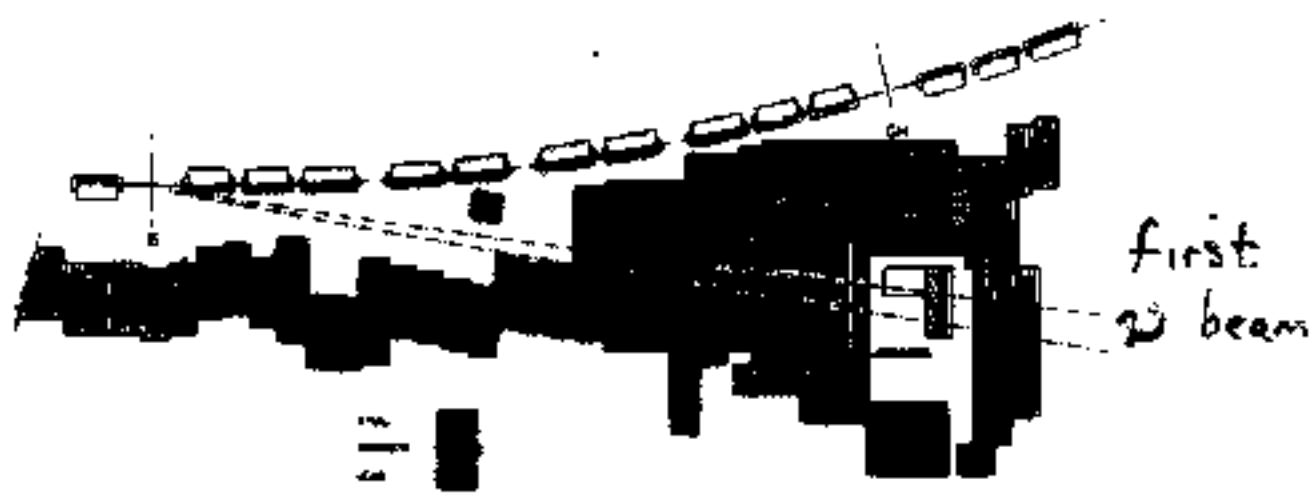


Figure 1. Plan view of the A.G.S. neutrino experiment.
BROOKHAVEN, NY.

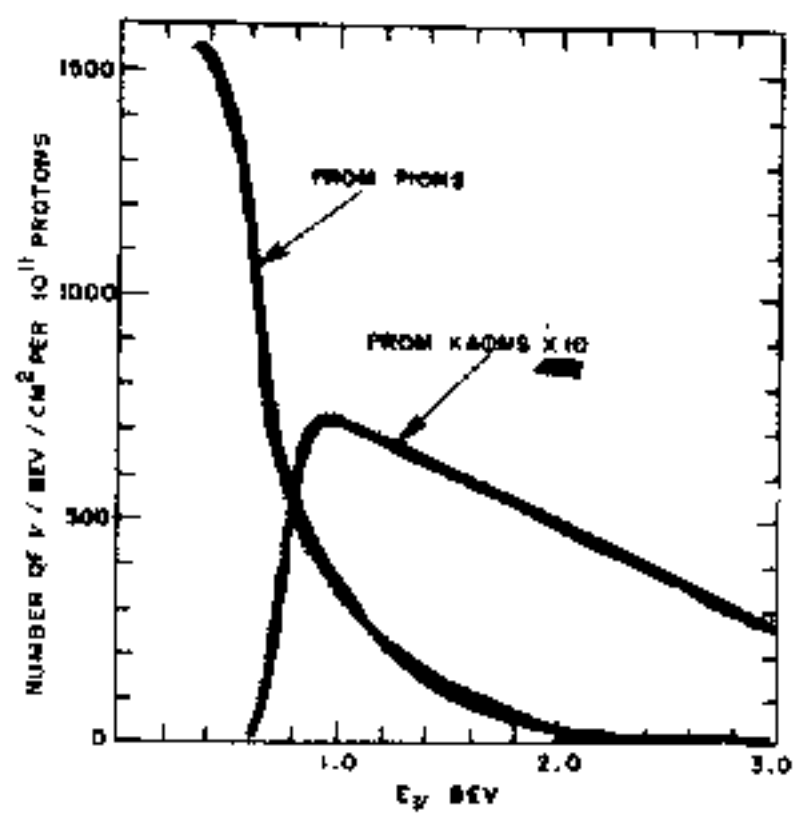


Figure 2. Energy spectrum of neutrinos as expected for A.G.S. running at 15 GeV

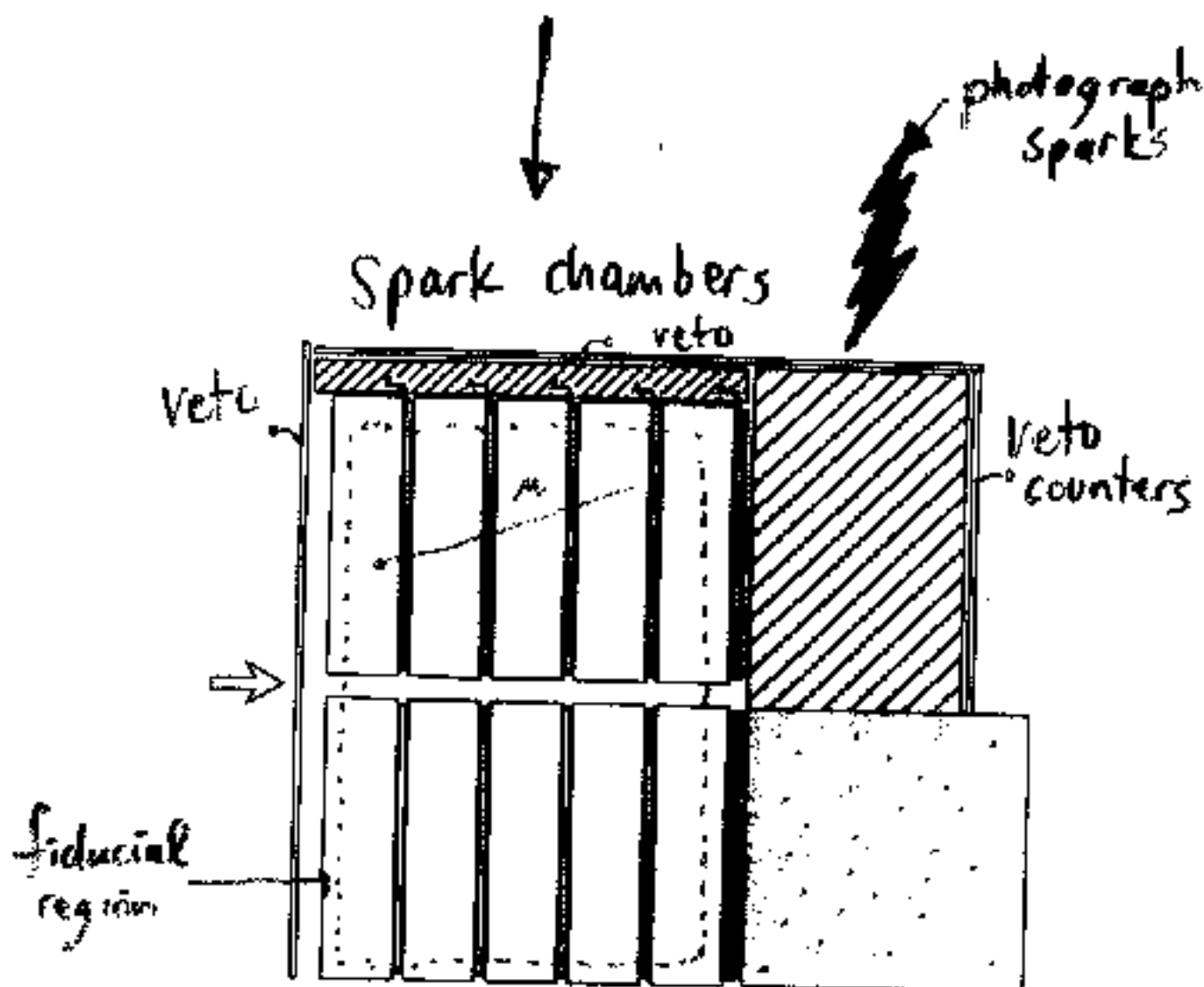
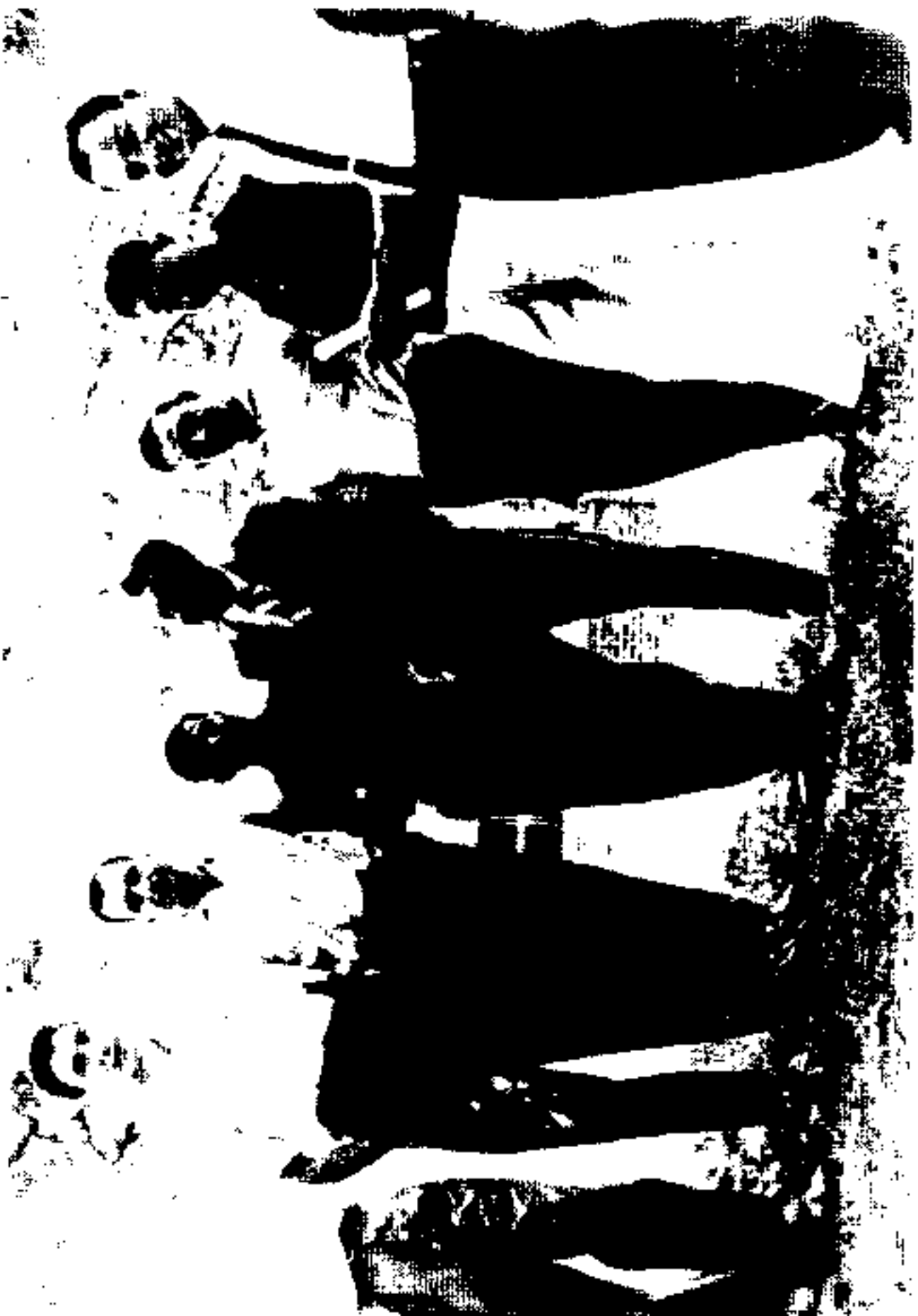


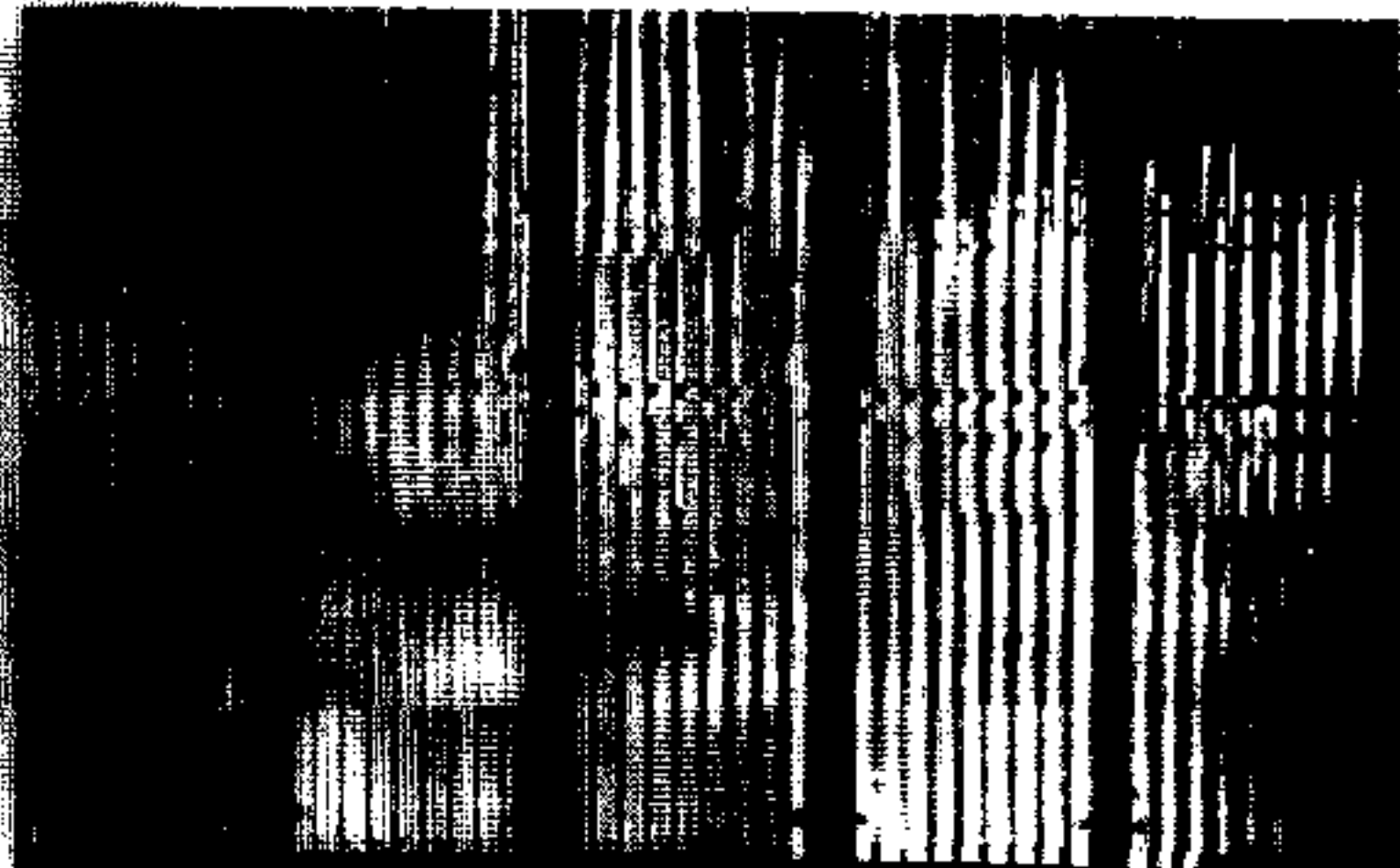
Figure 3. Spark chamber and counter arrangement. This is the front view with neutrinos entering on the left. A are the trigger counters. B, C and D are used in anti-coincidence.



Figure 4. A photograph of the chambers and counters.



for ten years of





Single Muon events

Elastic.

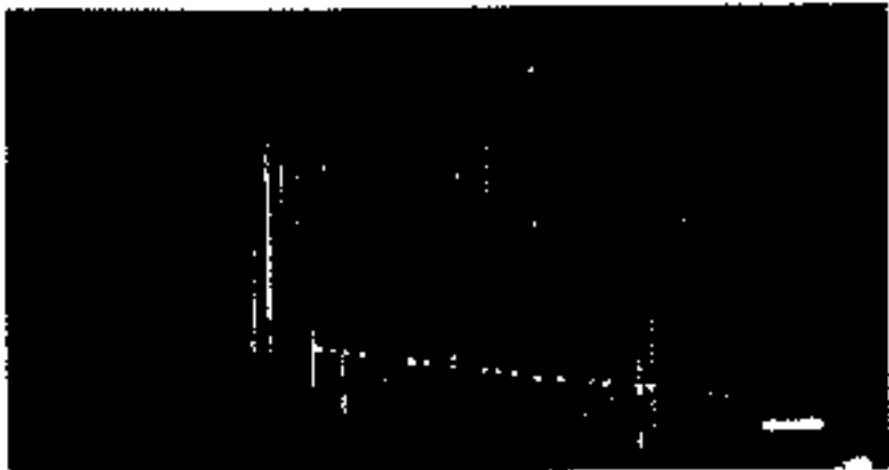


3.10

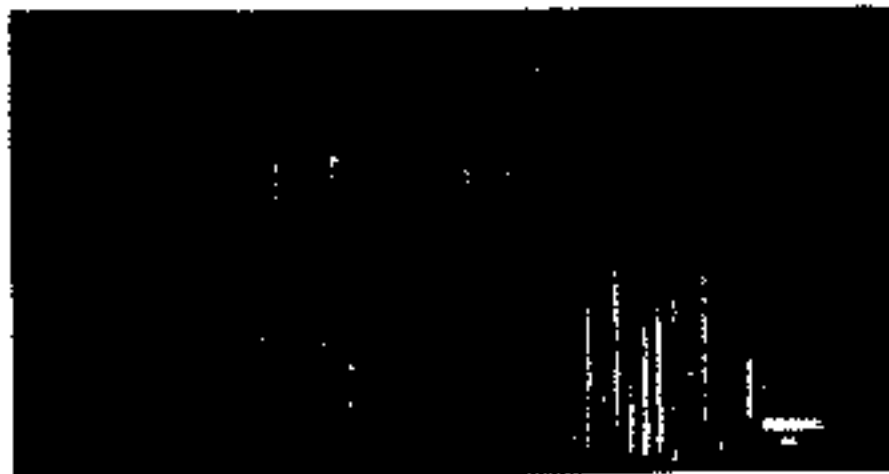
3.10

MUON

PA 7540



A



B



C

Vertex events (inelastic)



M
 $p_A > 500 \text{ MeV}$
 and e-type



A



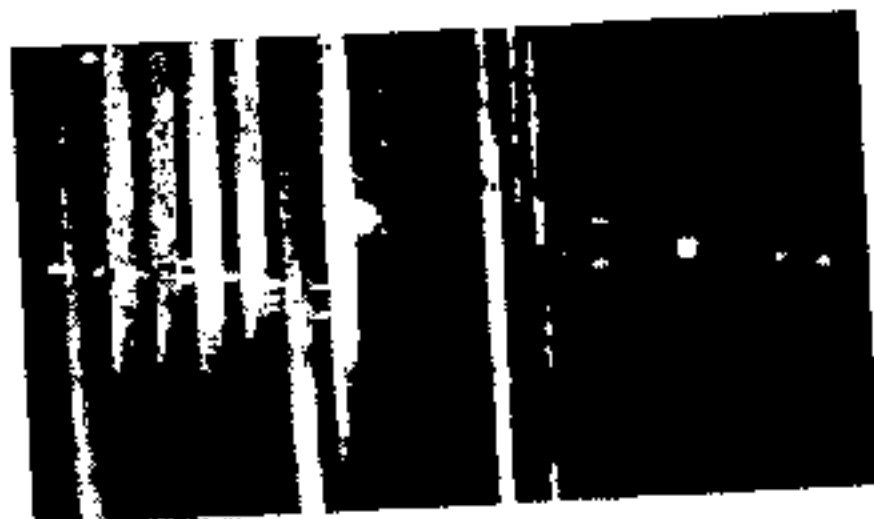
B



C

this is what electrons look
like

3.12



A



B



C

Results of μ beam experiment

- 113 events total

- 34 single muon events $p_{\mu} > 300 \text{ MeV}$



- 22 vertex events



- 49 short single tracks $p_{\mu} \leq 300 \text{ MeV}$
(neutron background) < 4 sparks

- 8 shower events
6 with $p > 300 \text{ MeV}$

- > Not cosmic rays - check by turning off beam
- > Not neutron induced - uniformity in detector
- > Due to π, K decay - block of steel early in beam

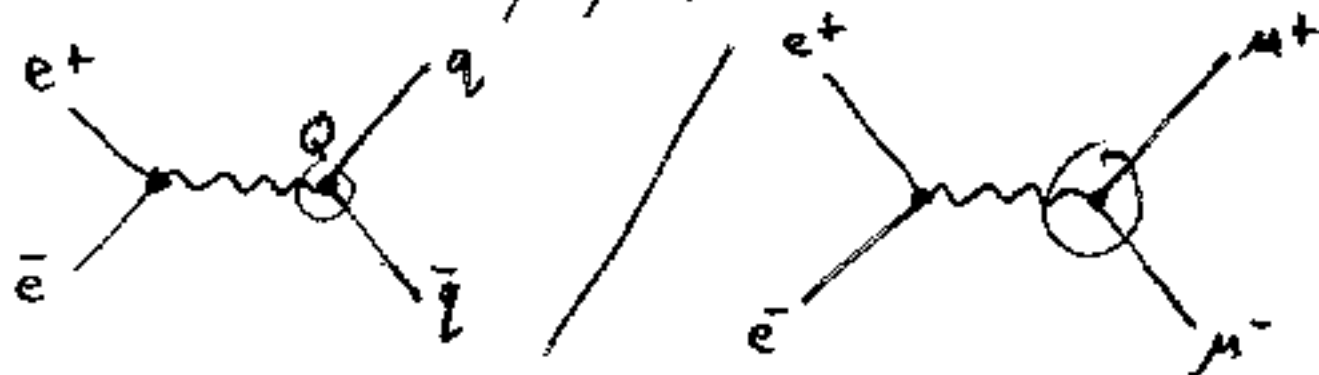
NOT ENOUGH SHOWER EVENTS \Rightarrow NO γ_e

e^+e^- colliders

One simple measurement R .

Small band of detector.

$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$



$$\sigma = \frac{\pi}{3} \left(\frac{\hbar c Q_c \alpha}{E} \right)^2 \quad \text{above threshold}$$

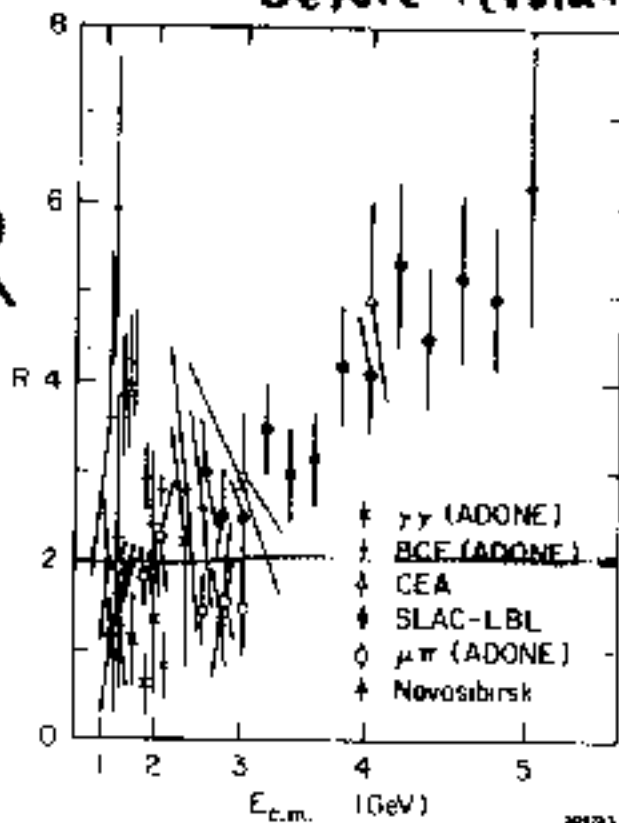
$$R = 3 \sum_i Q_i^2$$

$\leftarrow i$
colour

\leftarrow
 i sum over quarks u, d, s, c, b, t

R

Before revolution

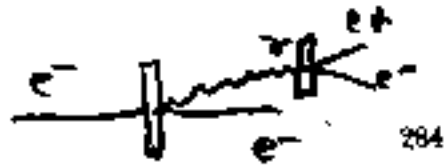
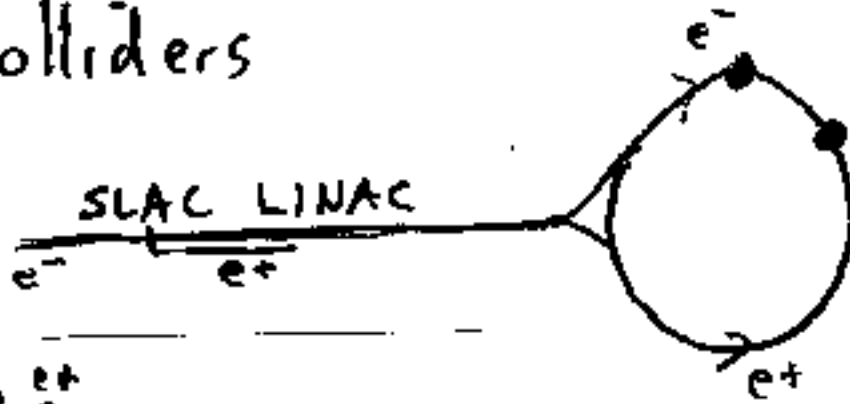


The ratio R as of July 1974.

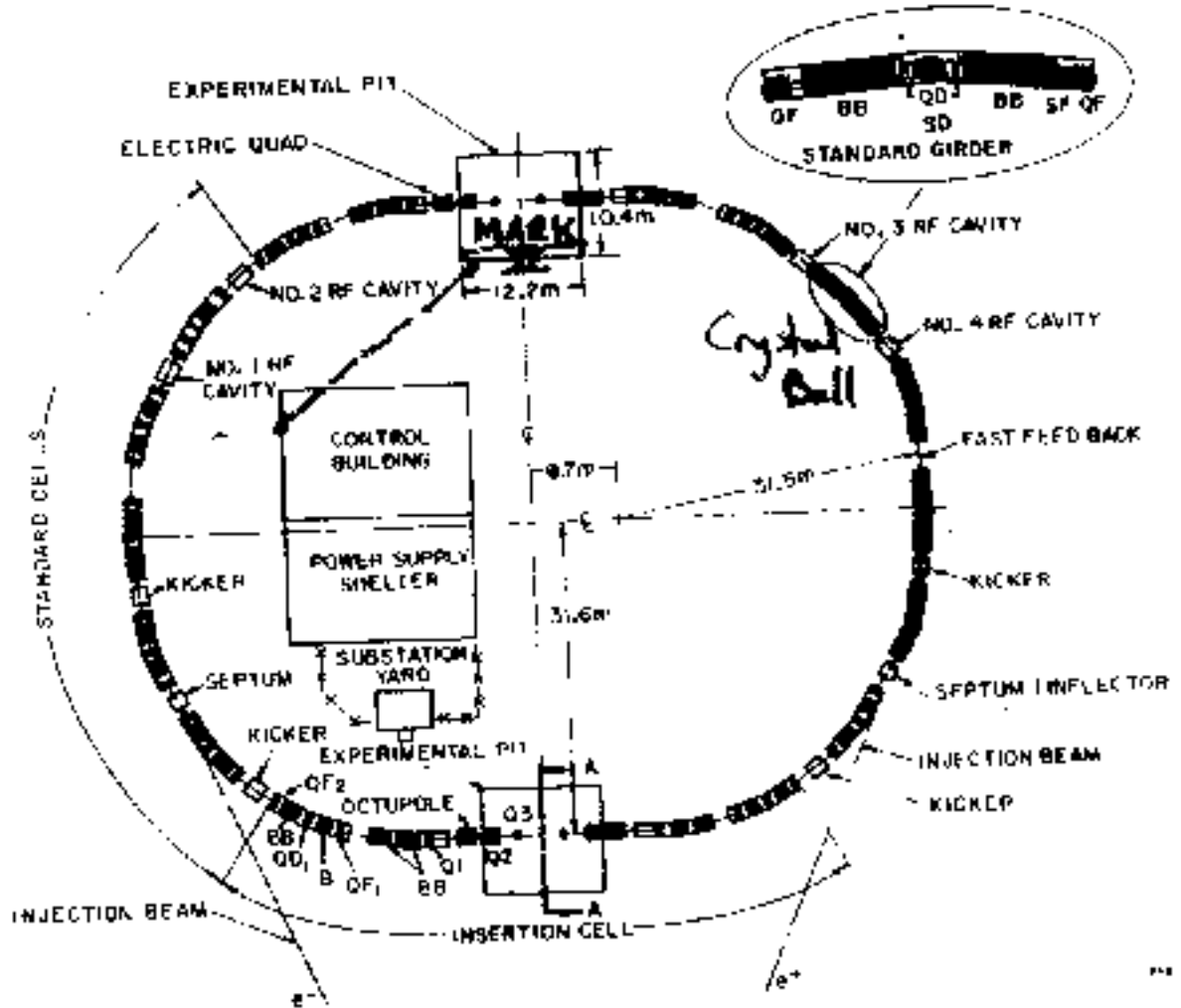
if only u, d, s

$$R = 3 \left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 \right] = 2$$

etc⁻ Colliders



Physics 1976



1. Schematic of the SPEAR storage ring.

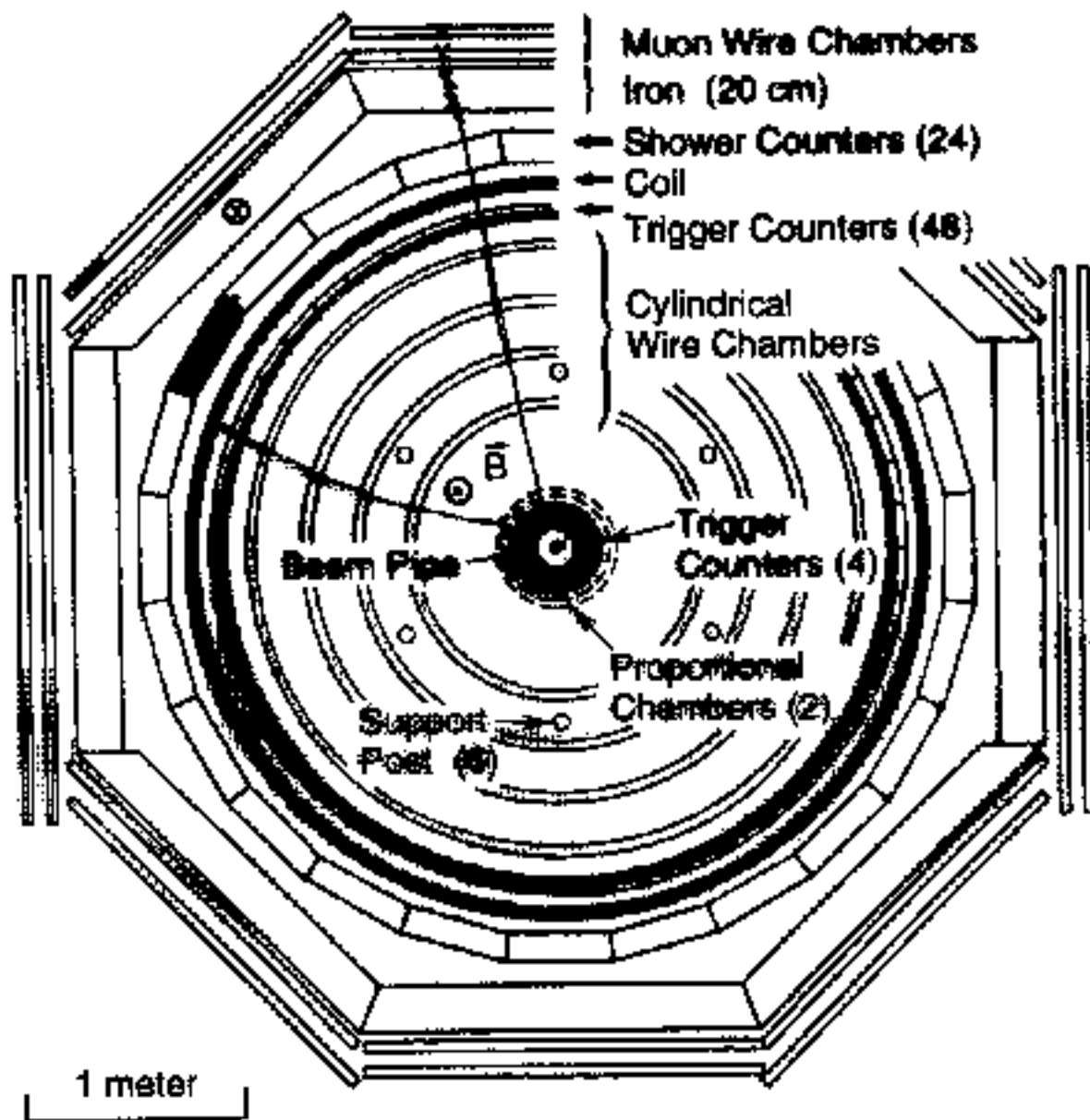


Figure 6 The initial train of the Mark I detector.

etc.

Mark II detector at SLAC.

hermetic,

"Typical" J/ψ event
in tracking chamber

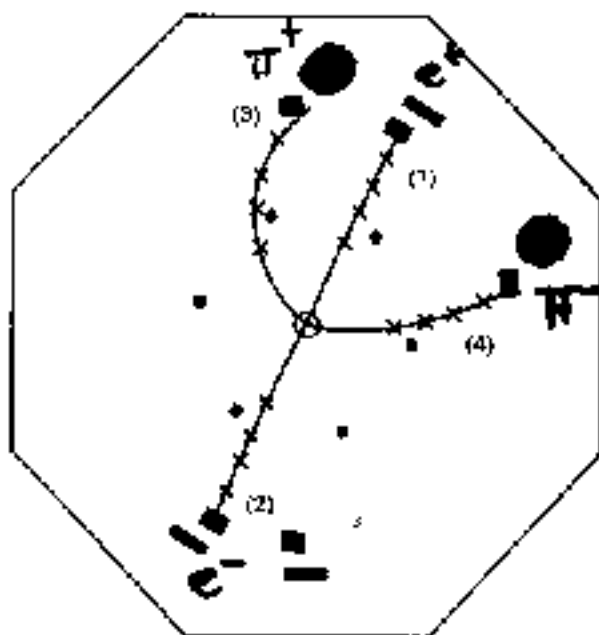
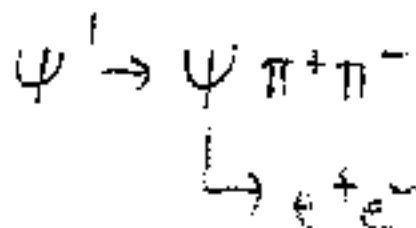


Fig. 4.4. Example of the decay $\psi(3.7) \rightarrow \psi(3.1) + \pi^+ + \pi^-$ observed in a spark chamber detector. The $\psi(3.1)$ decays to $e^+ + e^-$. Tracks (3) and (4) are due to the relatively low energy (150 MeV) pions, and (1) and (2) to the 1.5 GeV electrons. The magnetic field and the SPEAR beam pipe are normal to the plane of the figure. The trajectory shown for each particle is the best fit through the sparks, indicated by crosses. (From Abrams *et al.* 1975.)



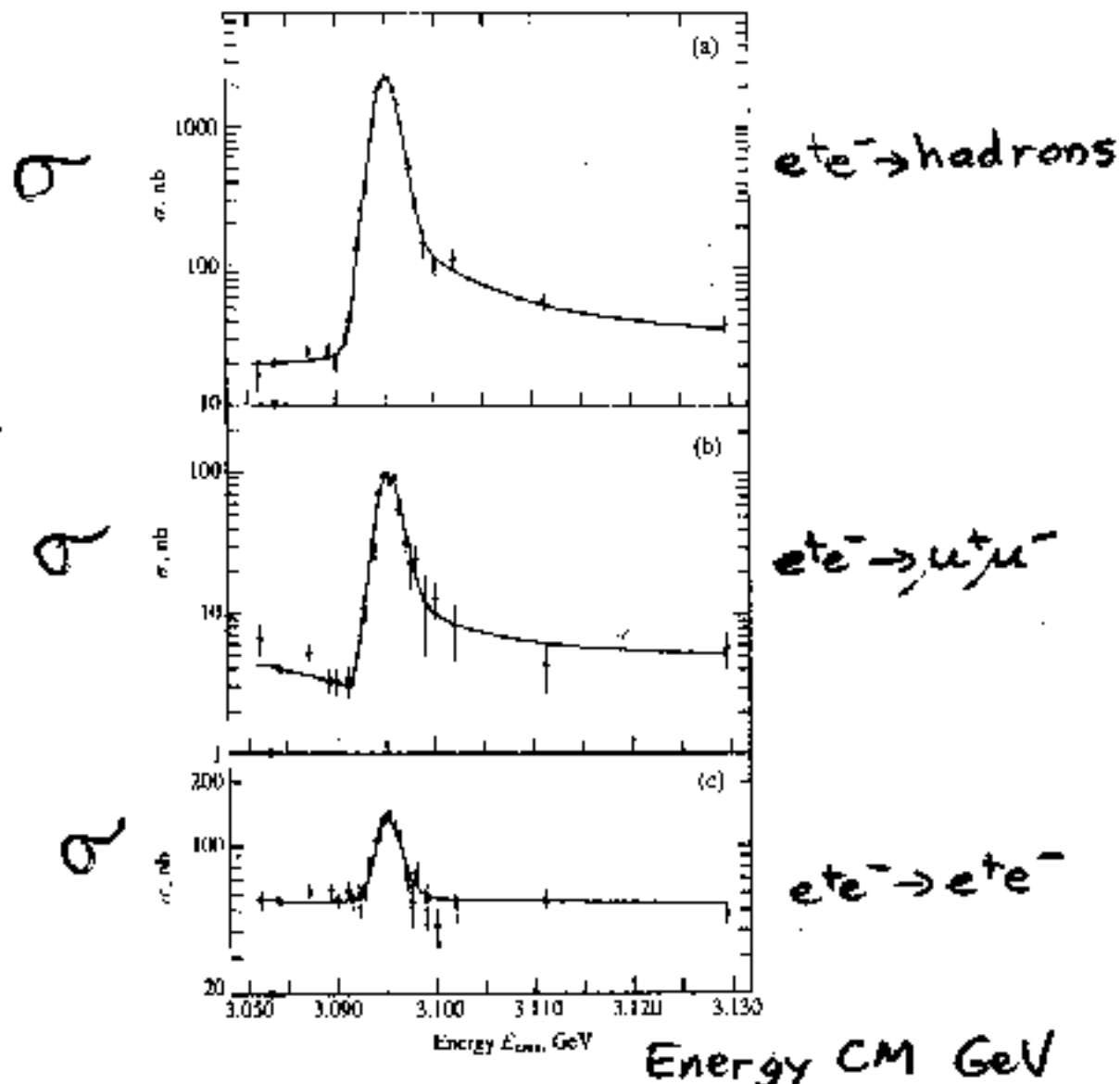
From e^+e^- 

Fig. 4.1. Results of Augustin *et al.* (1974) showing the observation of the J/ψ resonance of mass 3.1 GeV, produced in e^+e^- annihilation at the SPEAR storage ring, SLAC. (a) $e^+e^- \rightarrow \text{hadrons}$; (b) $e^+e^- \rightarrow \mu^+\mu^-$, $|\cos\theta| \leq 0.6$; (c) $e^+e^- \rightarrow e^+e^-$, $|\cos\theta| \leq 0.6$.

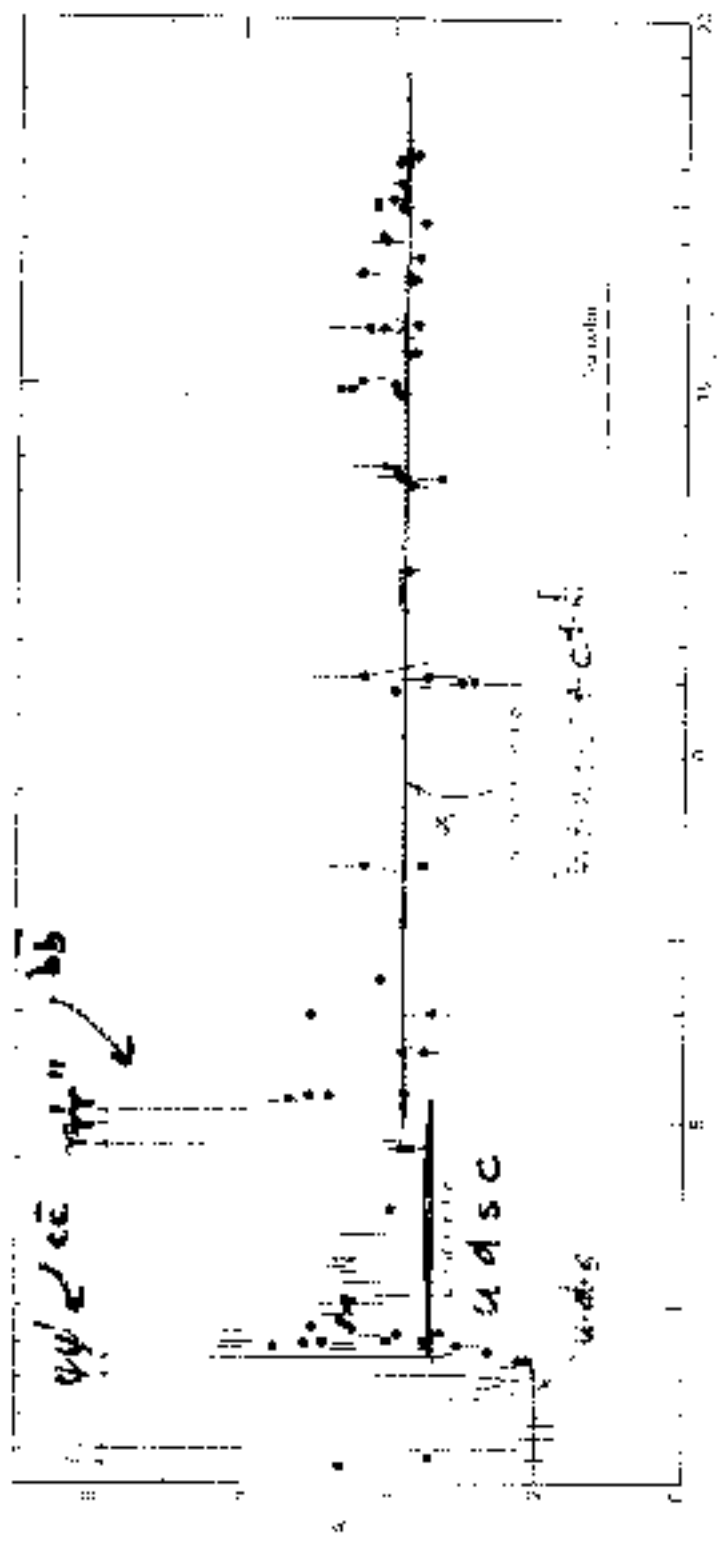


Figure 8.5. R is plotted against electron energy for GeV1. (Source: F. Halzen and A. D. Martin, *Quarks and Leptons* (New York: Wiley, copyright © 1984), p. 225. Reprinted by permission of John Wiley & Sons, Inc.)

Spectroscopy
 differences w. th. are really
 small
 marks

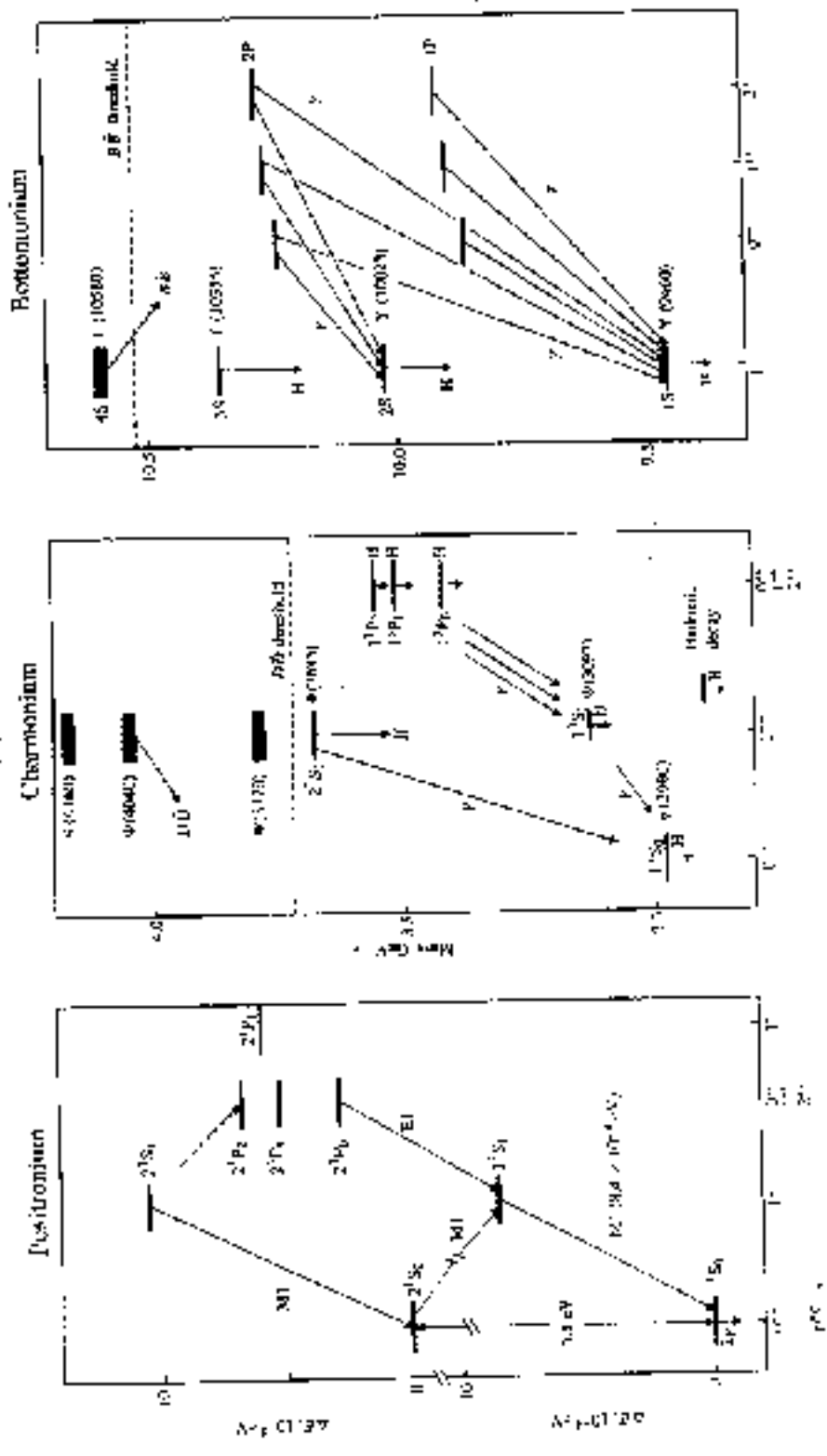
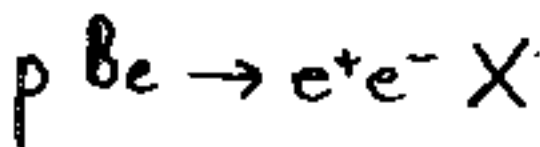


Fig. 4.8. The energy-level diagrams for positronium, charmonium and bottomonium. Note the changes in scale for positronium. Only states with J^{PC} can be accessed in e^+e^- annihilation experiments. Note that the atomic physics convention is to label the lowest-lying P states of positronium as $2P$, while for the charmonium and bottomonium states the nuclear physics nomenclature $1P$ is

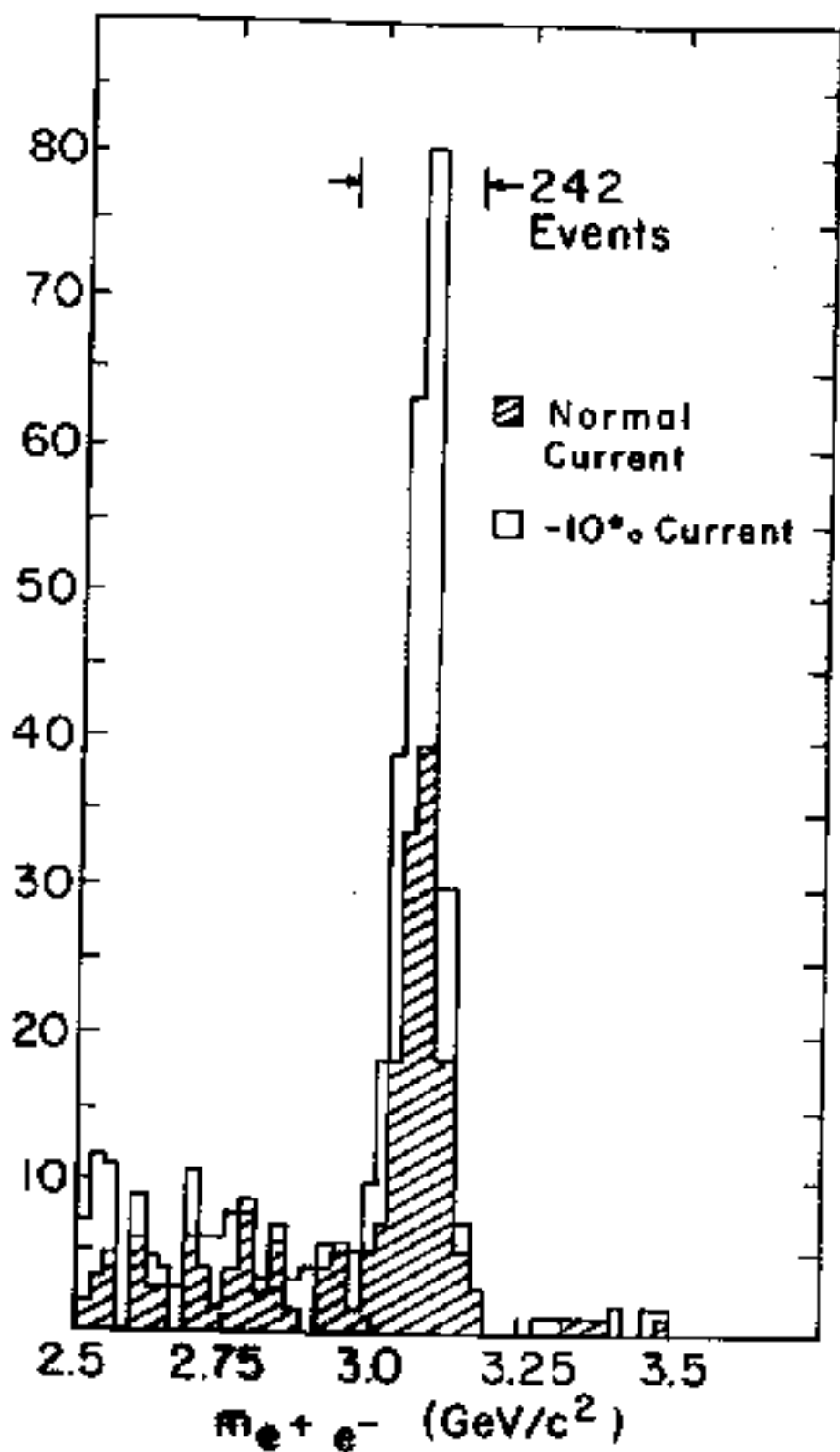
e^+e^-
 e^+e^-
 (ΔE)
 (ΔE)
 $P = ($
 the v
 quantum
 the upper
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Ting @ Brookhaven

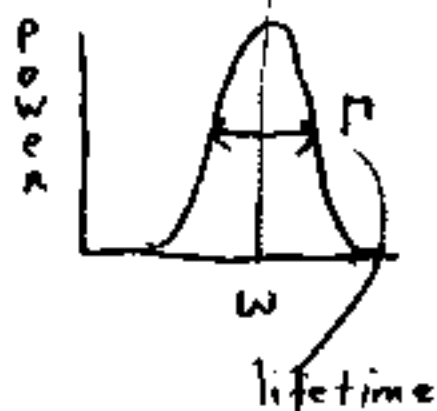
3.17



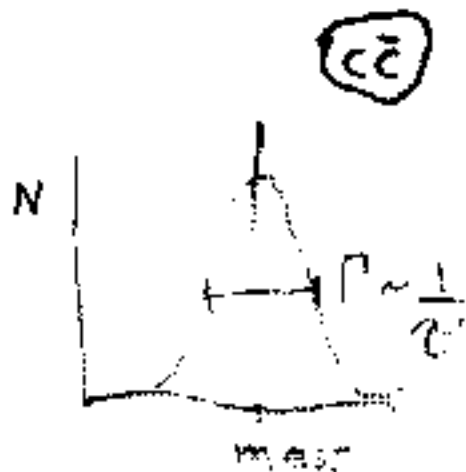
two arm spectrometer



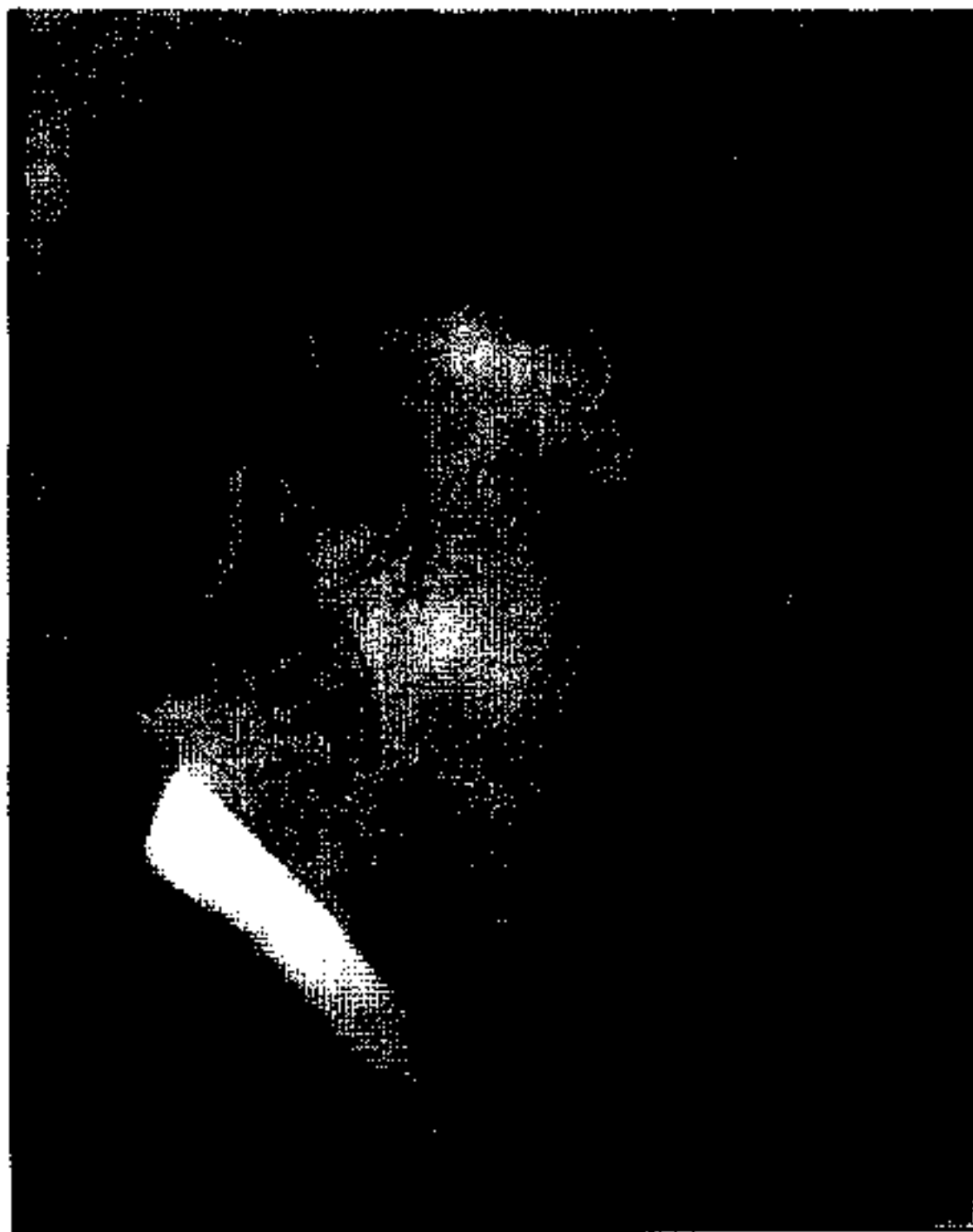
Classical Resonance



quantum resonance



My advisor



Martin Perl τ

Try to understand $e - \mu$
 What is different? Mass, Lepton #

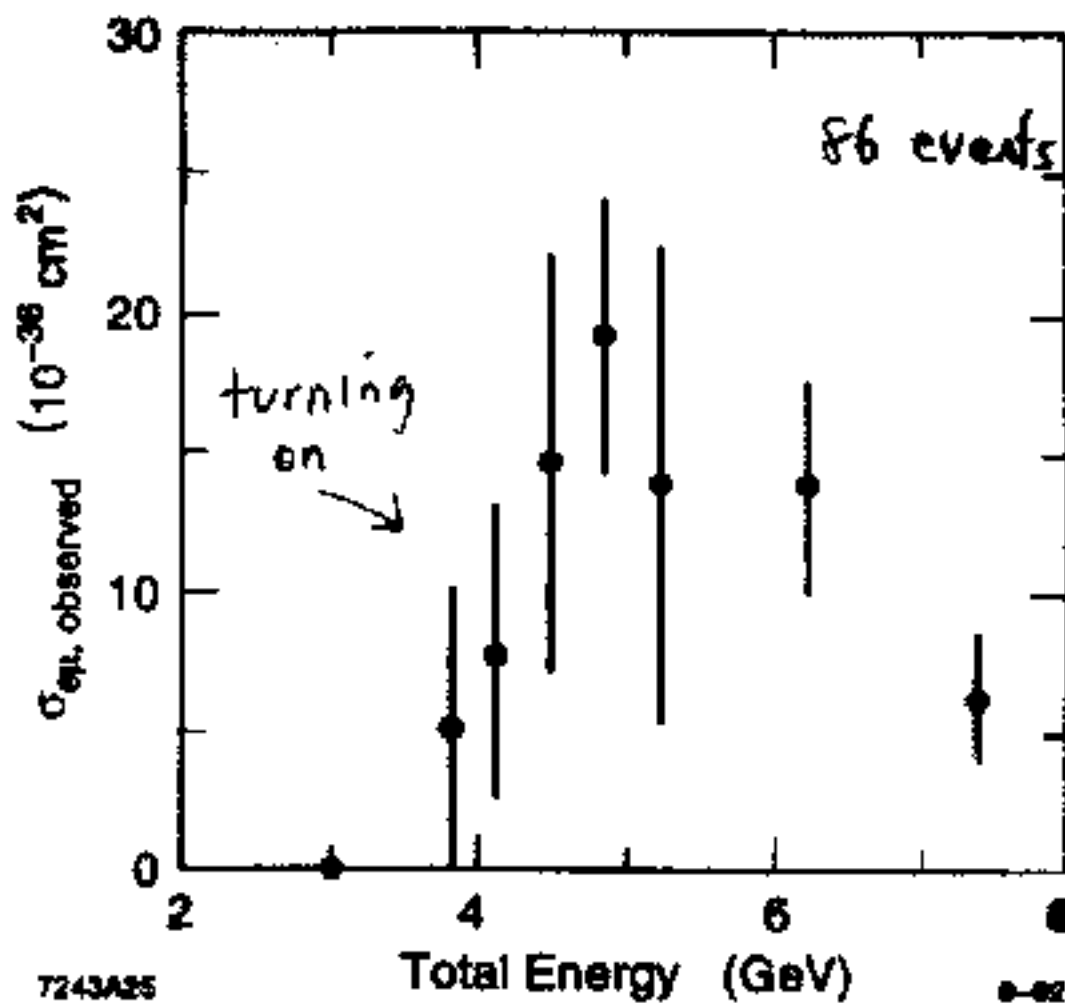


Figure 6. From Peri et al. (1975b): "The observed cross section for the signature $e\mu$ events from the Mark I experiment at SLAC. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events."

$\bar{\mu} \rightarrow e \bar{\nu}_e \nu_\mu \Rightarrow$ Look for heavy μ

$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ Look for

$e^+e^- \rightarrow \tau^+\tau^-$
 $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ clean signature

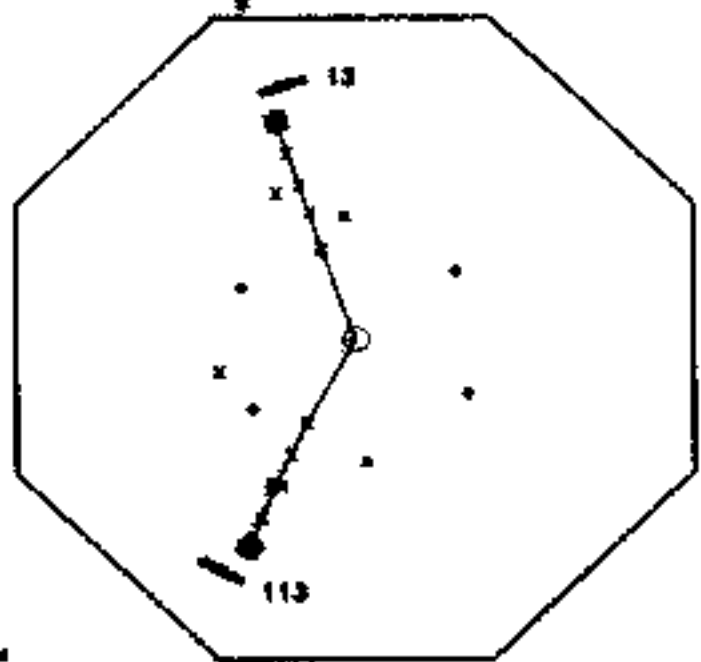
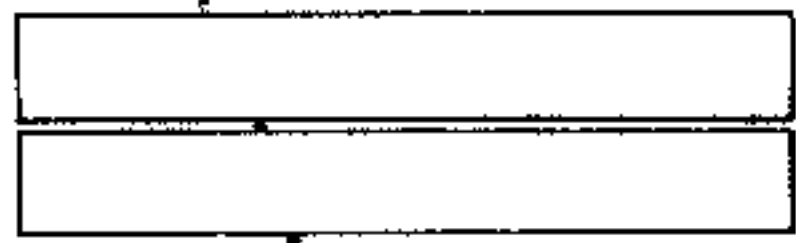
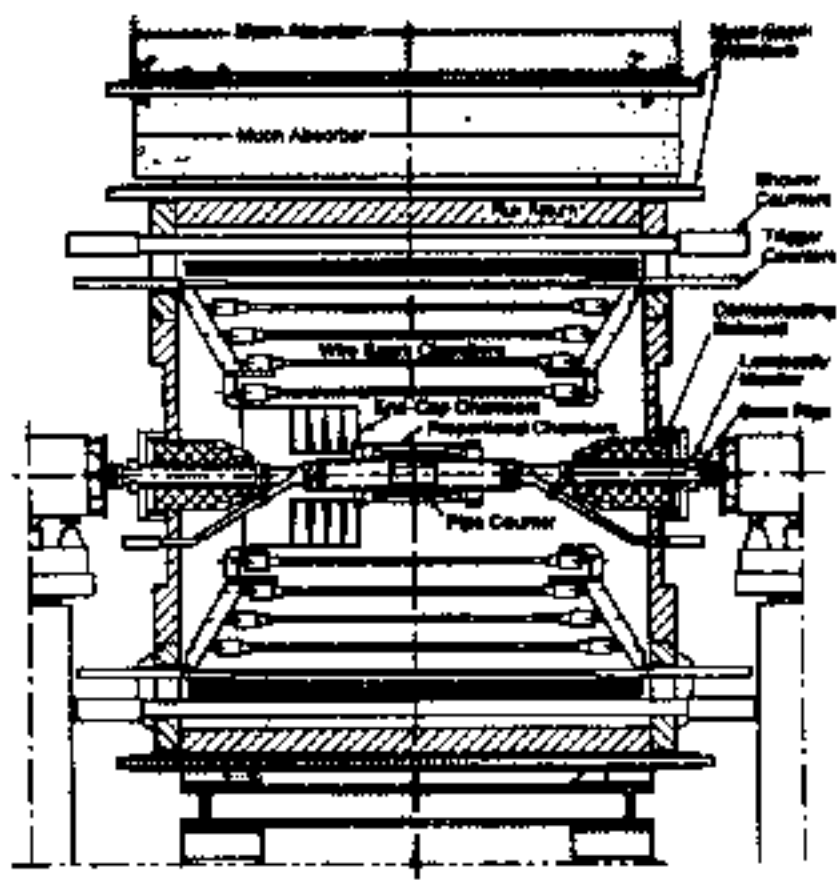
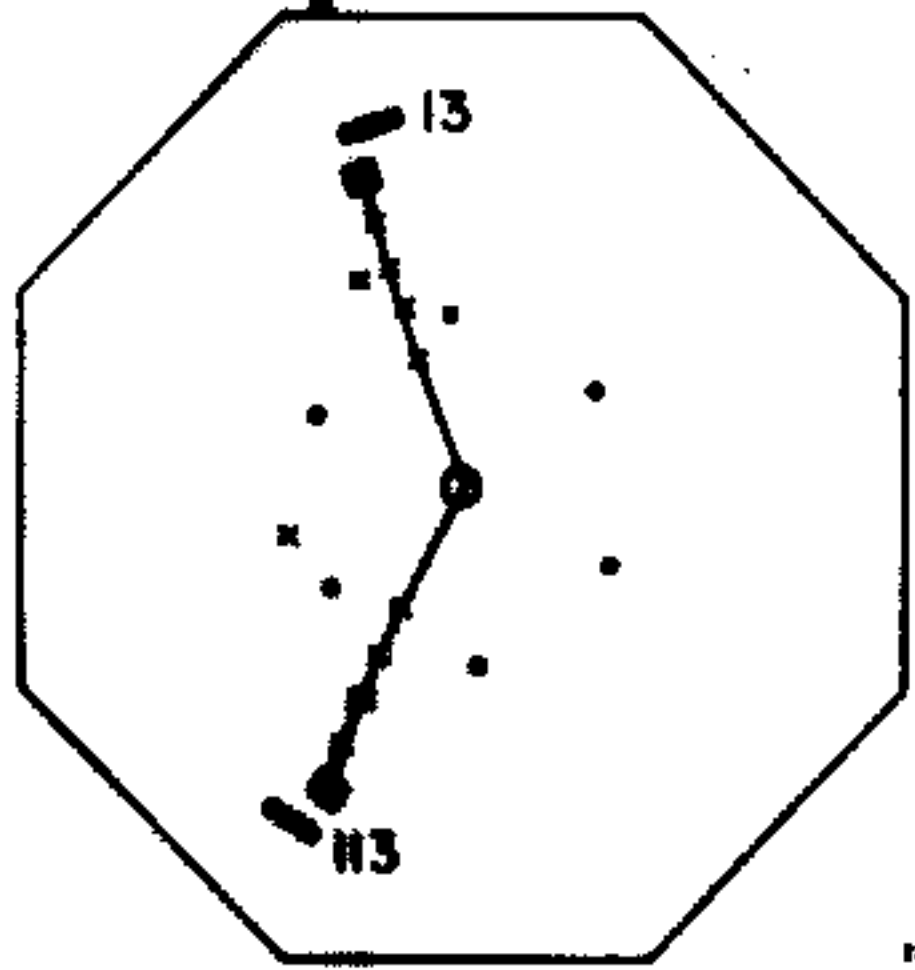
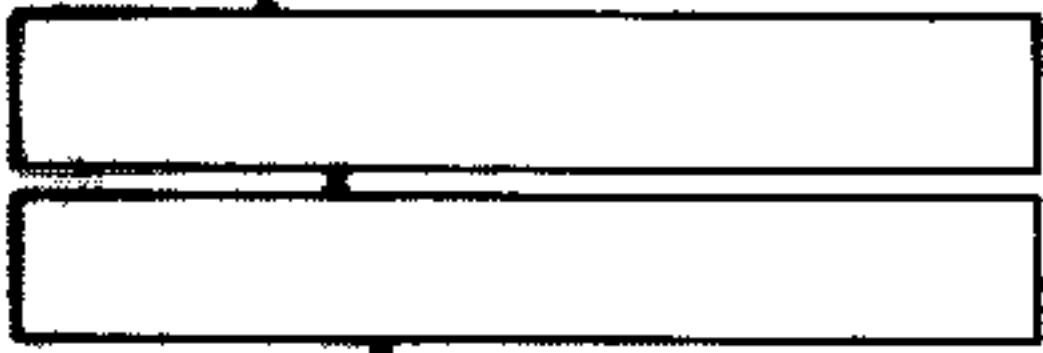


Figure 7. (a) The Mark II detector with the muon tower; (b) one of the first μp events using the tower. The μ moves upward through the muon detector tower and the e moves downward. The numbers 13 and 113 give the relative amounts of electromagnetic shower energy deposited by the μ and e . The six square dots show the positions of longitudinal support posts of the magnetostrictive spark chamber used for tracking.

$$e^+ e^- \rightarrow \tau^+ \tau^-$$

\downarrow
 \downarrow

$$\begin{aligned} & \rightarrow e^- \bar{\nu}_e \nu_\tau \\ & \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau \end{aligned}$$



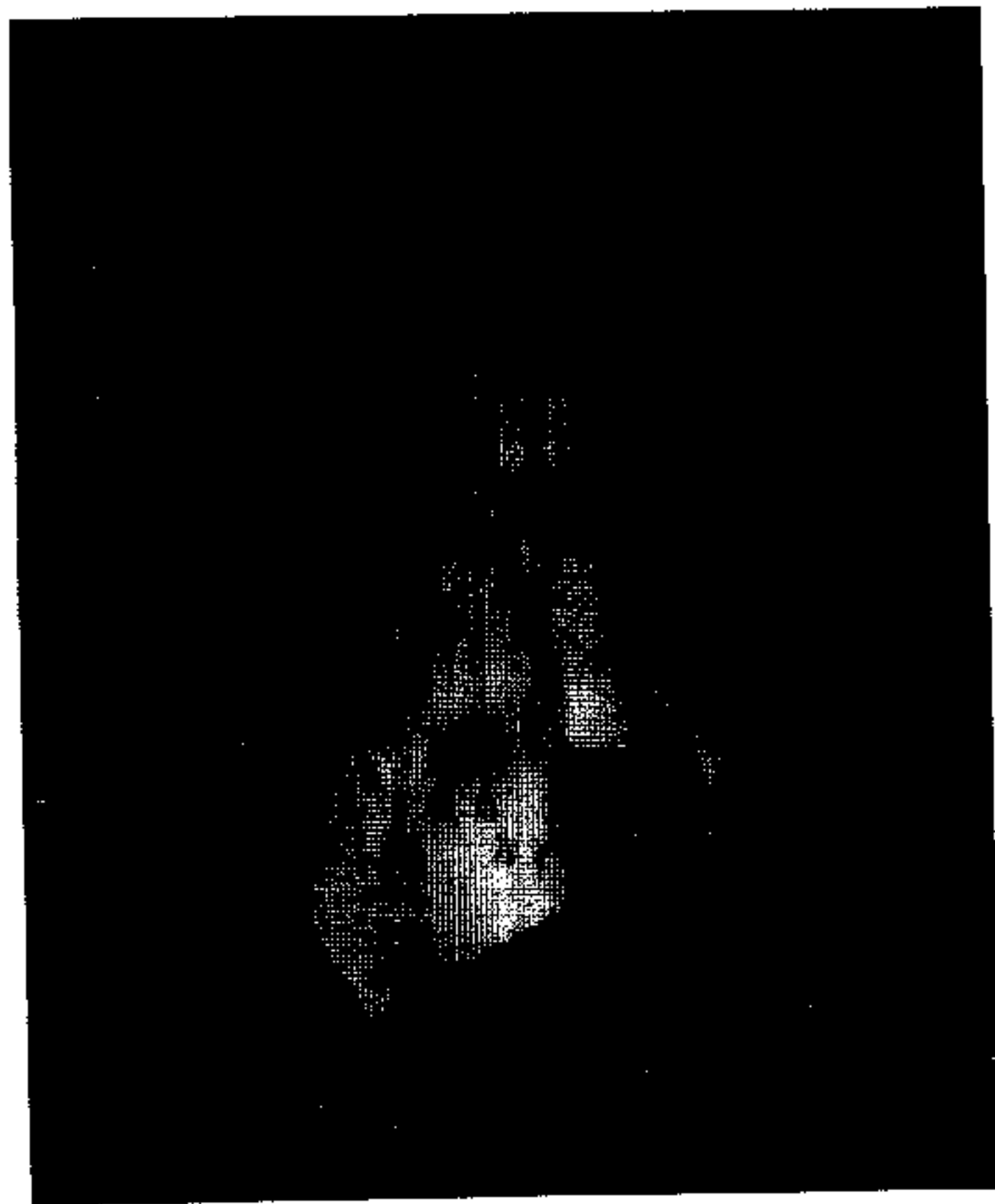
(1984)

CONSIDER DARK MATTER

- KNOWN TO EXIST FOR 10 YEARS
- DISTRIBUTION IN GALACTIC CLUSTERS SHOWN THIS SPRING
- WHAT IS IT?

Someone gives you a beam of dark matter, or a block of it, can you devise experiments to figure out what it is?

"Cosmic Mirage"

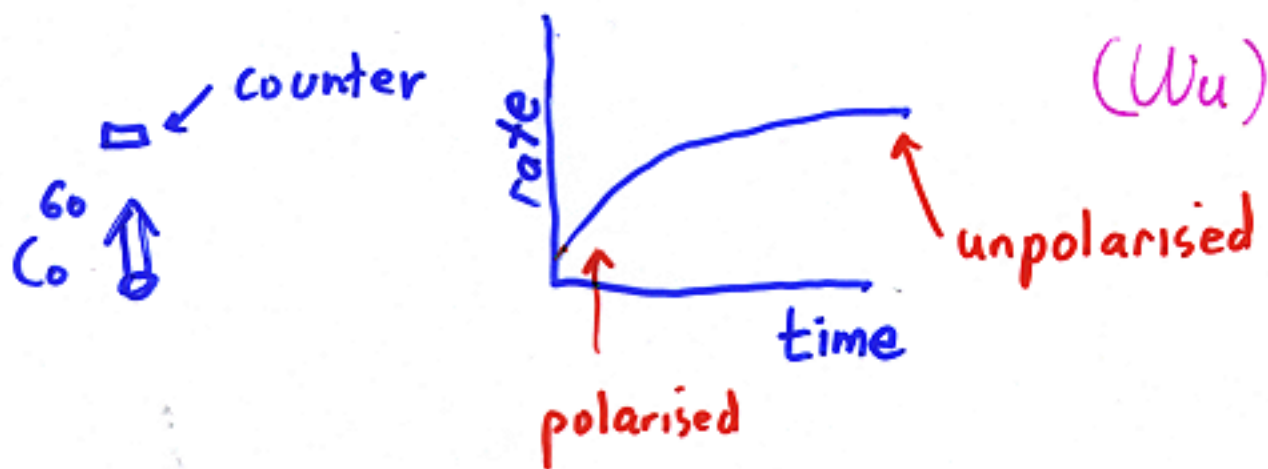


Galactic Cluster CL0024+1654
2 billion light years distant (Pisces)

Lecture 2 : Re-Cap

Parity violation in Weak Interactions

- Polarised β -decay $n \rightarrow p e \bar{\nu}$ Count electrons vs. θ .
Wu
- Polarised muon decay $\mu \rightarrow e \nu_e \bar{\nu}_\mu$ "
Lederman



count rate changes \Rightarrow parity violated. electron prefers to come out opposite Co spin

- polarize muons by weak decay of pions
measure θ (Lederman)



electron counter fixed so use B field
To precess muon spin to get full angular
distribution.

Lecture 2: ReCap continues

3.0

- Measure helicity $\sim \vec{\sigma} \cdot \vec{p}$ of the ν in electron capture

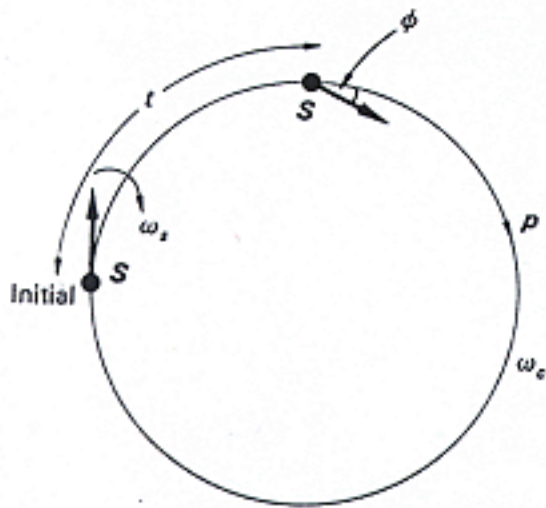


Use photon polarisation $\rightarrow \gamma + Sm$
to determine ν polarisation.

Neutrino left-handed \Rightarrow 

(Goldhaber)

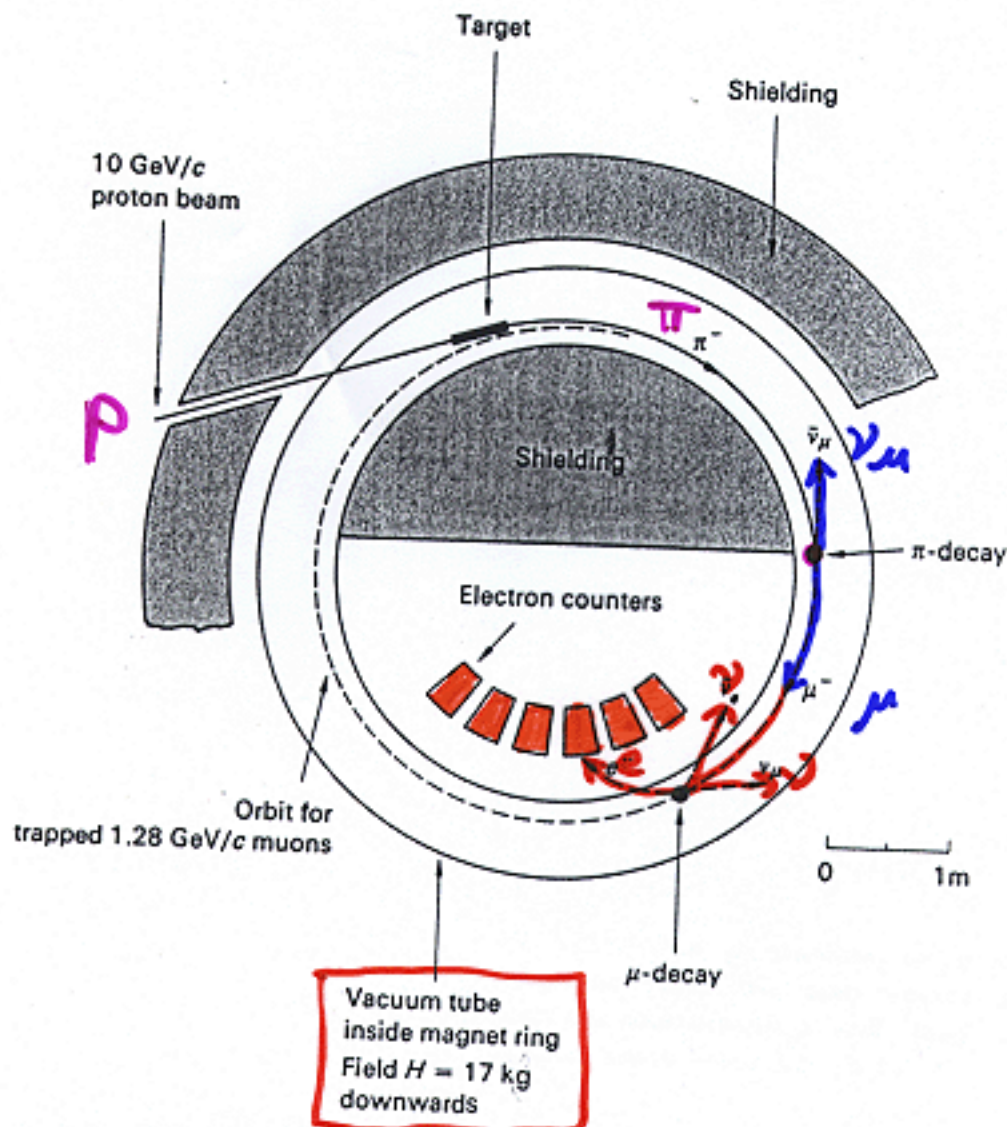
And more magnetic moment: Dirac pt. particle²
 $\mu = \frac{ge}{2m} |\vec{S}|$ ← spin



ω_c - cyclotron frequency = $\frac{eB}{mc}$

ω_s - precession frequency = $\frac{geB}{2mc}$

Fig. 5.2 For a particle of $g \neq 2$ in a uniform magnetic field, the spin vector s , initially aligned with the momentum p , will "lead" by a phase angle ϕ at later times—see Eq. (5.7).



Vacuum tube inside magnet ring
 Field $H = 17$ kg downwards

Fig. 5.3 Experimental arrangement employed in determination of the muon g -factor using a "muon storage ring" (Bailey et al., 1968)

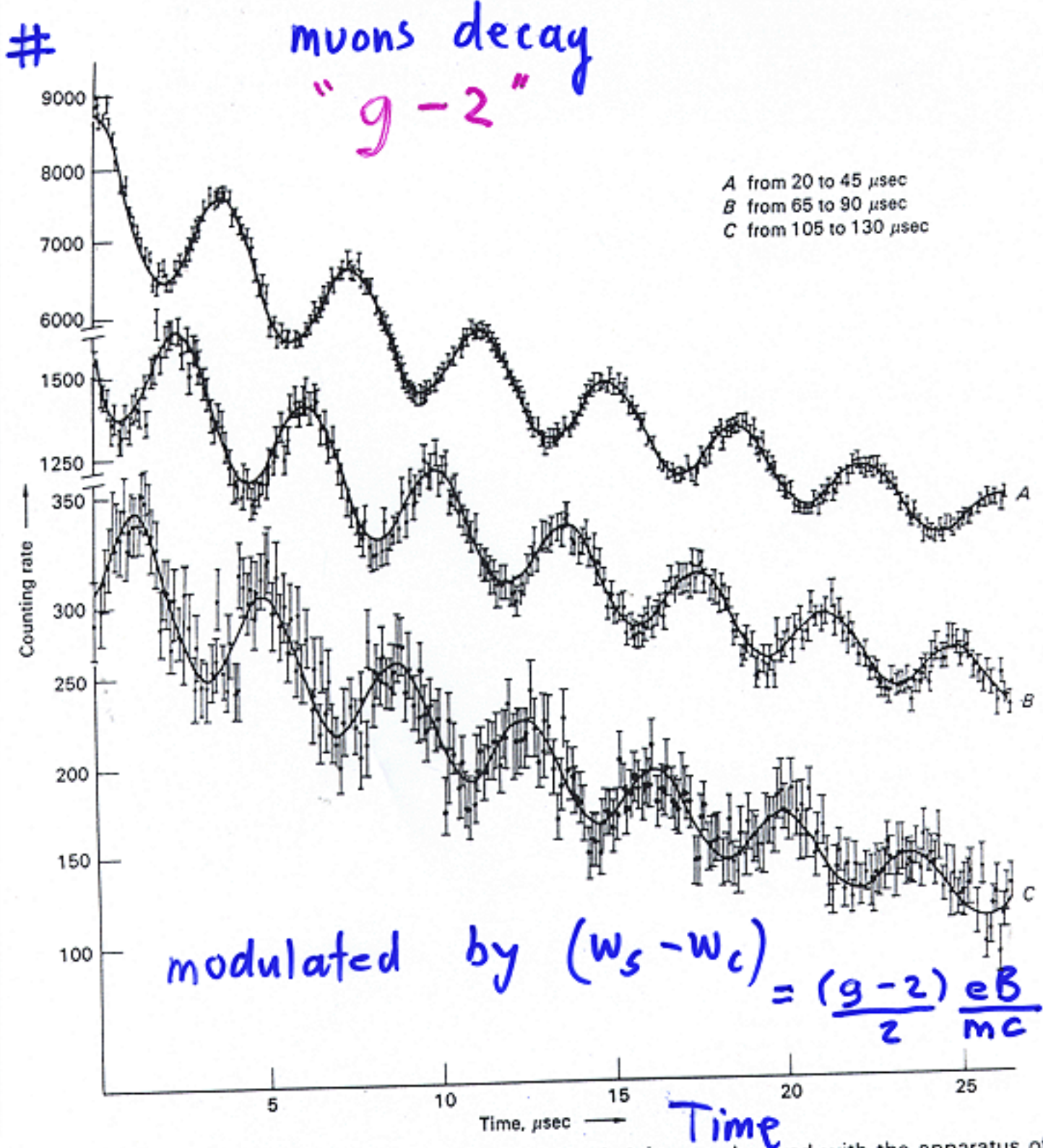


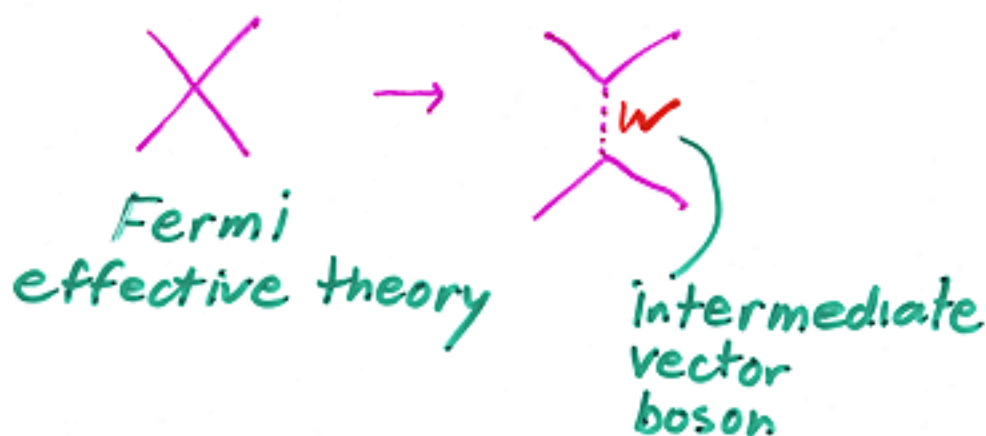
Fig. 5.5 Time dependence of the counting rate of electrons observed with the apparatus of Fig. 5.3. The general exponential decrease corresponds to a lifetime $\tau = 26 \mu\text{sec}$ in the laboratory system. The rate is modulated by the frequency $(\omega_s - \omega_c)$, which measures $(g - 2)$.

period of the anomalous moment $2\pi/(\omega_s - \omega_c)$ is about $3.7 \mu\text{sec}$, so that, by using high energy muons, the modulation can be followed out over some thirty periods and measured with great accuracy. The field H is calibrated by means of

TWO NEUTRINOS?

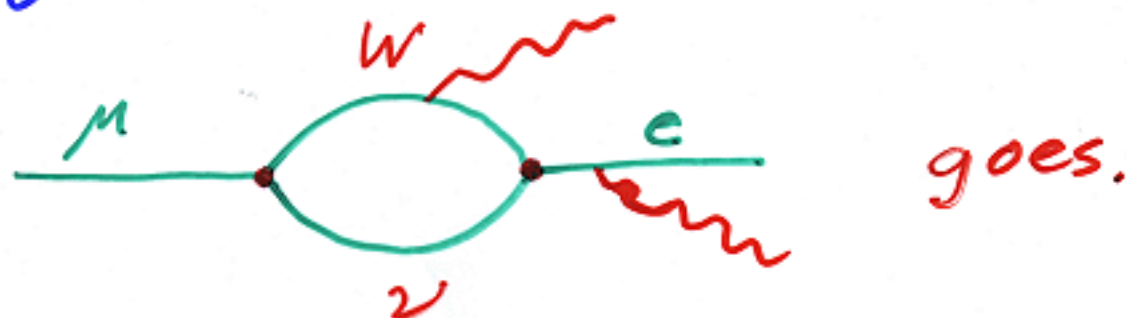
PONTECORVO puzzles over e, μ

SCHWARZ wants to see Fermi break down



Both thought of ν beams.

We knew $\text{Rate}(\mu \rightarrow e \gamma) \sim 0$, but if only one kind of ν , then



Make ν beam: π beam

$\pi \rightarrow \mu \nu$ ($K \rightarrow \mu \nu$)

($\pi \rightarrow e \nu$ small).

Look for



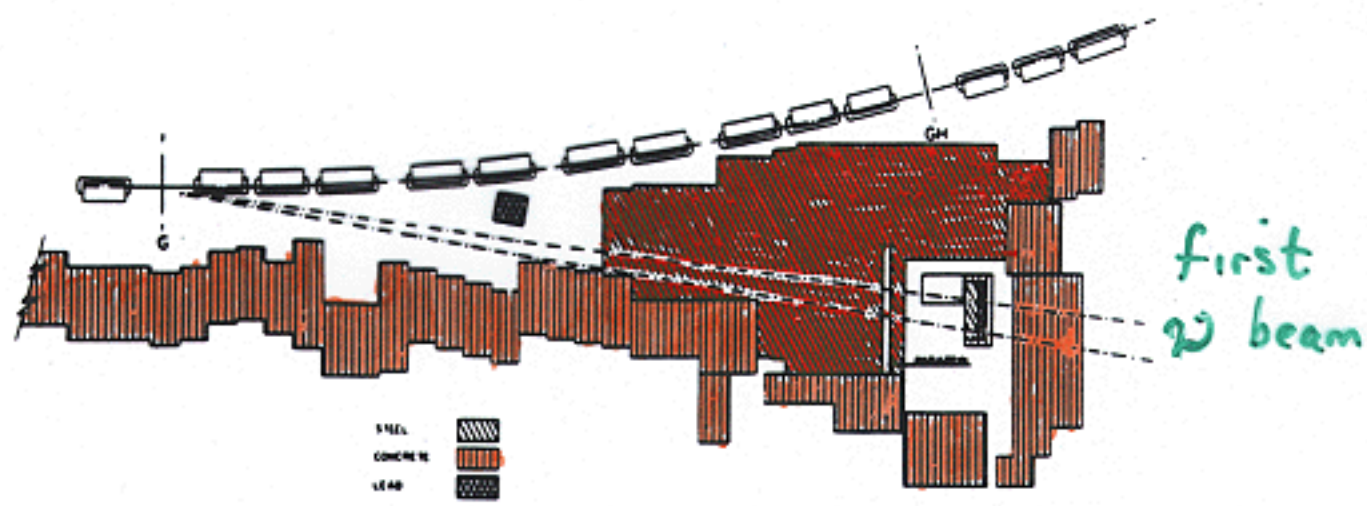


Figure 1. Plan view of the A.G.S. neutrino experiment.
BROOKHAVEN, NY.

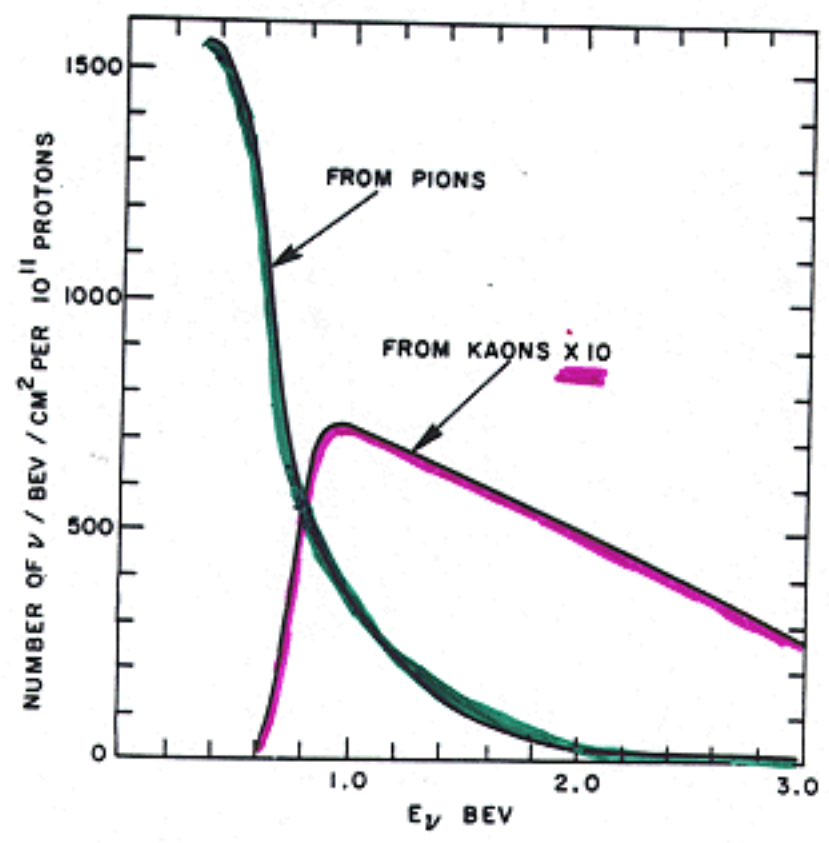


Figure 2. Energy spectrum of neutrinos as expected for A.G.S. running at 15 GeV.

Muon and electron signatures

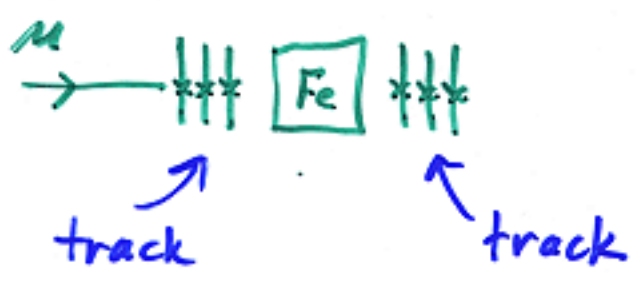
- electron showers in matter



loses energy early and often

- muons ionize but penetrate through steel

identify muons



72



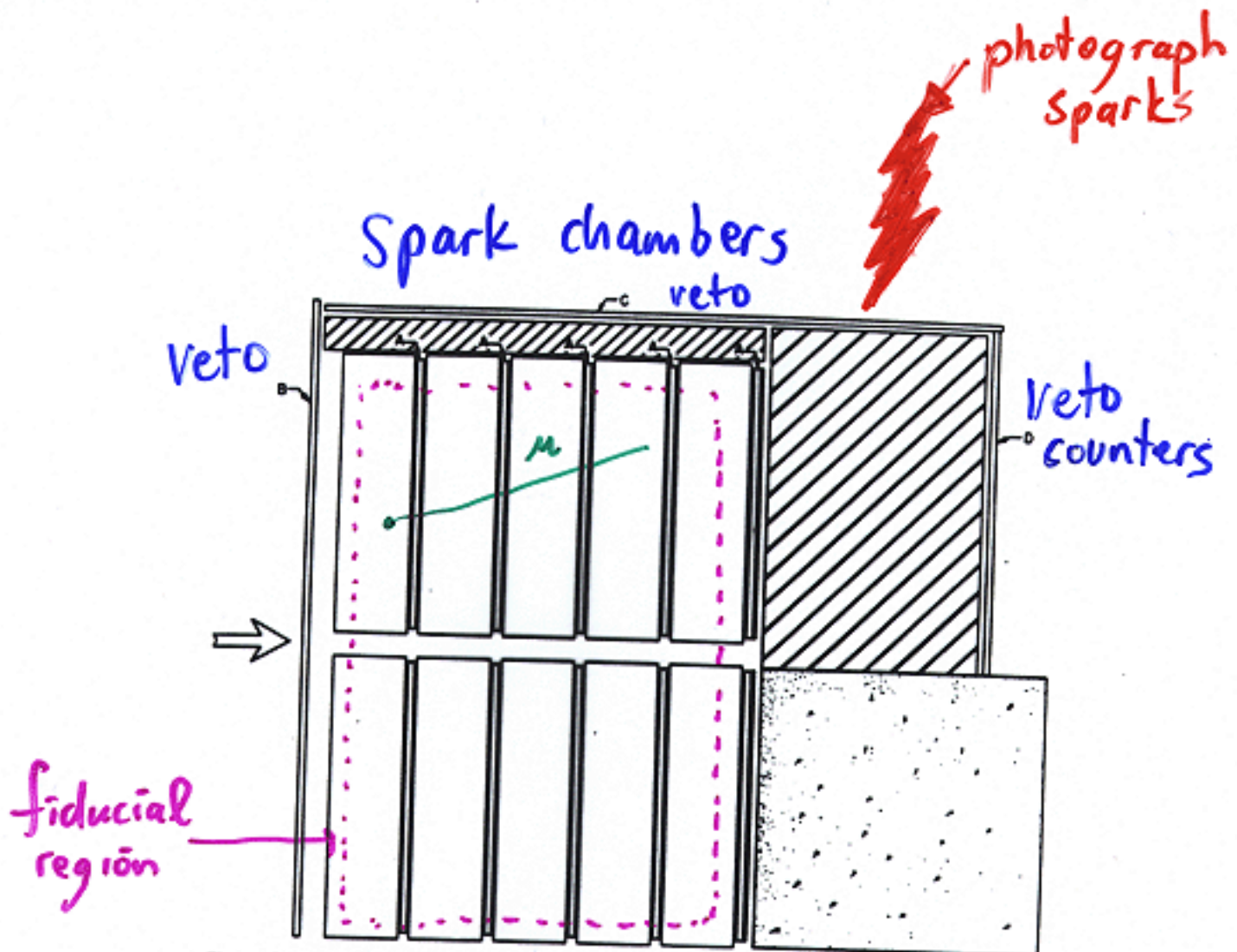


Figure 3. Spark chamber and counter arrangement. This is the front view with neutrinos entering on the left. A are the trigger counters. B, C and D are used in anti-coincidence.

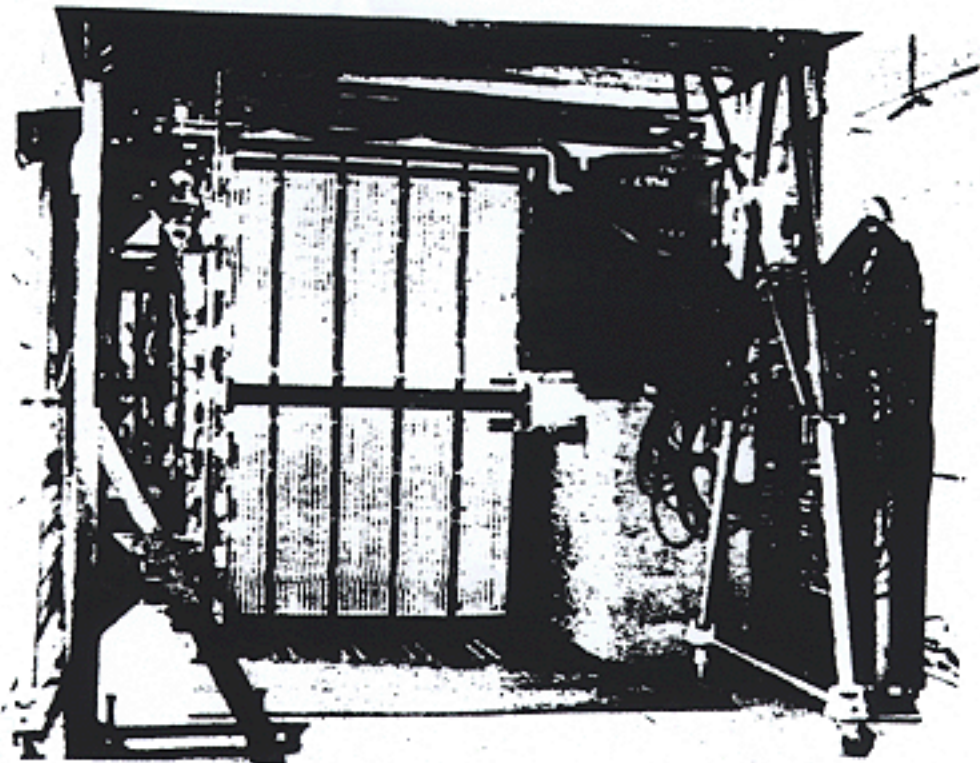
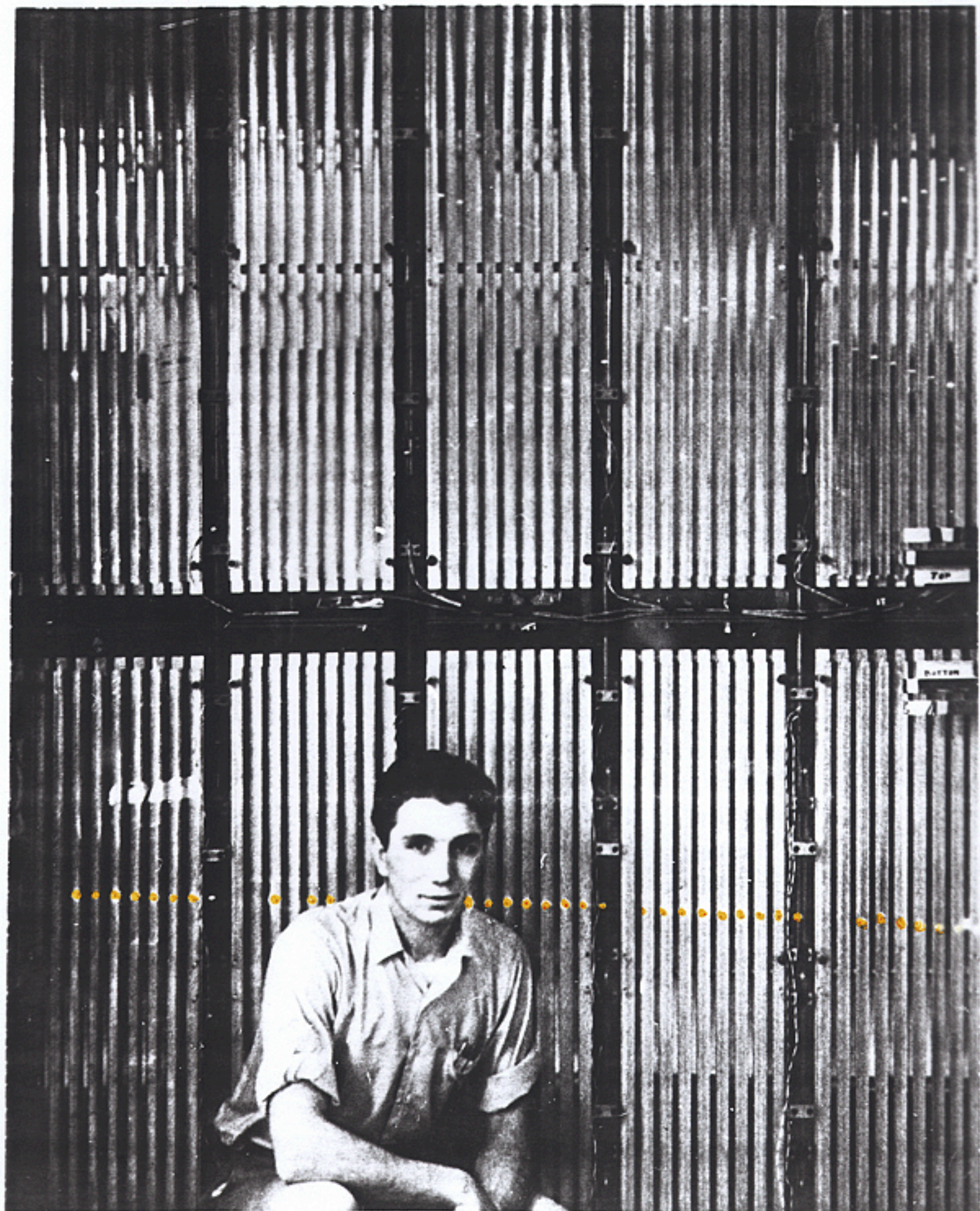
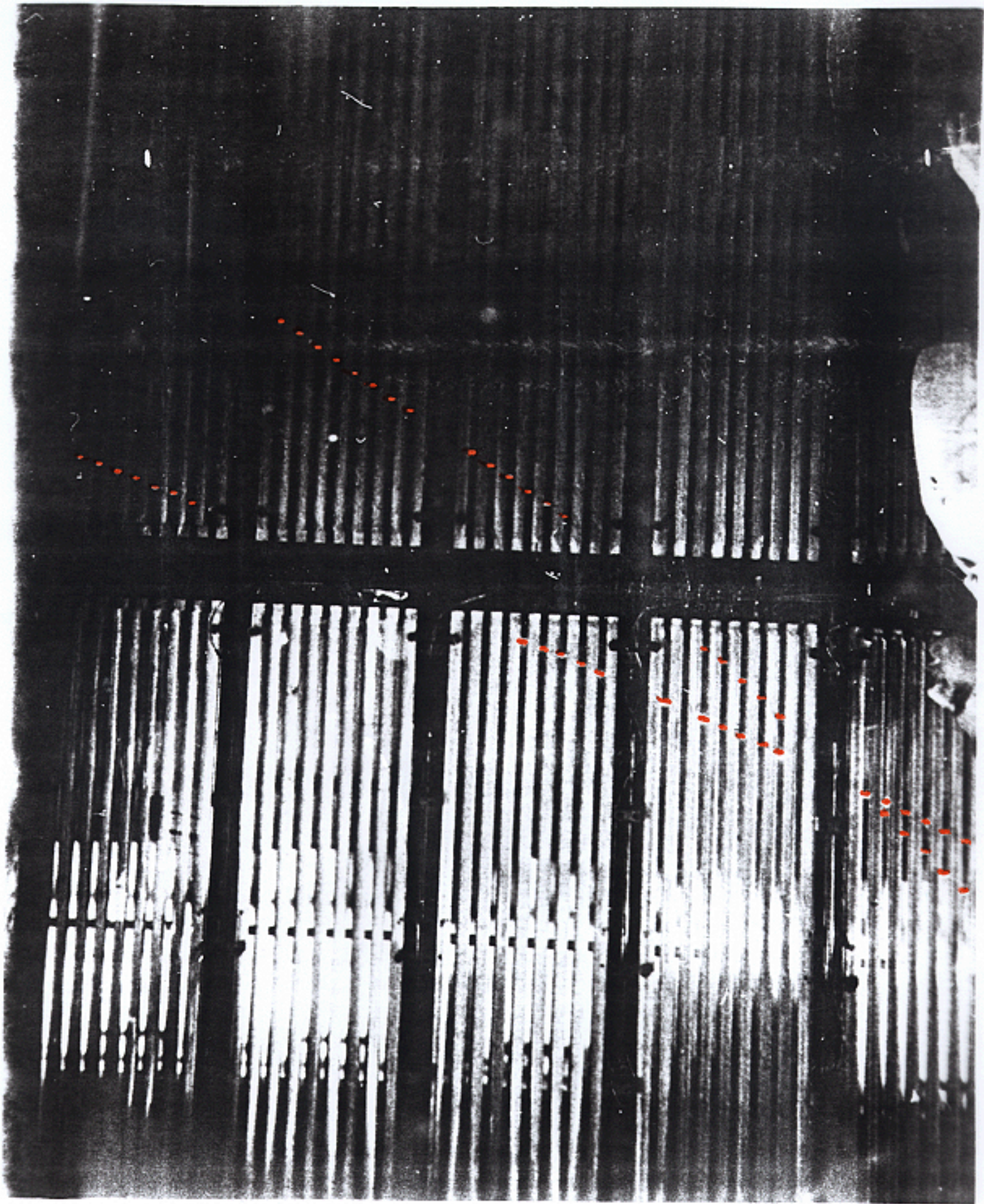


Figure 4. A photograph of the chambers and counters.

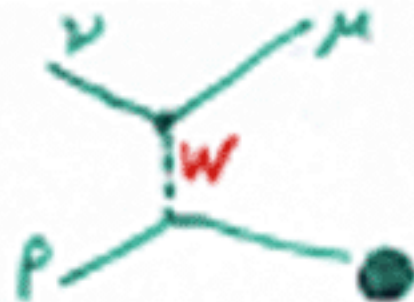
γ beam not hot





Single Muon events

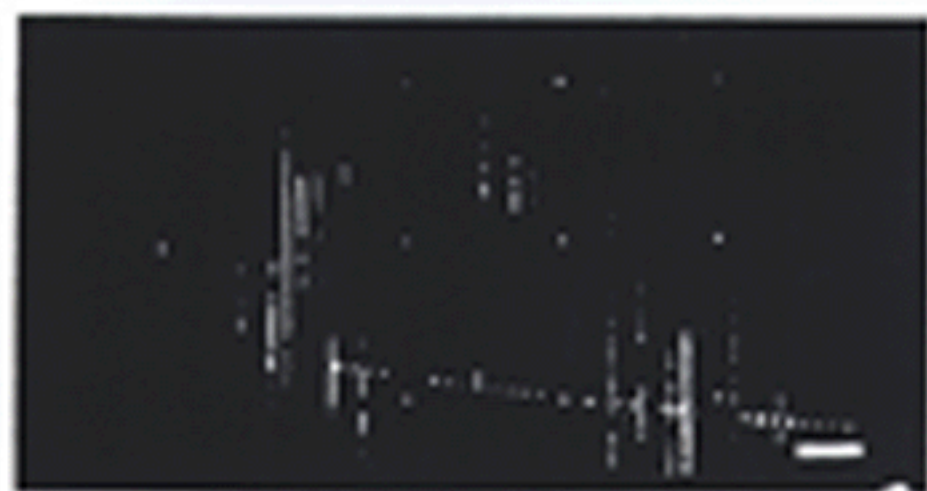
Elastic



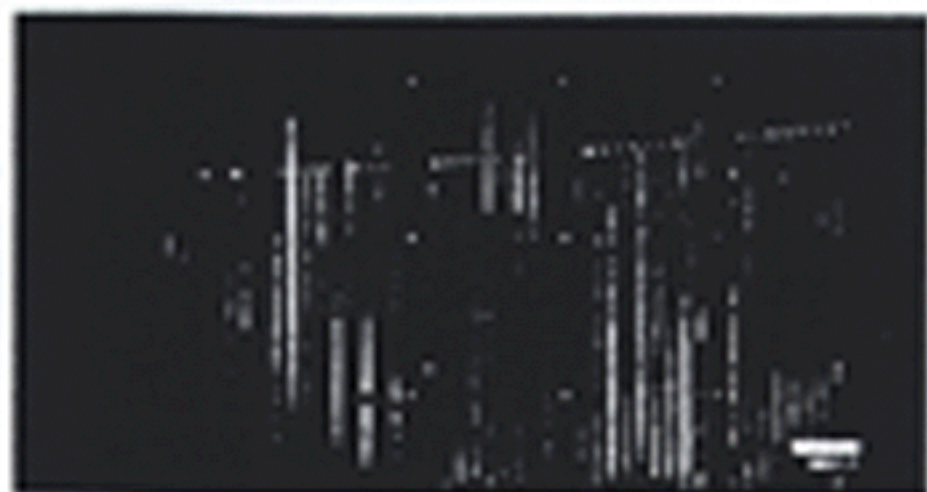
3.10

muon

$P_\mu > 540$



A

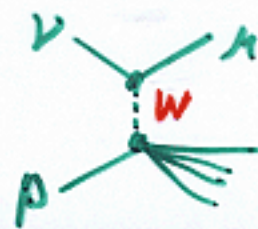


B

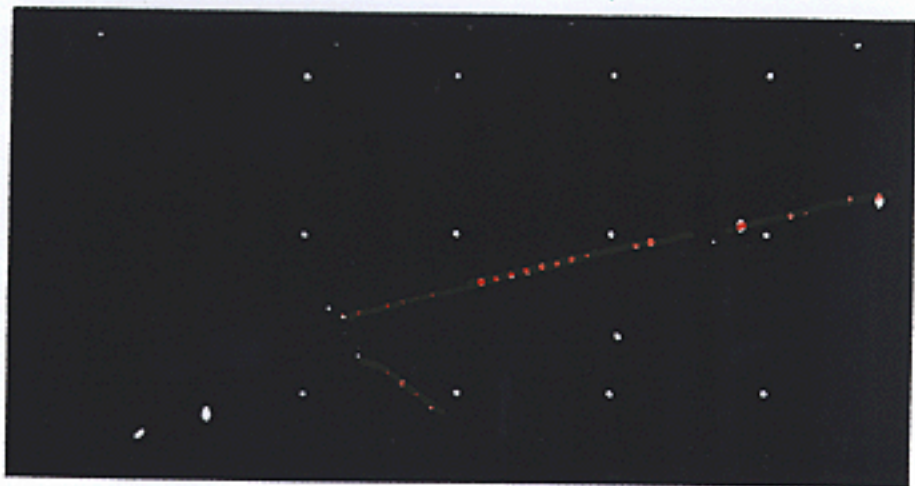


C

Vertex events (inelastic)



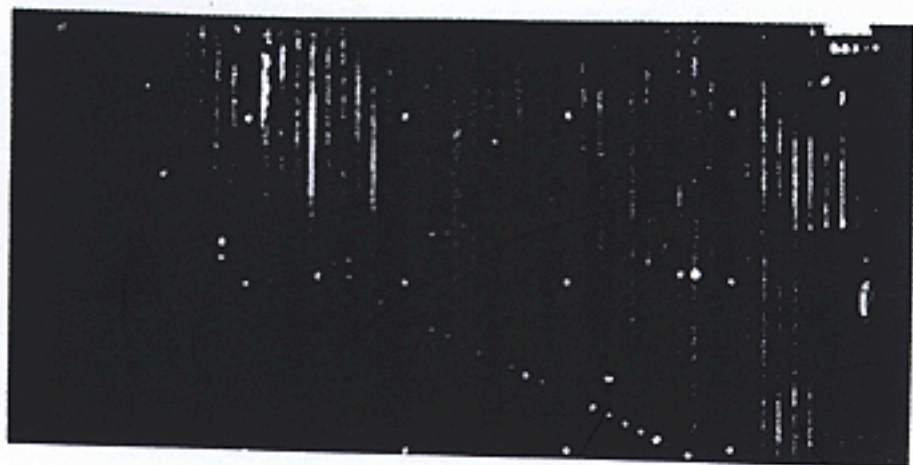
M
 $p_M > 500 \text{ MeV}$
and e-type



A



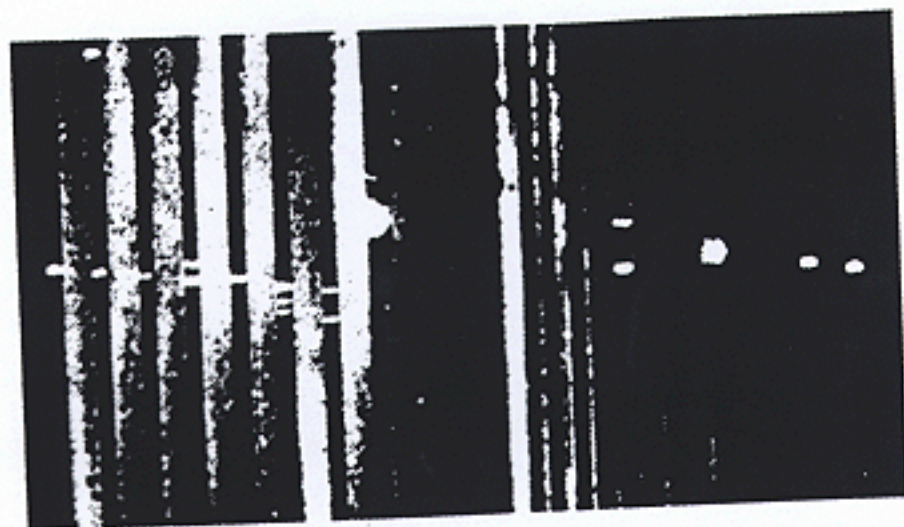
B



C

This is what electrons look like
like

3.12



A



B



C

Results of γ beam experiment

- 113 events total
- 34 single muon events $p_{\mu} > 300 \text{ MeV}$



- 22 vertex events



- 49 short single tracks $p_{\mu} < 300 \text{ MeV}$
(neutron background) < 4 sparks

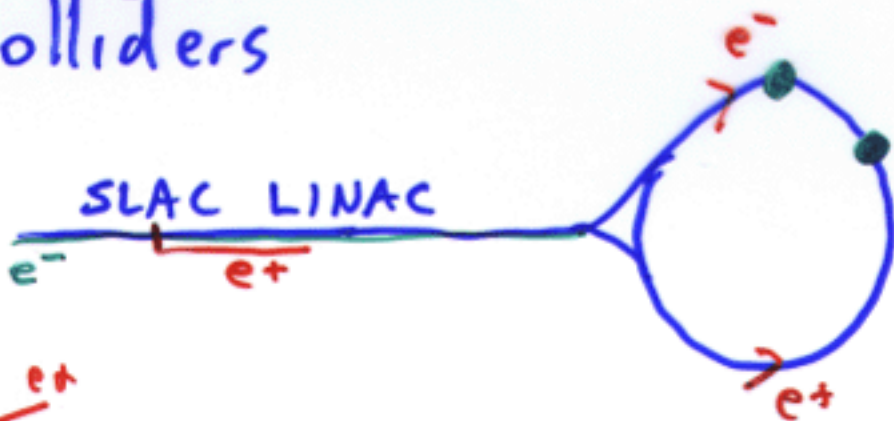
- 8 shower events e, γ
6 with $p > 300 \text{ MeV}$

- > Not cosmic rays - check by turning off beam
- > Not neutron induced - uniformity in detector
- > Due to π, K decay - block of steel early in beam

NOT ENOUGH SHOWER EVENTS \Rightarrow NO γ_e
 $\Rightarrow \gamma$'s from $\pi \rightarrow \mu \nu$ ARE DIFFERENT

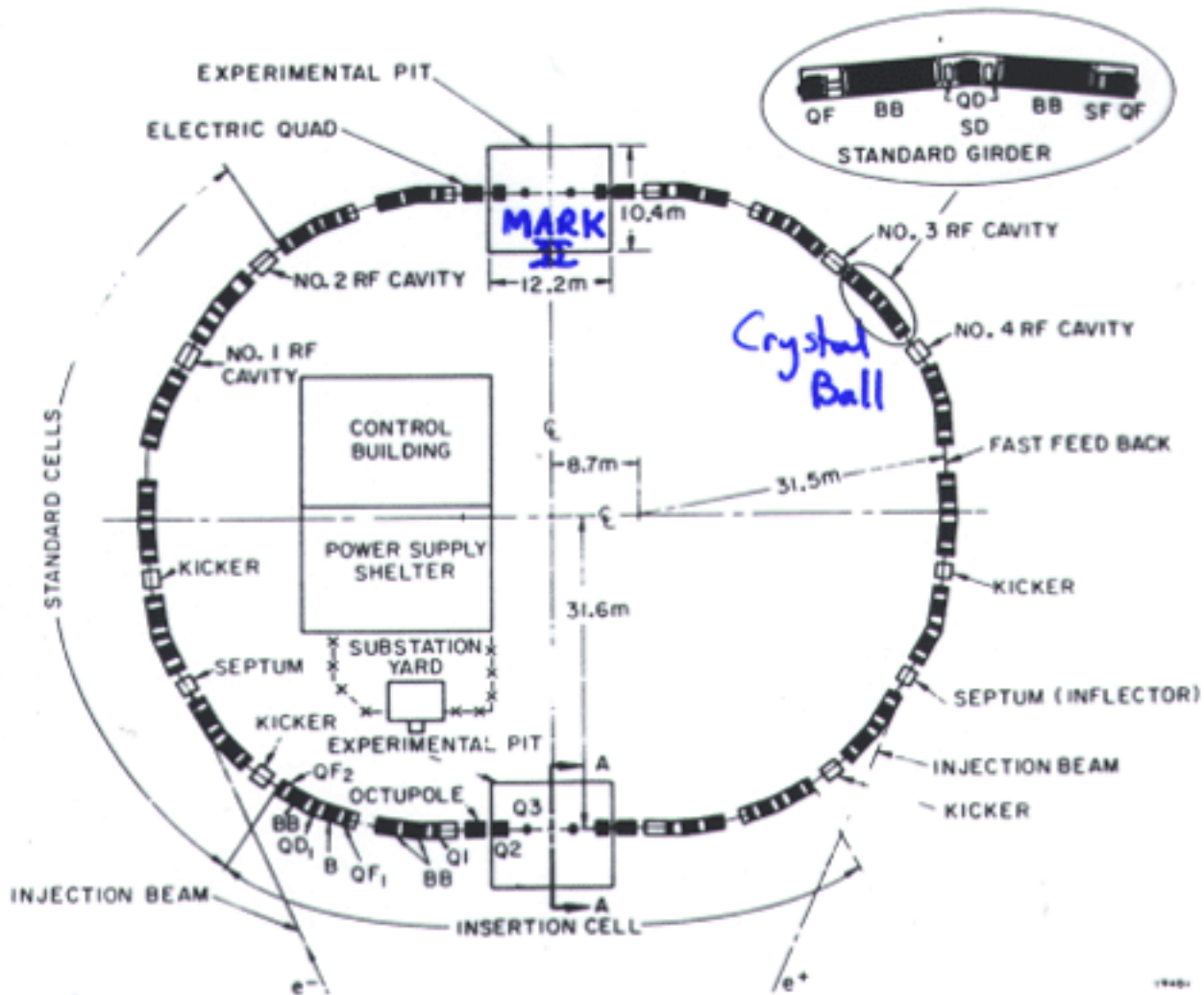
etc⁻
Colliders

3.16



284

Physics 1976

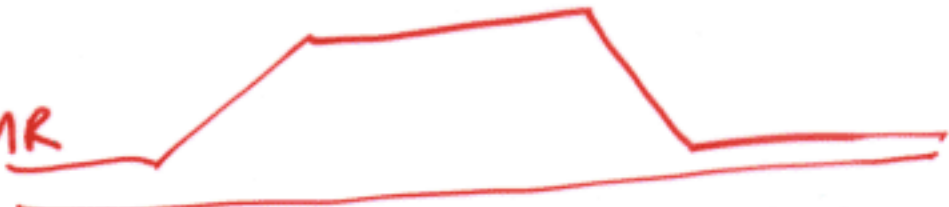


1. Schematic of the SPEAR storage ring.

3.14

MR

TeVatron

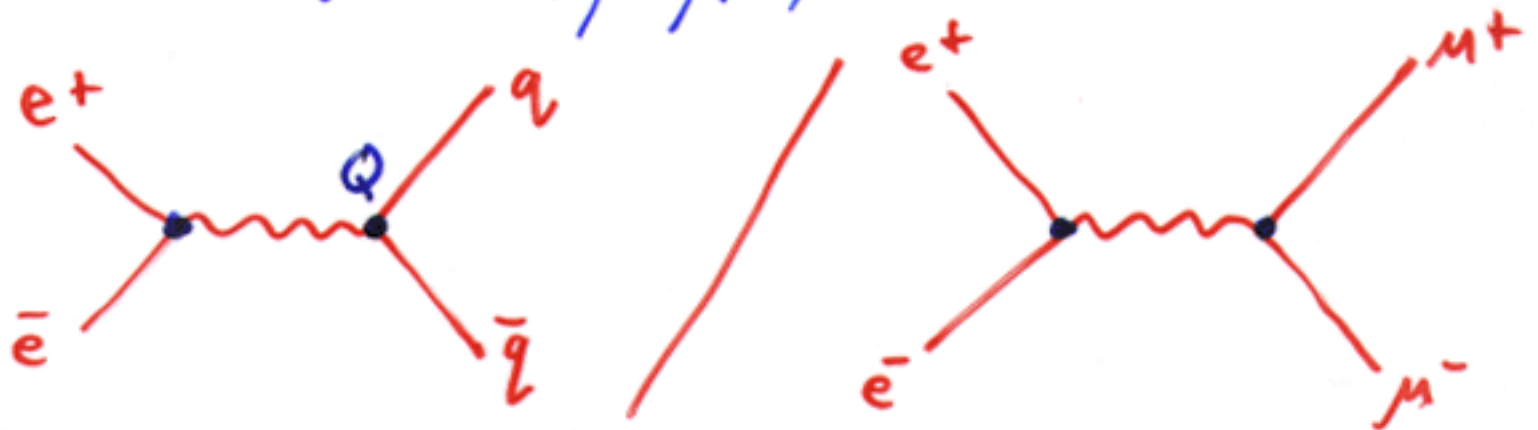


Edwards & Sypher
Intro to Accelerator Physics



DON EDWARDS

$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$



$$\sigma = \frac{\pi}{3} \left(\frac{k Q c \alpha}{E} \right)^2 \quad \text{above threshold}$$

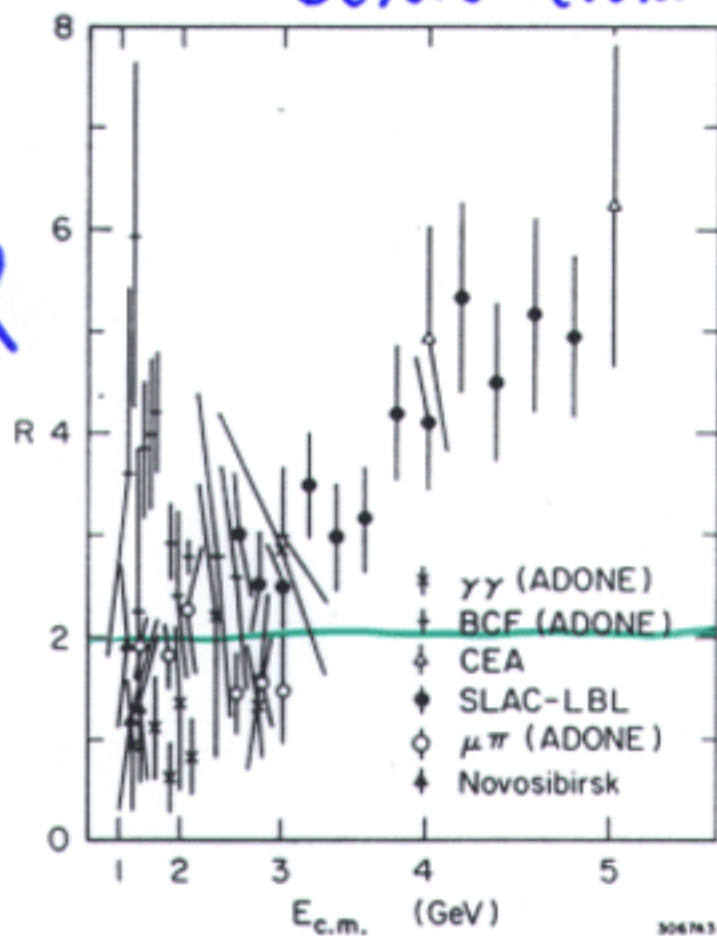
$$R = 3 \sum_i Q_i^2$$

↑
colour

↓
sum over quarks u, d, s, c, b, t

R

Before revolution



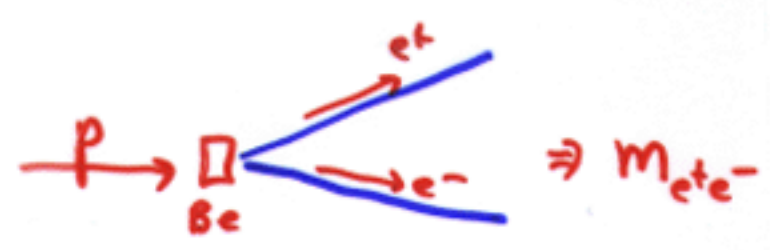
The ratio R as of July 1974.

if only u, d, s

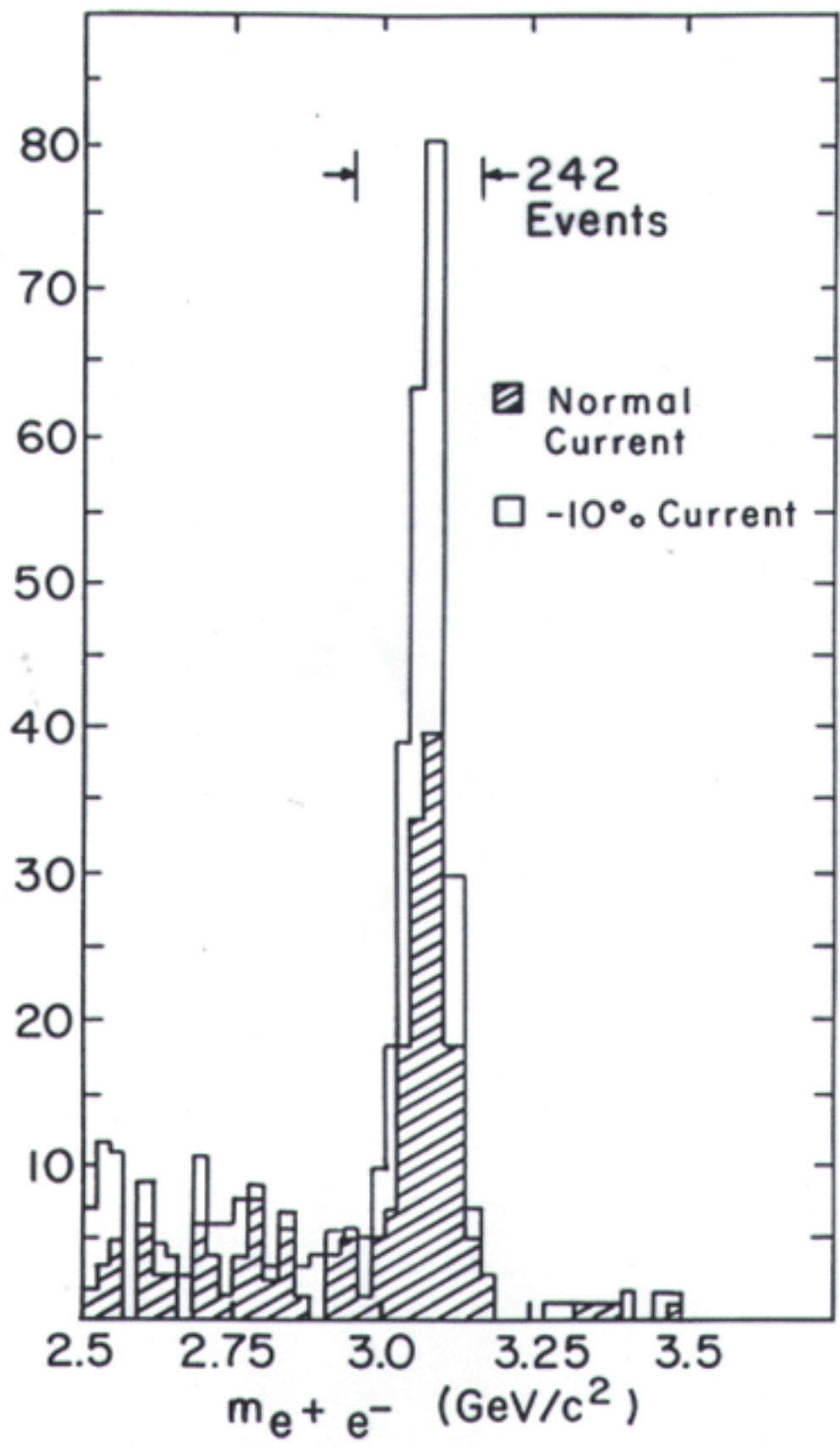
$$R = 3 \left[\left(\frac{2}{3} \right)^2 + \left(-\frac{1}{3} \right)^2 + \left(-\frac{1}{3} \right)^2 \right] = 2$$

Ting @ Brookhaven

$p Be \rightarrow e^+ e^- X$



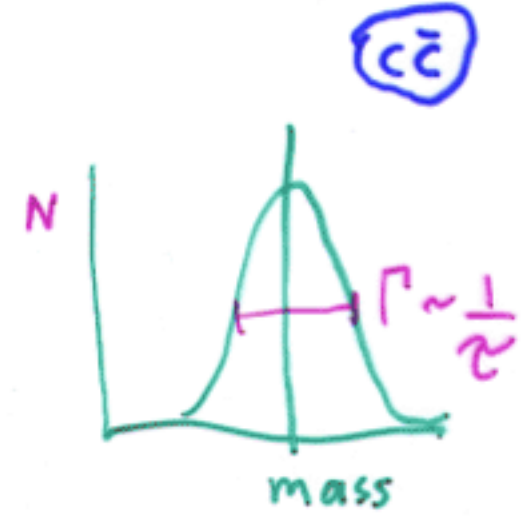
two arm spectrometer



Classical Resonance 



↓
quantum resonance



$c\bar{c}$

7b. Dielectron data from the BNL experiment showing the peak at 3.1 GeV which was $c\bar{c}$.

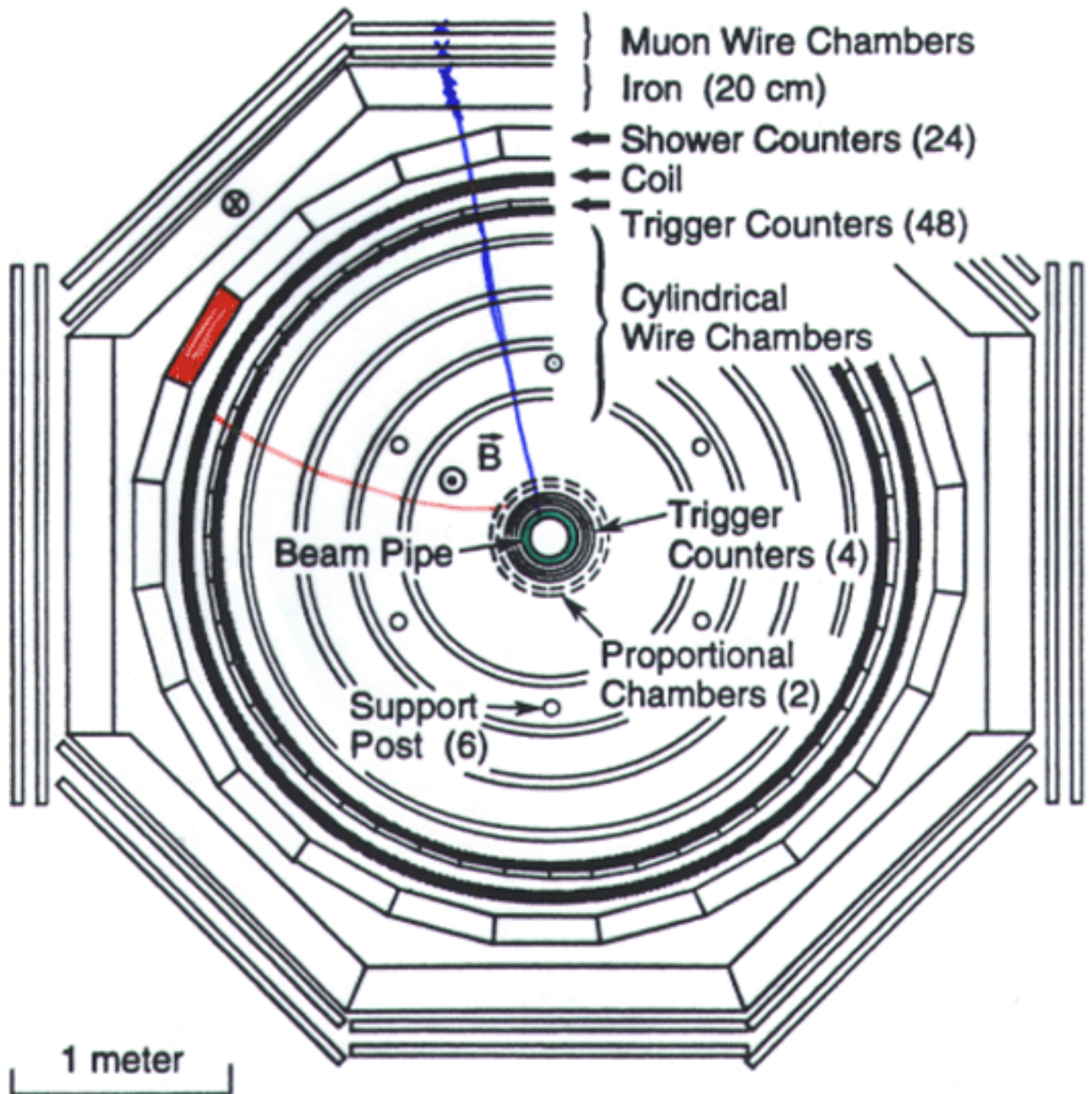


Figure 5. The initial form of the Mark I detector.

etc⁻

Mark I detector at SLAC

hermetic,

"Typical" J/ψ event
in tracking chamber

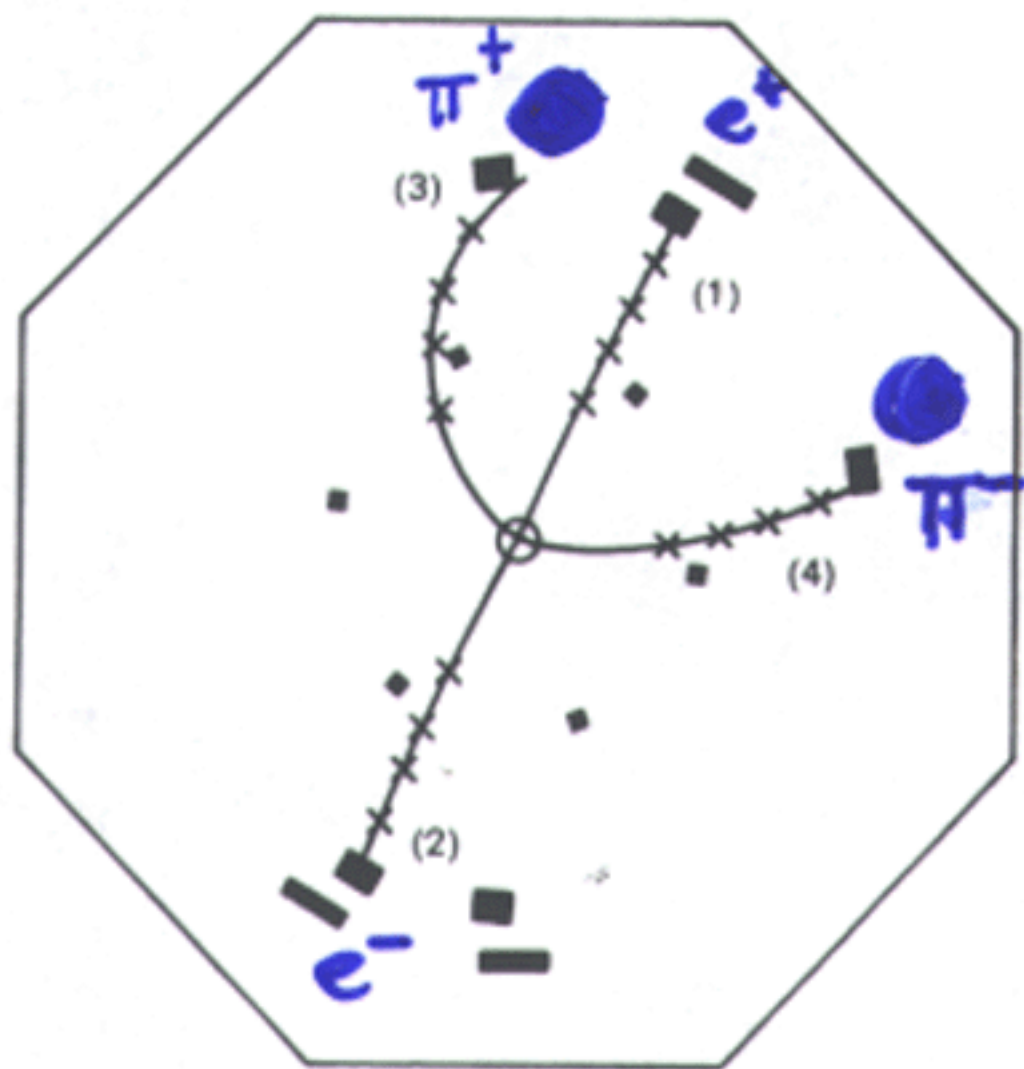
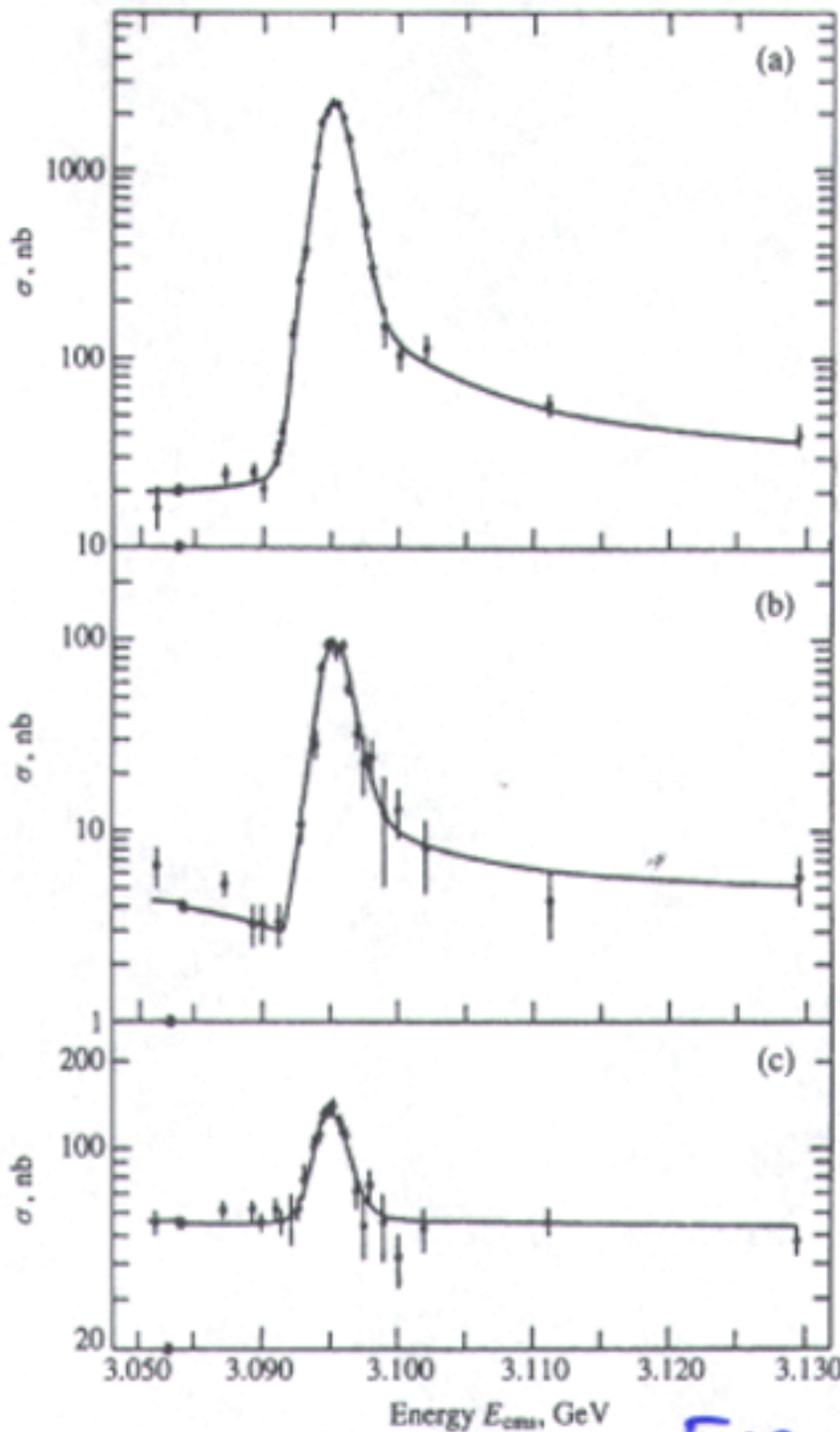


Fig. 4.4. Example of the decay $\psi(3.7) \rightarrow \psi(3.1) + \pi^+ + \pi^-$ observed in a spark chamber detector. The $\psi(3.1)$ decays to $e^+ + e^-$. Tracks (3) and (4) are due to the relatively low energy (150 MeV) pions, and (1) and (2) to the 1.5 GeV electrons. The magnetic field and the SPEAR beam pipe are normal to the plane of the figure. The trajectory shown for each particle is the best fit through the sparks, indicated by crosses. (From Abrams *et al.* 1975.)

From e^+e^-

9



$e^+e^- \rightarrow \text{hadrons}$

9

$e^+e^- \rightarrow \mu^+\mu^-$

9

$e^+e^- \rightarrow e^+e^-$

Energy CM GeV

Fig. 4.1. Results of Augustin *et al.* (1974) showing the observation of the J/ψ resonance of mass 3.1 GeV, produced in e^+e^- annihilation at the SPEAR storage ring, SLAC. (a) $e^+e^- \rightarrow \text{hadrons}$; (b) $e^+e^- \rightarrow \mu^+\mu^-$, $|\cos\theta| \leq 0.6$; (c) $e^+e^- \rightarrow e^+e^-$, $|\cos\theta| \leq 0.6$.

Spectroscopy convinces us that there really are $b\bar{b}$ quarks.

e^+e^-

$c\bar{c}$

$b\bar{b}$

are quarks.

Positronium

Charmonium

Bottomonium

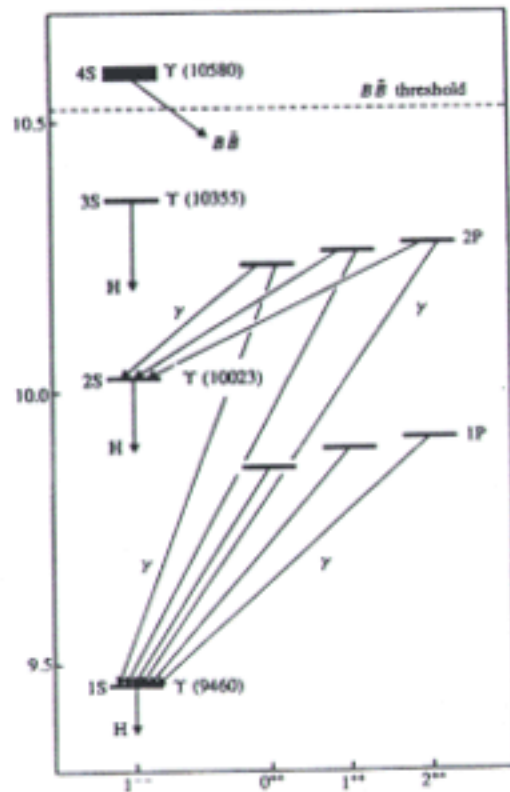
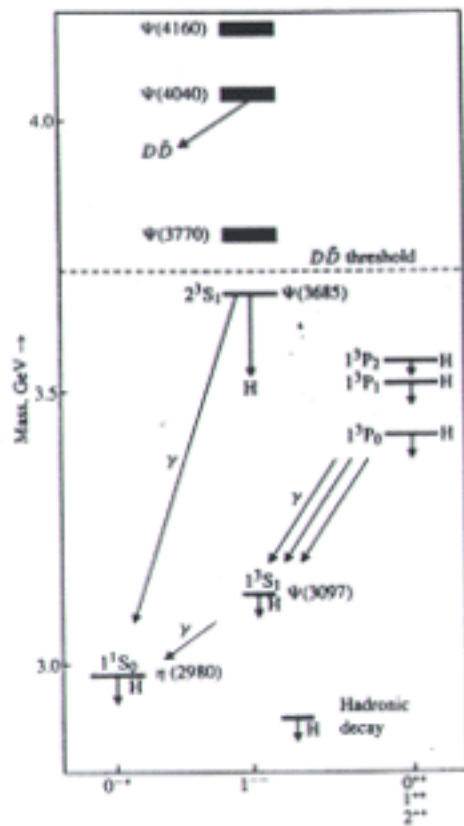
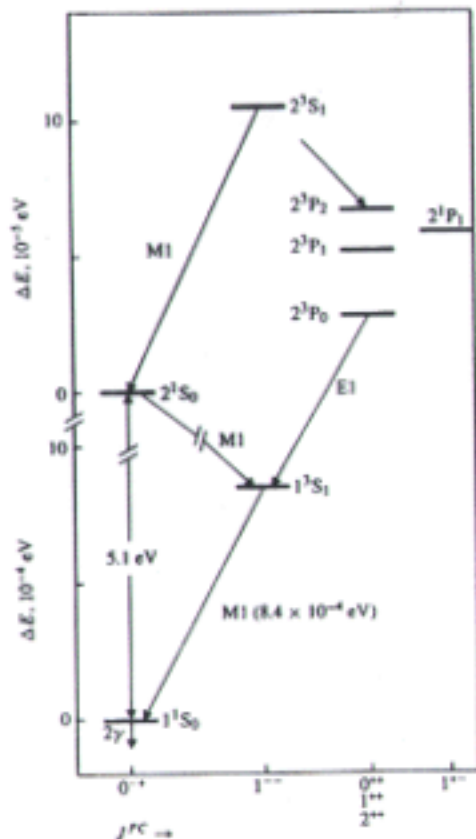


Fig. 4.8. The energy-level diagrams for positronium, charmonium and bottomonium. Note the changes in scale for positronium. Only states with $J^{PC} = 1^{--}$ can be accessed in e^+e^- annihilation experiments. Note that the atomic physics convention is to label the lowest-lying P states of positronium as 2P, while for the charmonium and bottomonium states the nuclear physics nomenclature 1P is

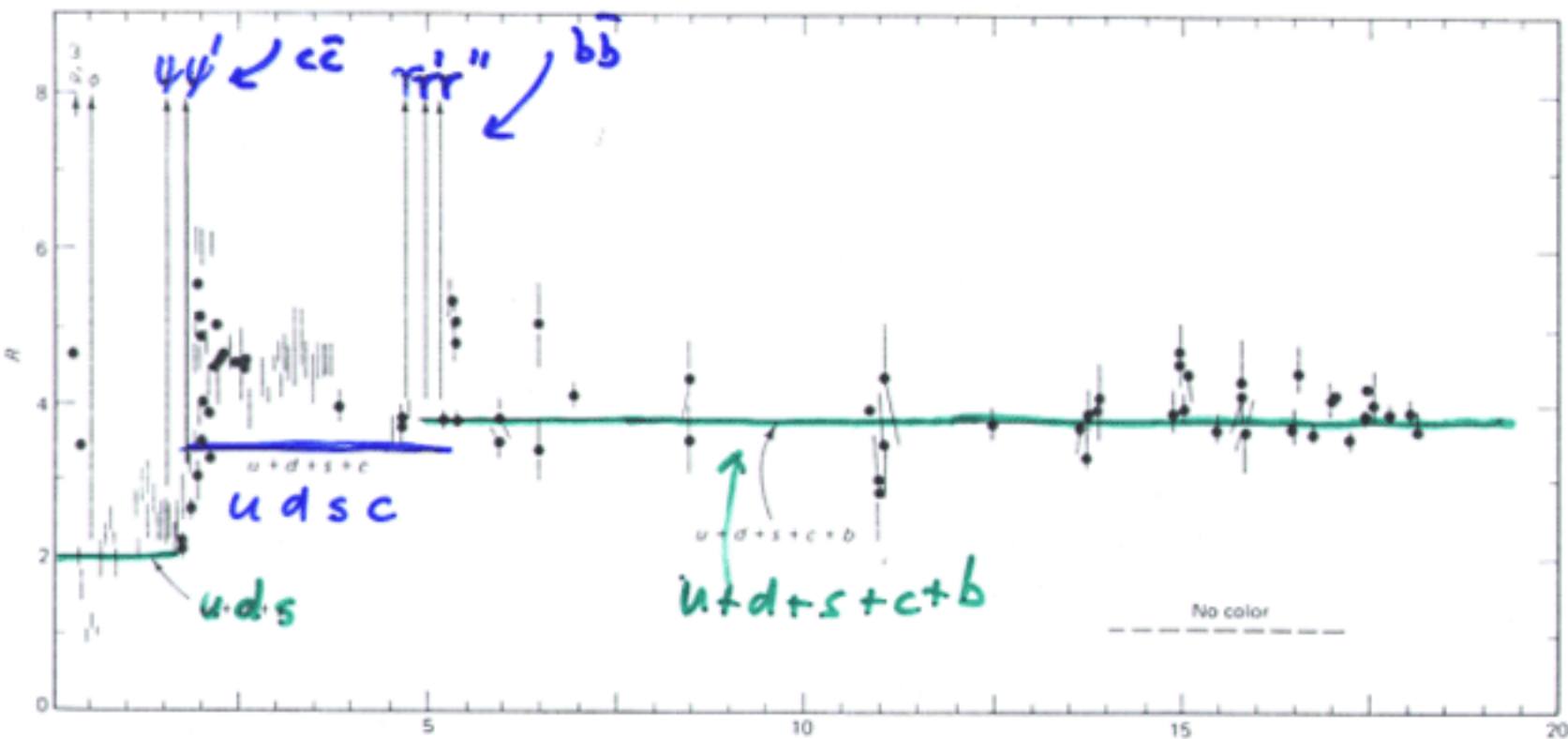
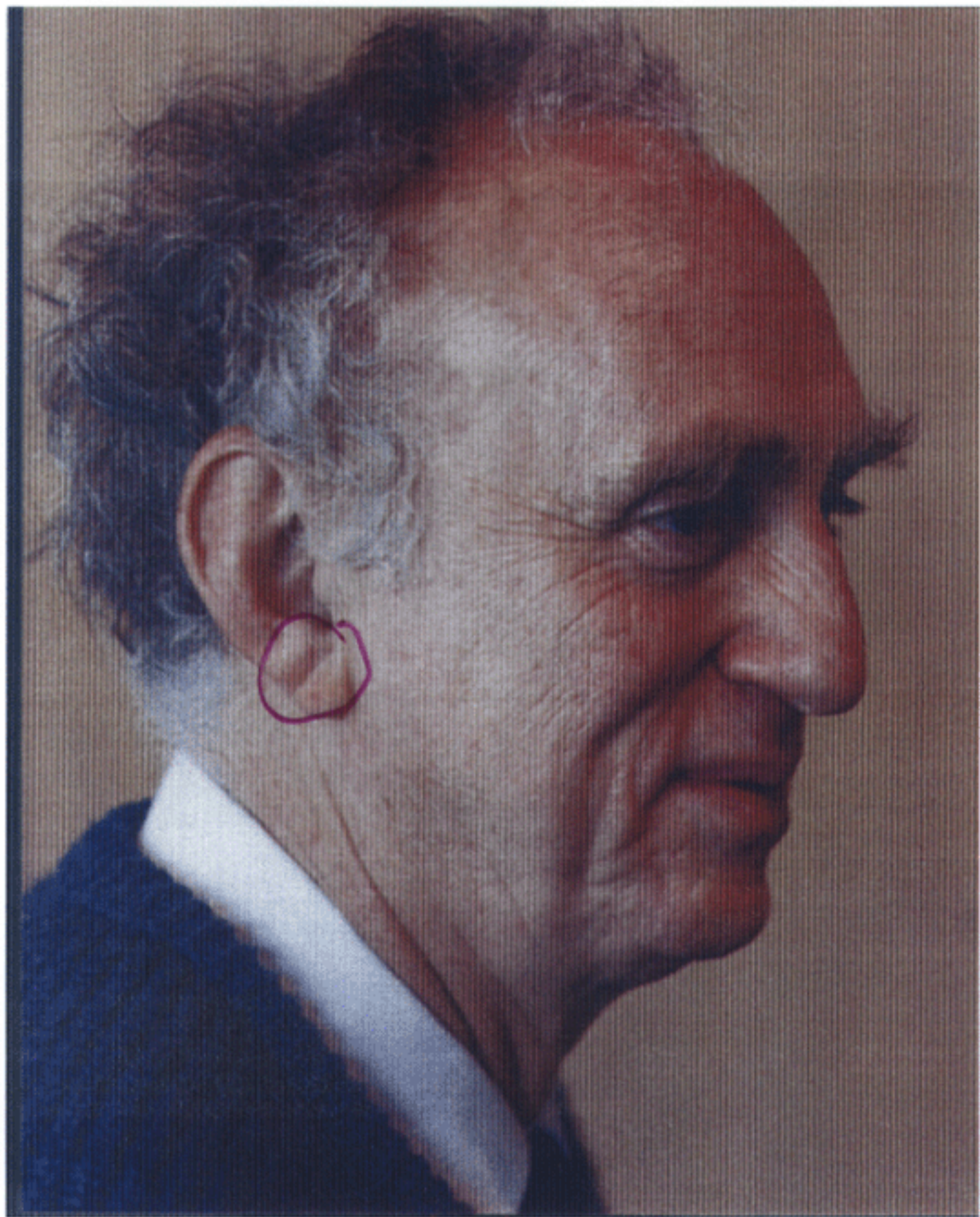


Figure 8.3 R is plotted against electron energy (in GeV). (Source: F. Halzen and A. D. Martin, *Quarks and Leptons* (New York: Wiley, copyright © 1984, p. 229. Reprinted by permission of John Wiley & Sons, Inc.)

My advisor



Martin Perl τ

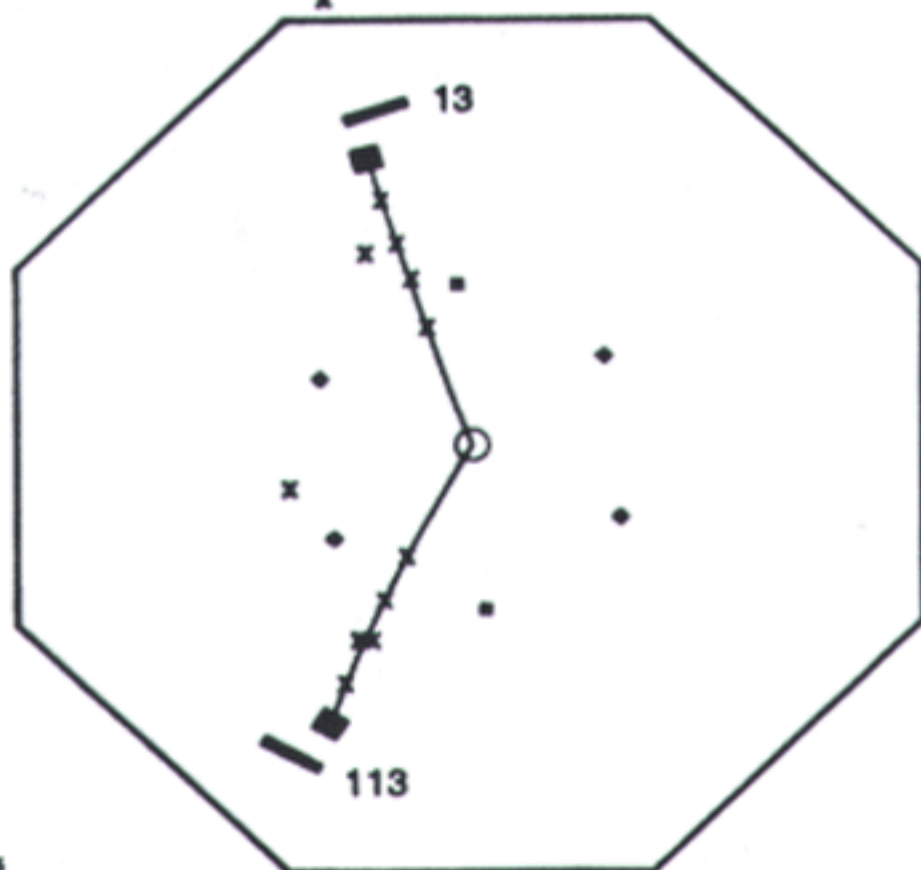
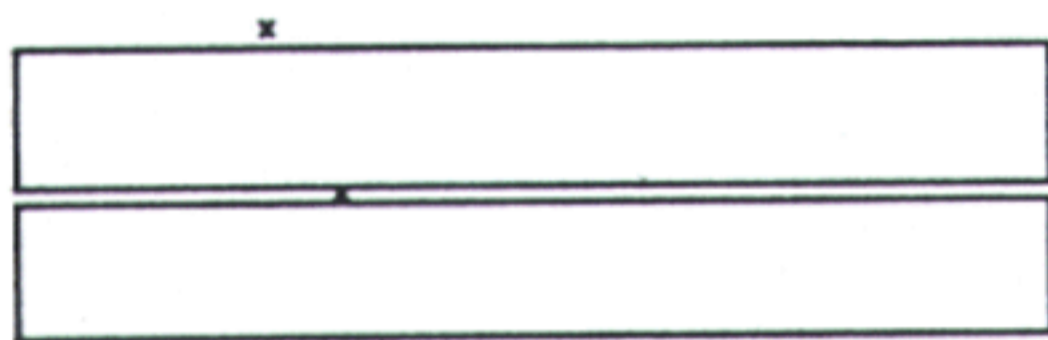
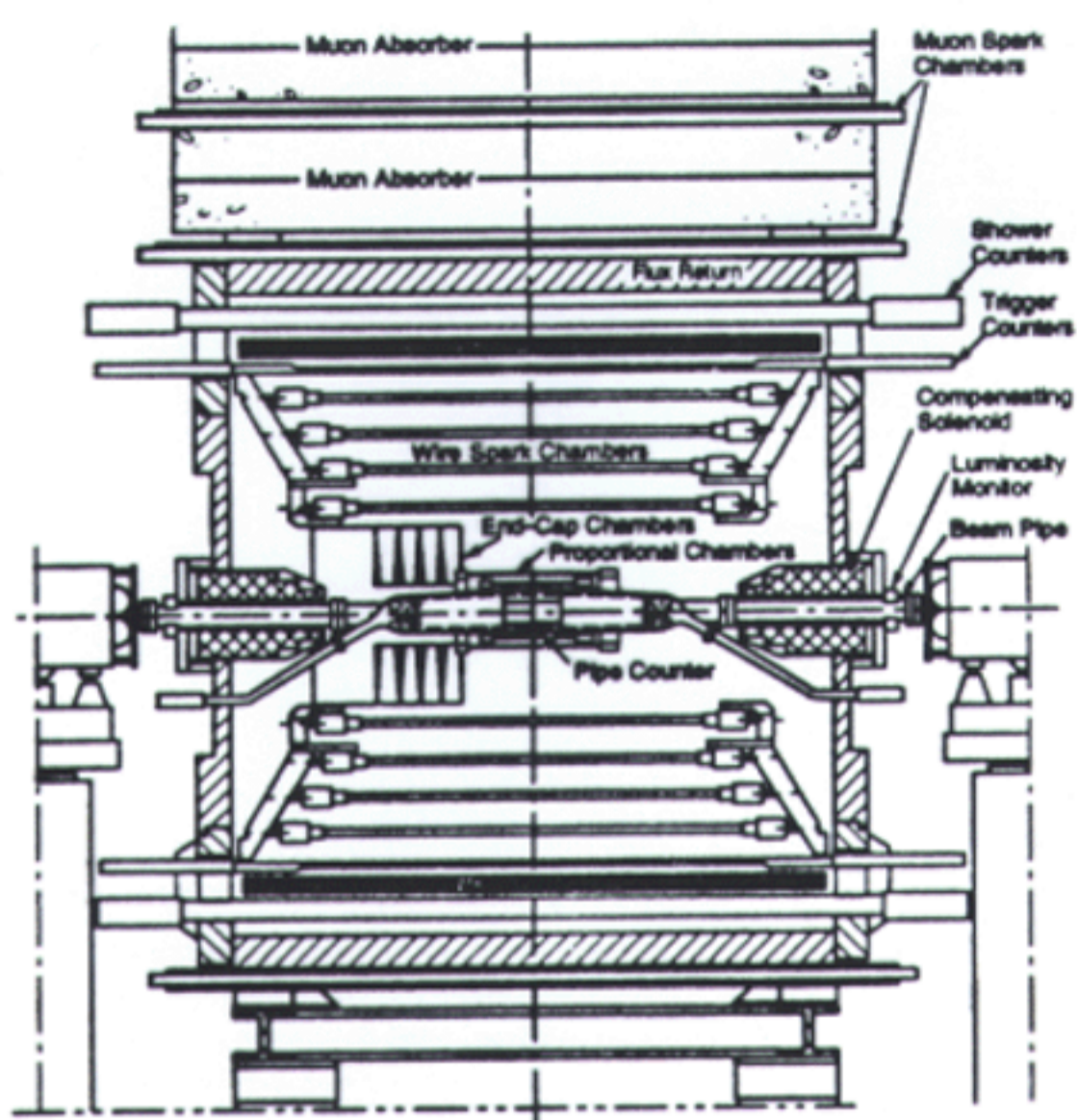
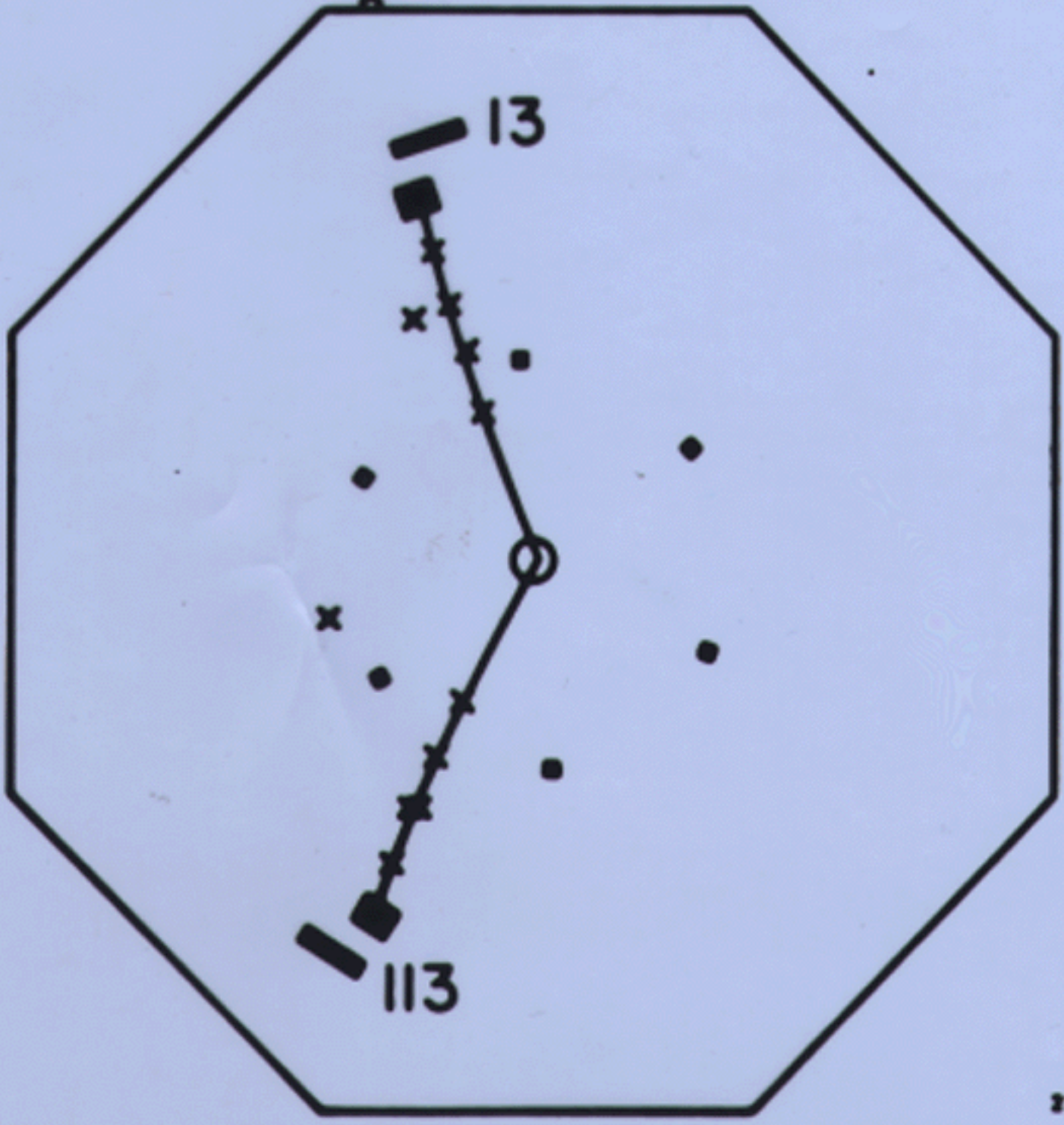
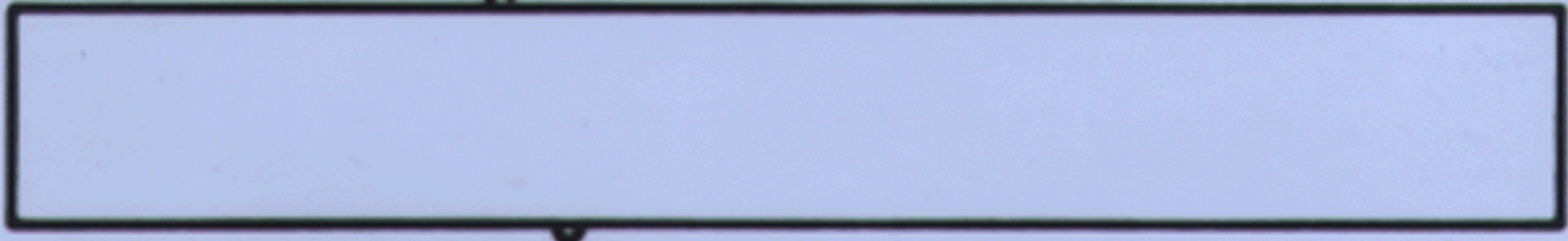


Figure 7. (a) The Mark I detector with the muon tower; (b) one of the first $e\mu$ events using the tower. The μ moves upward through the muon detector tower and the e moves downward. The numbers 13 and 113 give the relative amounts of electromagnetic shower energy deposited by the μ and e . The six square dots show the positions of longitudinal support posts of the magnetostrictive spark chamber used for tracking.

$$e^+ e^- \rightarrow \tau^+ \tau^-$$

$\swarrow \searrow$

$$\begin{aligned} & \rightarrow e^- \bar{\nu}_e \nu_\tau \\ & \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau \end{aligned}$$



ELEMENTARY PARTICLES

Quarks

u up	c charm	t top
d down	s strange	b bottom

Leptons

ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
e electron	μ muon	τ tau

Force Carriers

γ photon
g gluon
Z Z boson
W W boson

I II III
Three Generations of Matter

References:

(Nobel Prize lectures are excellent where applicable)

Evidence for Anomalous Lepton production in e^+e^- Annihilation Phys. Rev. Lett. 35, 1489 (1975)

Experimental Tests of Parity Conservation in beta Decay Wu et al. Phys. Rev. 105, 1413 (1957)

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the magnetic moment of the free muon

Garwin et al, Phys. Rev. 105, 1415 (1957)

Helicity of Neutrinos Goldhaber et al.,

Phys. Rev. 109, 1015 (1957)

Observation of High Energy Neutrino Reactions and the existence of two kinds of Neutrinos

Phys. Rev. Lett. 9, 36 (1962)

Elastic scattering of 188 MeV Electrons from the proton & alpha particles Phys. Rev., 102, 851 (1956)

Observed Behaviour of Highly Inelastic Electron Proton Scattering Phys. Rev. Lett. 23, 935 (1969)

Experimental observation of a heavy particle J Phys. Rev. Lett., 33, 1404 (1974)

Discovery of a narrow resonance in e^+e^- annihilation Phys. Rev. Lett. 33, 1406 (1974)

First Resource

2-3

Particle Data Group PDG

<http://pdg.lbl.gov>

Look at each best measurement

eg. muon mass 105.658389 ± 0.000034

how is it measured?

<u>value</u>	<u>document</u>	<u>technique</u>	<u>charge</u>	<u>comment</u>
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best mariam '82 PKL 49, 993

look it up in library

→ hyperfine Zeeman transition in groundstate of muonium !!!
....



$$J = \frac{1}{2}$$

μ MASS

The mass is known more precisely in u (atomic mass units) than in MeV (see the footnote to COHEN 87). The conversion from u to MeV, $1 u = 931.49432 \pm 0.00078$ MeV, involves the relatively poorly known electronic charge.

Where m_{μ}/m_e was measured, we have used the 1986 CODATA value for $m_e = 0.510998946 \pm 0.00000015$ MeV.

VALUE (MeV)	DOCUMENT ID	TECH	CHG	COMMENT
105.658389 \pm 0.000034	¹ COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
105.65841 \pm 0.00033	² BELTRAMI	86	SPEC	- Muonic atoms
105.658432 \pm 0.000064	³ KLEMP	82	CNTR	+ Incl. in MARIAM 82
105.658386 \pm 0.000044	⁴ MARIAM	82	CNTR	+
105.65856 \pm 0.00015	⁵ CASPERSON	77	CNTR	+
105.65836 \pm 0.00026	⁶ CROWE	72	CNTR	
105.65865 \pm 0.00044	⁷ CRANE	71	CNTR	

¹ The mass is known more precisely in u : $m = 0.113428913 \pm 0.000000017 u$. COHEN 87 makes use of the other entries below.

² BELTRAMI 86 gives $m_{\mu}/m_e = 206.76830(64)$.

³ KLEMP 82 gives $m_{\mu}/m_e = 206.76835(31)$.

⁴ MARIAM 82 gives $m_{\mu}/m_e = 206.768259(62)$.

⁵ CASPERSON 77 gives $m_{\mu}/m_e = 206.76859(29)$.

⁶ CROWE 72 gives $m_{\mu}/m_e = 206.7682(5)$.

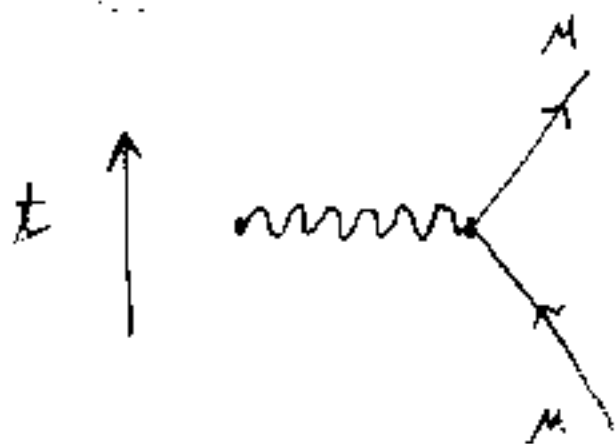
⁷ CRANE 71 gives $m_{\mu}/m_e = 206.76878(85)$.

μ MEAN LIFE τ

Measurements with an error $> 0.001 \times 10^{-6}$ s have been omitted.

VALUE (10^{-6} s)	DOCUMENT ID	TECH	CHG
2.19703 \pm 0.00004	OUR AVERAGE		
2.197078 \pm 0.000073	BARDIN	84	CNTR +
2.197025 \pm 0.000155	BARDIN	84	CNTR -
2.19695 \pm 0.00006	GIOVANETTI	84	CNTR +
2.19717 \pm 0.00008	BALANDIN	74	CNTR +
2.1973 \pm 0.0003	DUCIOS	73	CNTR +

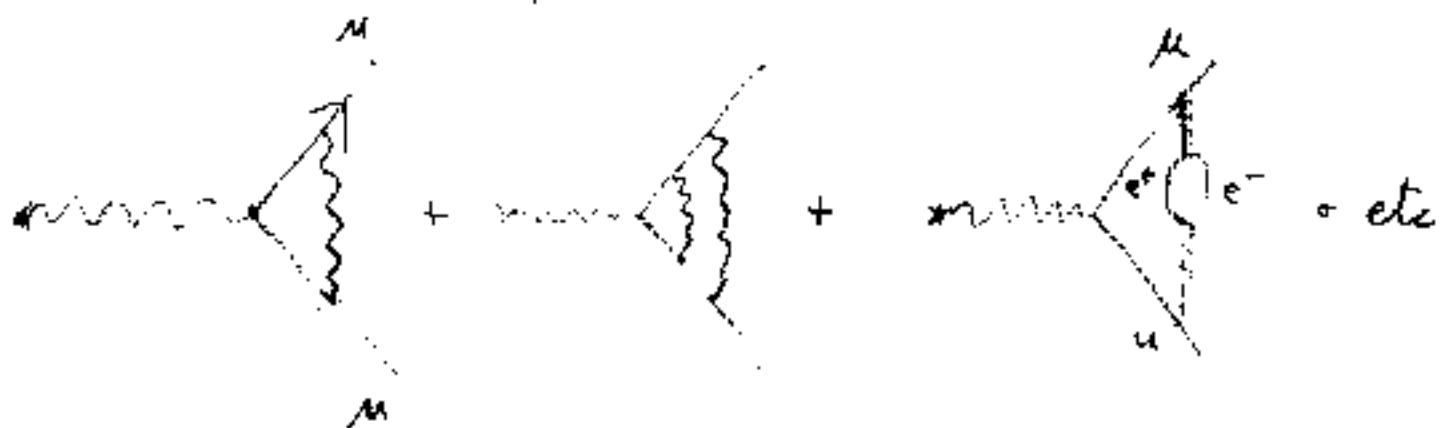
Muon magnetic moment



photon couples to the magnetic moment

Compare e to μ ?

is there new physics in μ ?



electromagnetic + weak + strong corrections



Dirac elementary particles

$$\vec{M} = \frac{qe}{2mc} |\vec{s}|$$

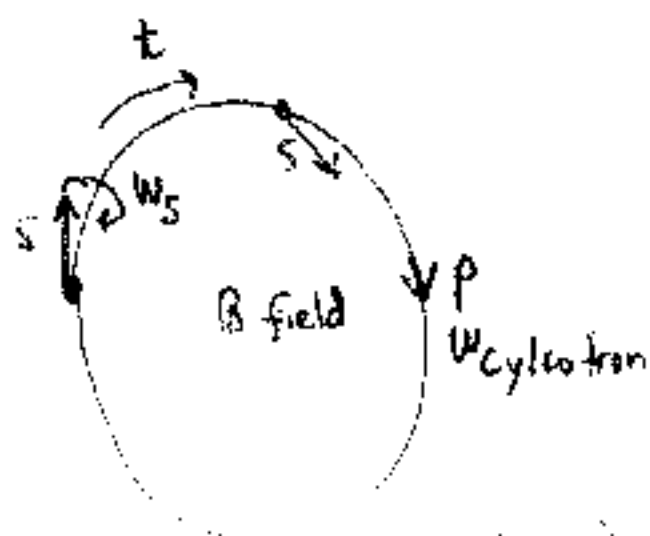
↑ spin
↑ g-factor

Anomalous contribution

$$g = \frac{4-2}{2}$$

Measure this precisely

Make muon storage ring



particle goes around w/ freq. ω_c
 spin precesses w/ freq. ω_s

$$\omega_c = \frac{eB}{\gamma mc}$$

lab frame

$$\omega_s = \frac{eB}{m\gamma} \left[1 + \left(\frac{g-2}{2} \right) \gamma \right]$$

Then muon decays

$$\vec{M} \rightarrow \vec{e} \vec{r} \vec{p} \vec{M}$$

$$\phi = (\omega_s - \omega_c) t$$

This year, new $g-2$ @ Brookhaven Lab

$$a_{\mu^+} = \frac{g-2}{2} = 11\,659\,202 \pm 14 \pm 6 \times 10^{-10}$$

1.3 parts/million

a_e measured to 4 parts/billion

but a_{μ} more sensitive to new physics

because $\left(\frac{m_{\mu}}{m_e}\right)^2 \approx 40,000$.

For example: QED only,

$$a_e = 0.5 \frac{d}{\pi} - 0.32848 \left(\frac{d}{\pi}\right)^2 + 1.19 \left(\frac{d}{\pi}\right)^3 + \dots$$

$$a_{\mu} = 0.5 \frac{d}{\pi} + 0.76578 \left(\frac{d}{\pi}\right)^2 + 24.45 \left(\frac{d}{\pi}\right)^3 + \dots$$

e^+e^- colliders

One simple measurement R .

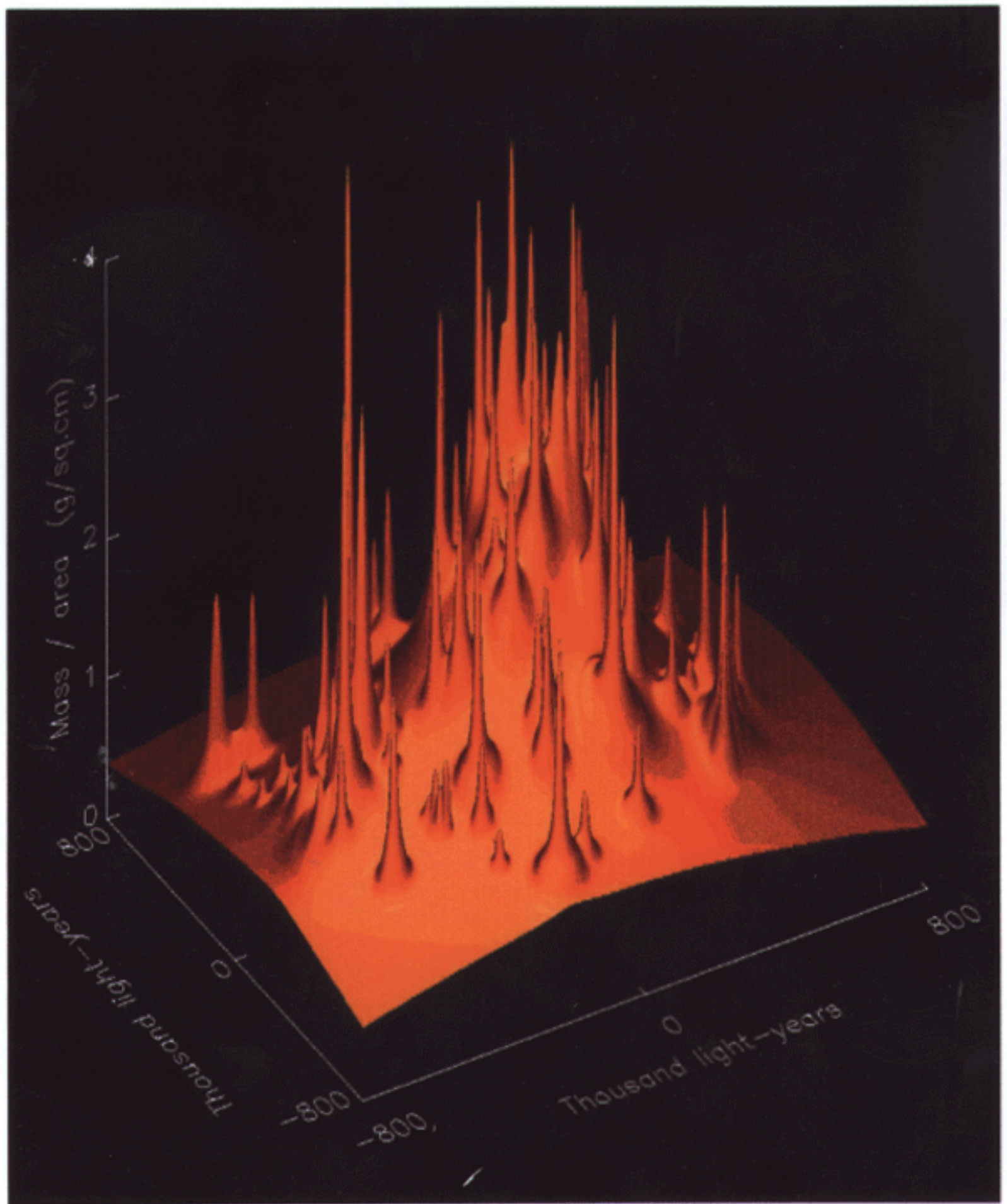
Small band of detector.

CONSIDER DARK MATTER

- KNOWN TO EXIST FOR 10 YEARS
- DISTRIBUTION IN GALACTIC CLUSTERS SHOWN THIS SPRING
- WHAT IS IT?

Someone gives you a beam of dark matter, or a block of it, can you devise experiments to figure out what it is?

"Cosmic mirage"



Galactic Cluster CL0024+1654
2 billion light years distant (Pisces)