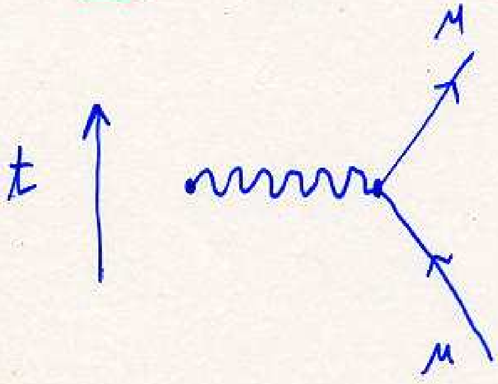
Lecture 3

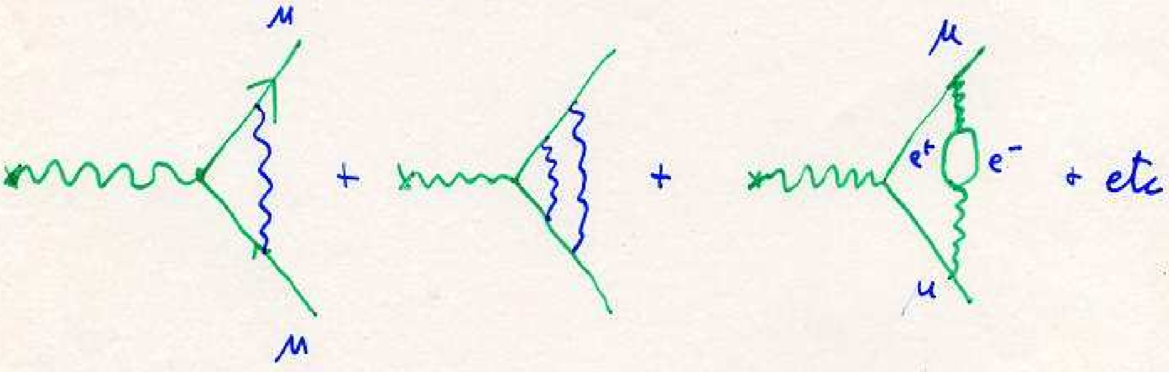
- understanding the μ
  - What is it? why? heavier?
  - measure magnet moment
- two neutrinos
  - ν_e, ν_μ ?
  - First ν beam
- colliders: e^+e^- @ SLAC
  - making resonances J/ψ
  - producing τ's.

Muon magnetic moment

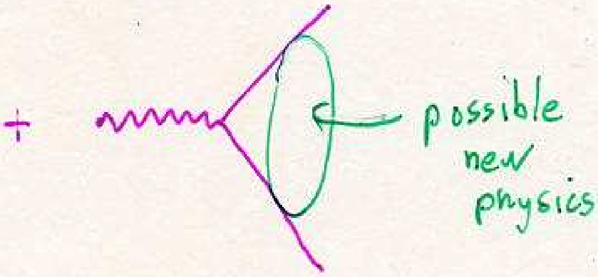


photon couples To
the magnetic
moment

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



electromagnetic + weak + strong corrections



possible
new
physics

Dirac elementary particles

$$\vec{\mu} = \frac{ge}{2mc}|\vec{s}|$$

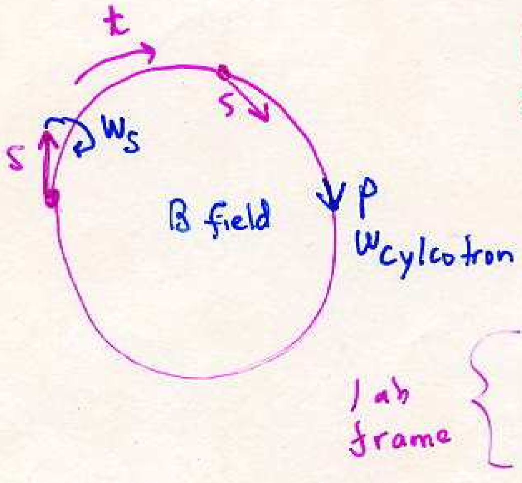
spin

g-factor

Anomalous contribution $a = \frac{g-2}{2}$

Measure this precisely

Make muon storage ring



particle goes around w/ freq. w_c

spin precesses w/ freq. w_s

lab frame

$$\left\{\begin{aligned} w_c &= \frac{eB}{\gamma mc} \\ w_s &= \frac{eB}{mc\gamma}\left[1 + \left(\frac{g-2}{2}\right)\gamma\right] \end{aligned}\right.$$

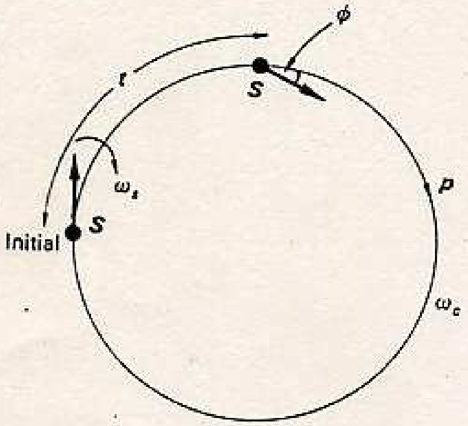
Then muon decays

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

$$\boxed{\phi = (w_s - w_c)t}$$

And more magnetic moment: Dirac pt. particle

$\mu = \frac{ge}{2m}|\vec{s}|$ ← spin



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

ω_s – precession frequency – $g\frac{eB}{2mc}$

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).

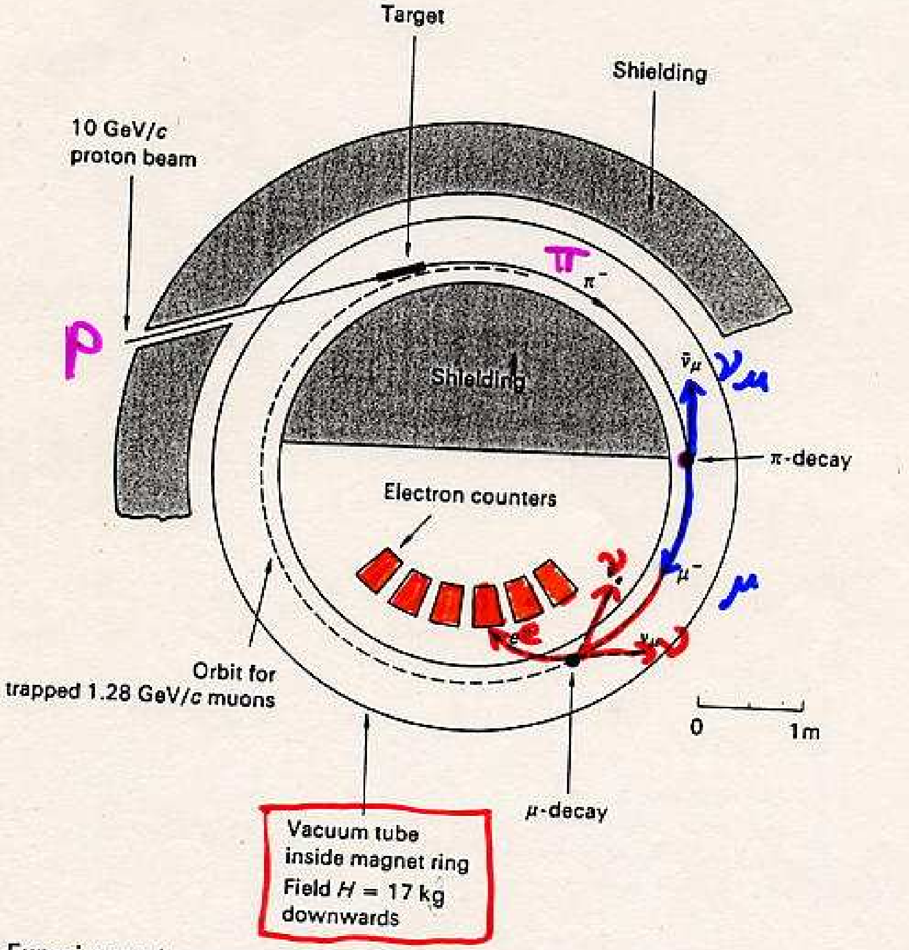
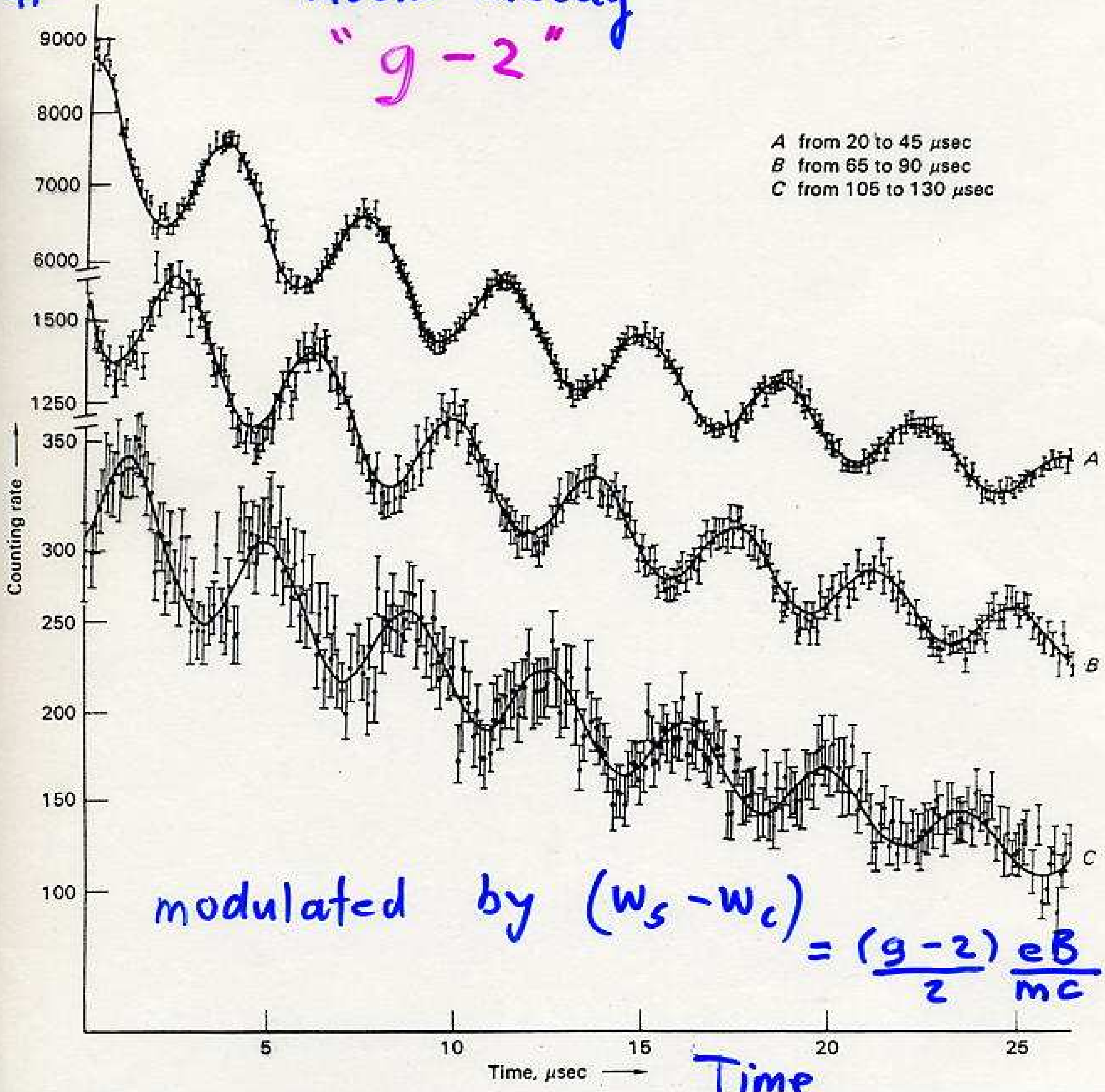


Fig. 5.3 Experimental arrangement employed in determination of the muon g-factor using a "muon storage ring" (Bailey *et al.*, 1968)

3.2

\# muons decay "g − 2"



modulated by $(w_s - w_c) = \frac{(g-2)}{2}\frac{eB}{mc}$

Time

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 $\tau = 26$ μsec 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 μsec, 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

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

TWO NEUTRINOS ?

PONTE CORVO puzzles over e, μ

SCHWARZ wants to see Fermi break down

Fermi
effective theory

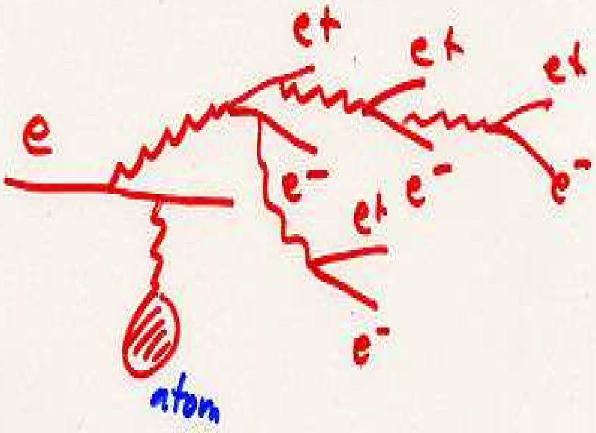
intermediate
vector
boson

Both thought of ν beams.

We knew Rate$(\mu \to e\gamma) \sim 0$, but

if only one kind of

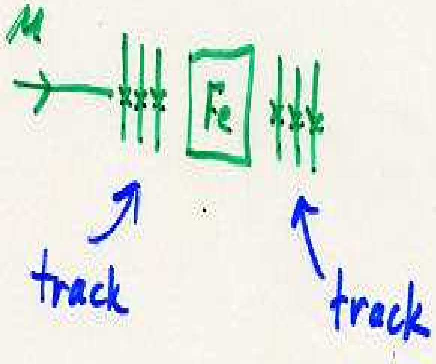
- electron showers in matter

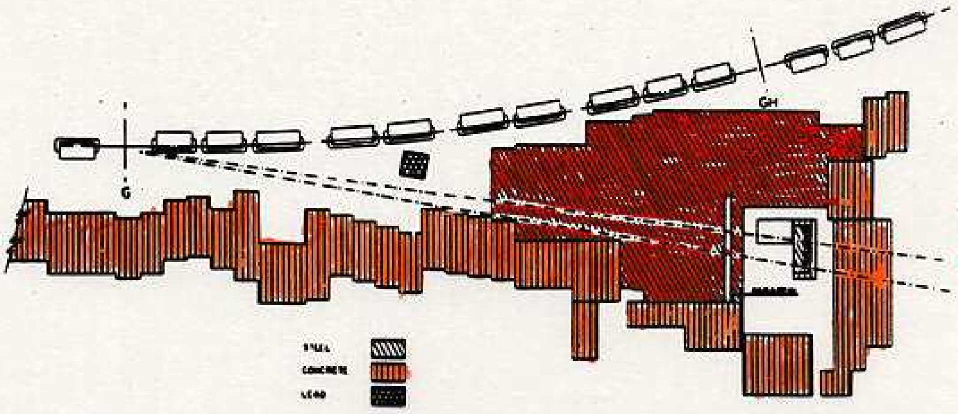


loses energy early and often

- muons ionize but penetrate through steel

identify muons





first
ν beam

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

BROOKHAVEN, NY.

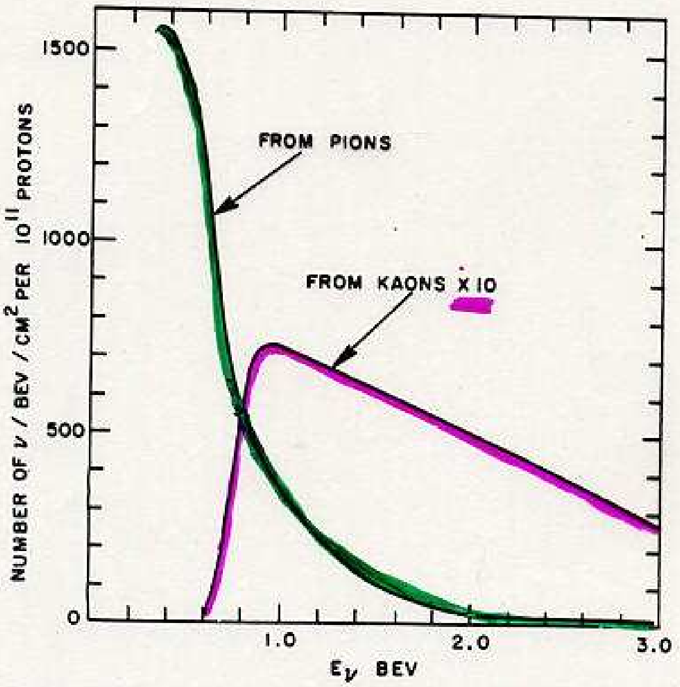


Figure 2. Energy spectrum of neutrinos as expected for A.G.S. running at 15 GeV.

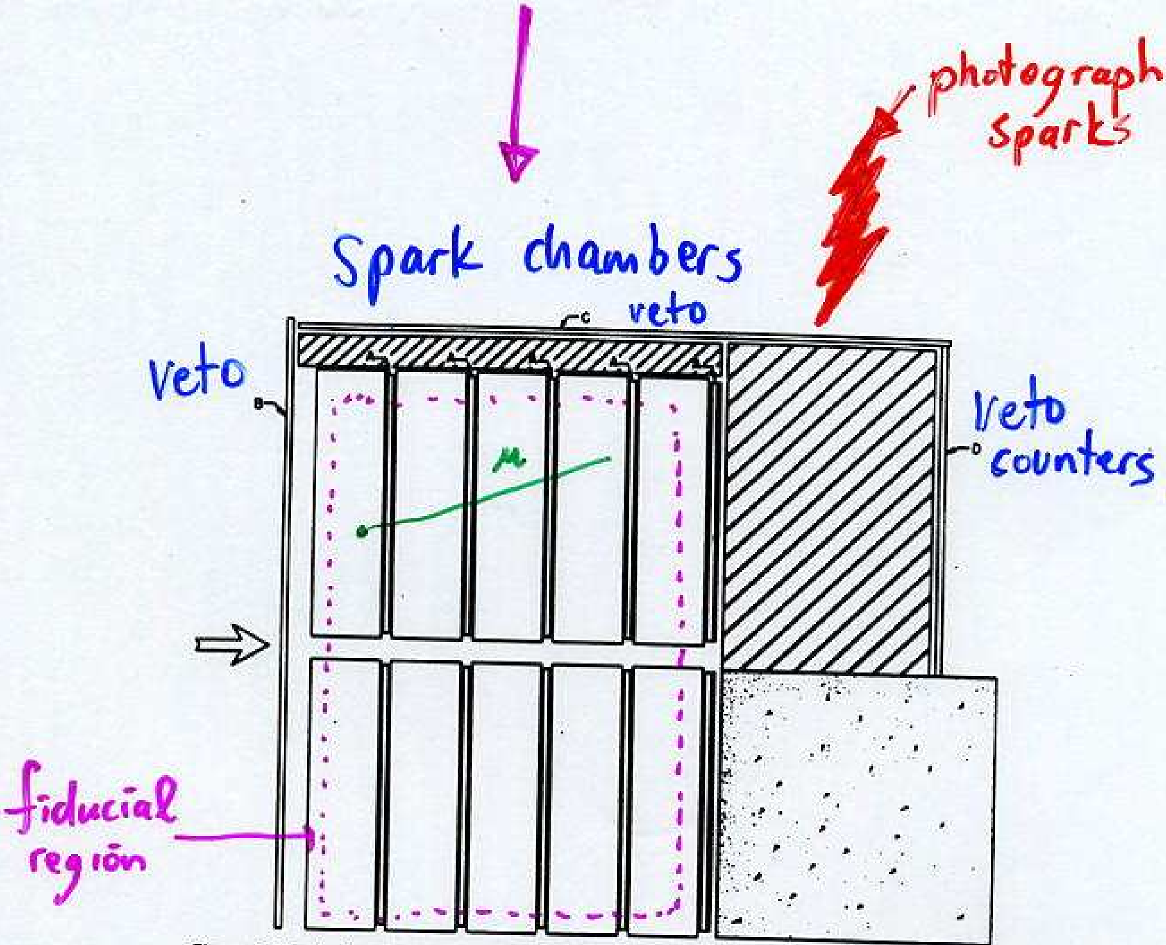


Figure 3. Spark chamber and counter arrangement. This is the front view with neutrinos entering on the left. A are the trigger counters. B, C and D are used in anti-coincidence.

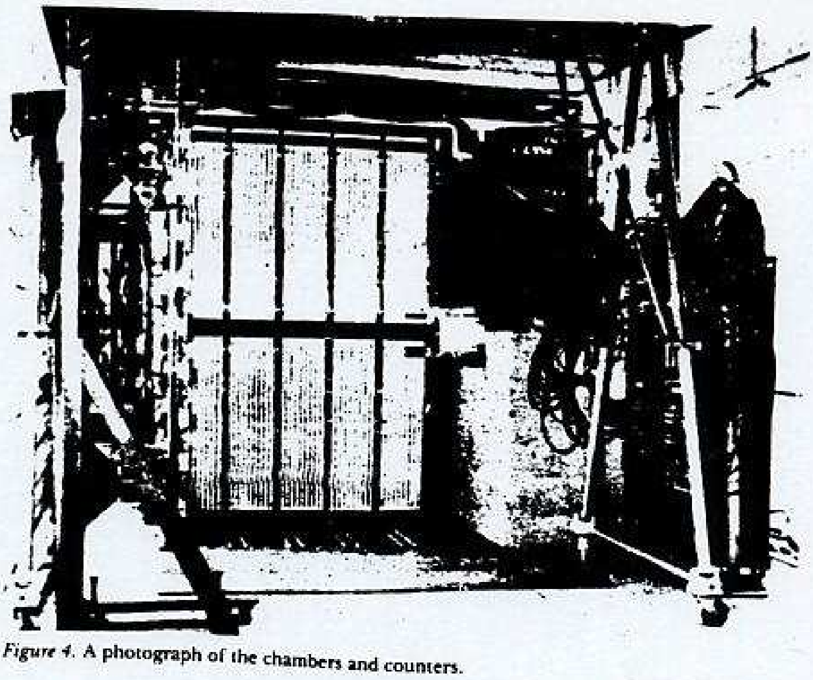
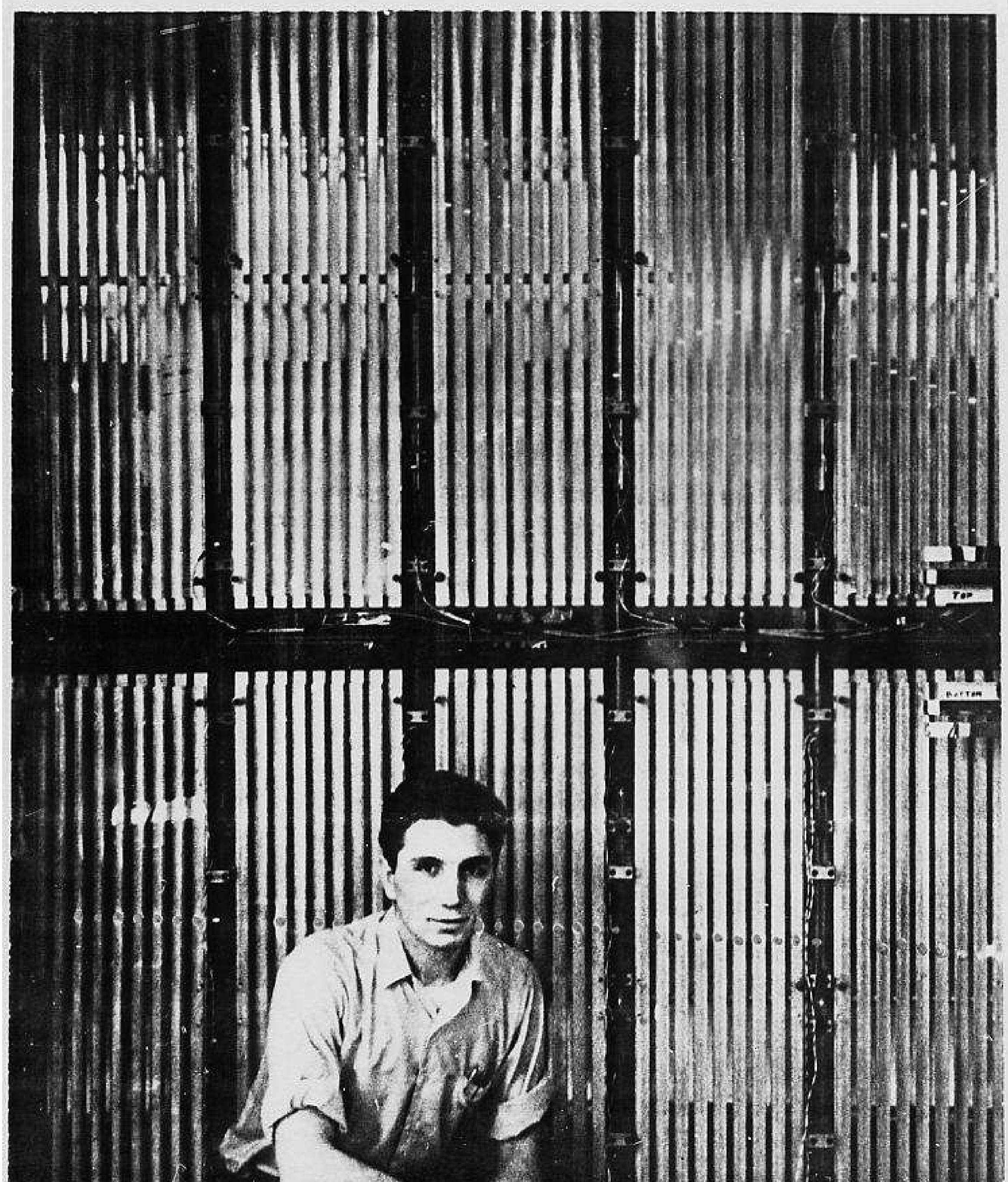


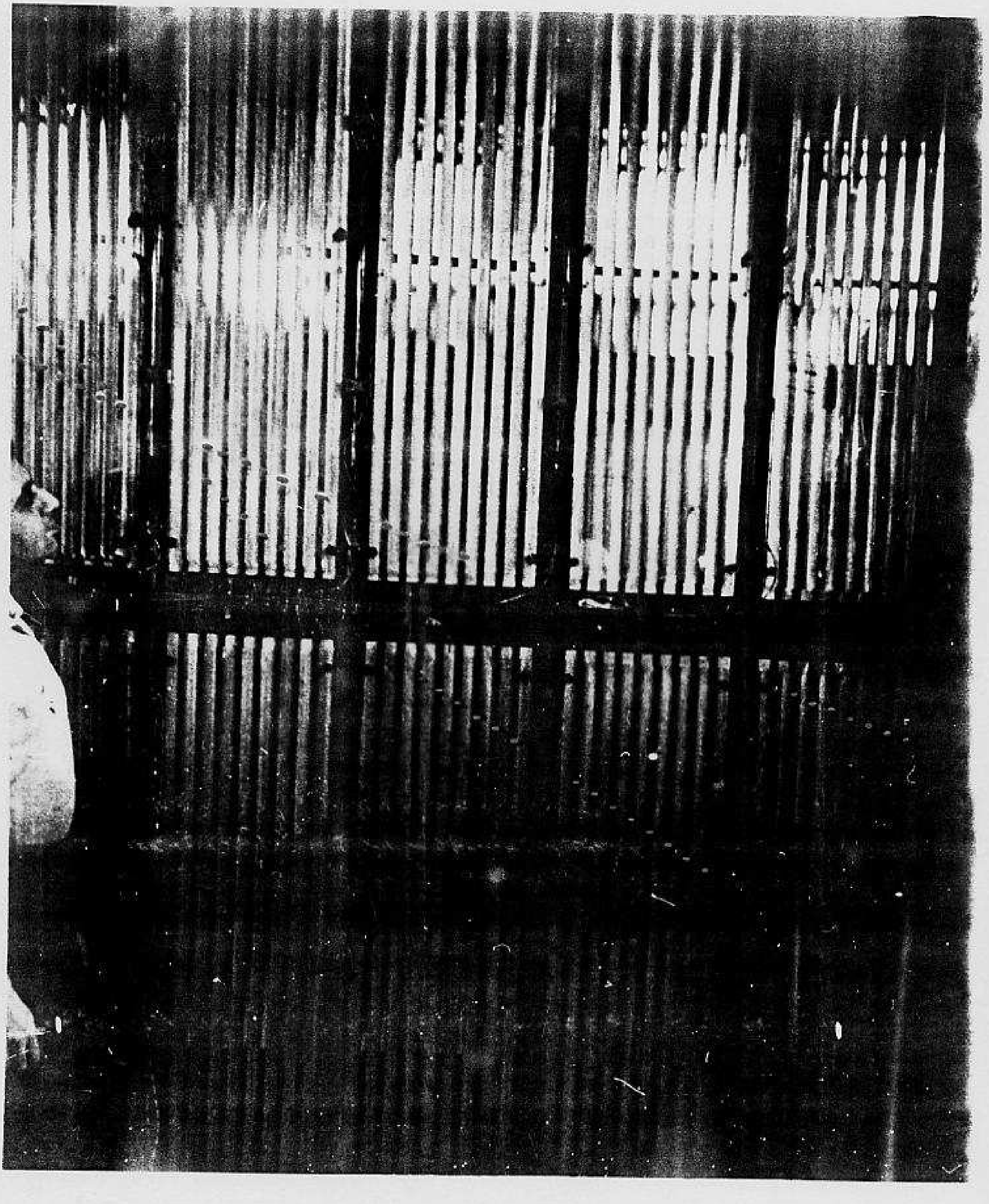
Figure 4. A photograph of the chambers and counters.

3.7

ν beam not hot

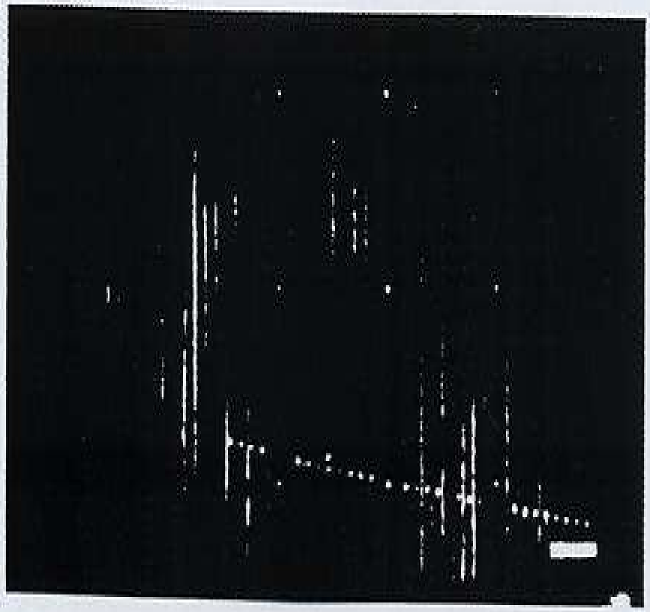


3.9

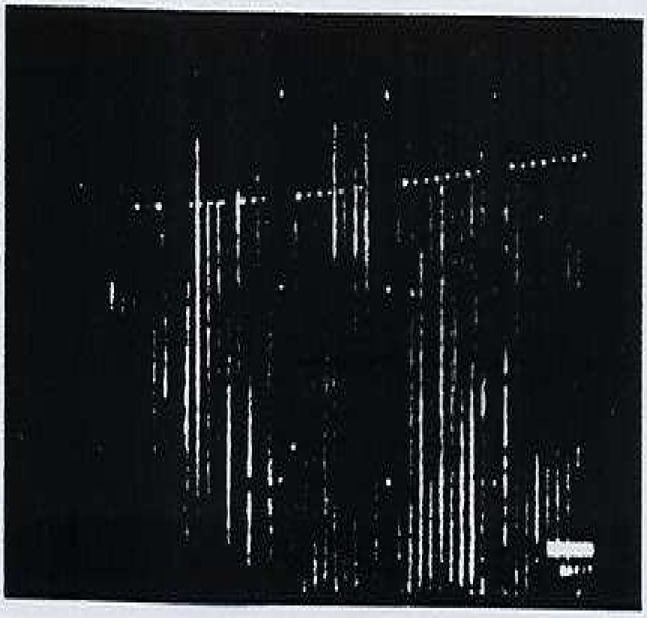


muon

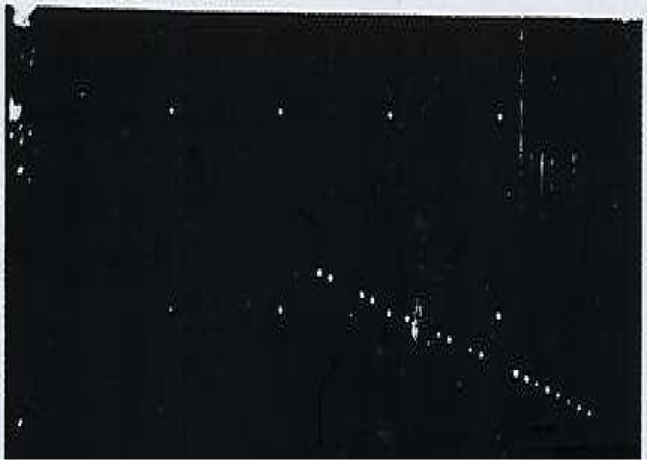
$P_\mu > 540$



A



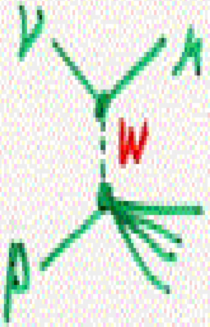
B



C

Vertex events

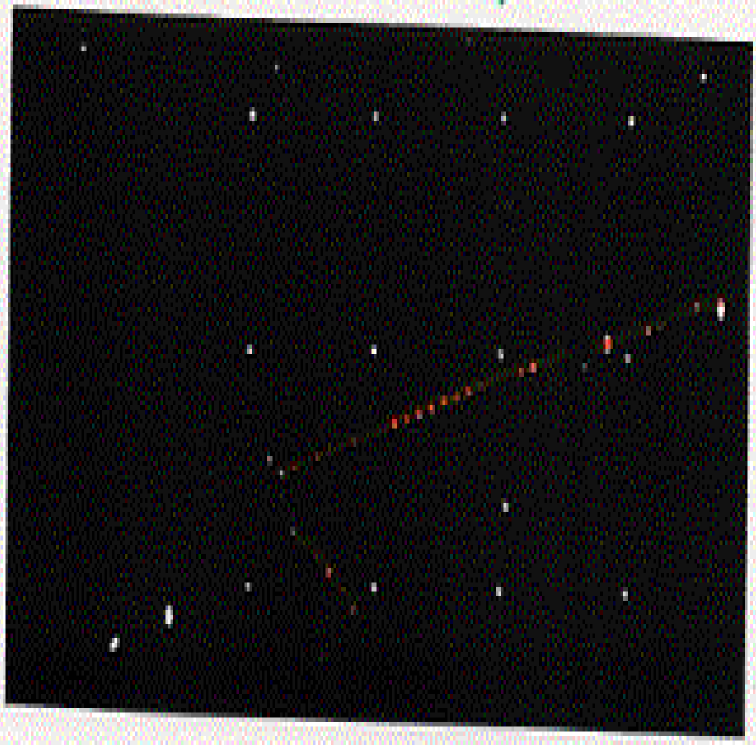
(inelastic)



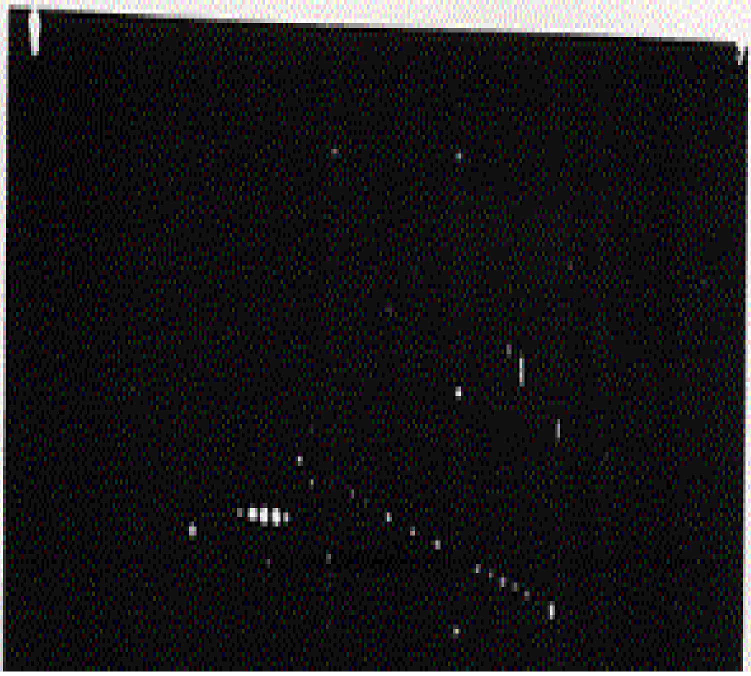
μ

$p_\mu > 500$ MeV

and e-type

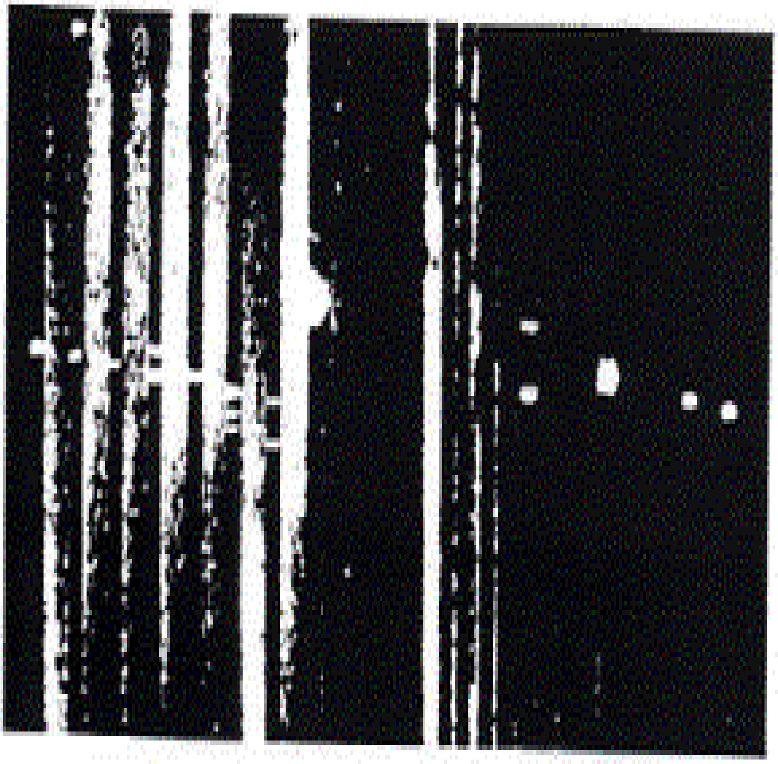


A

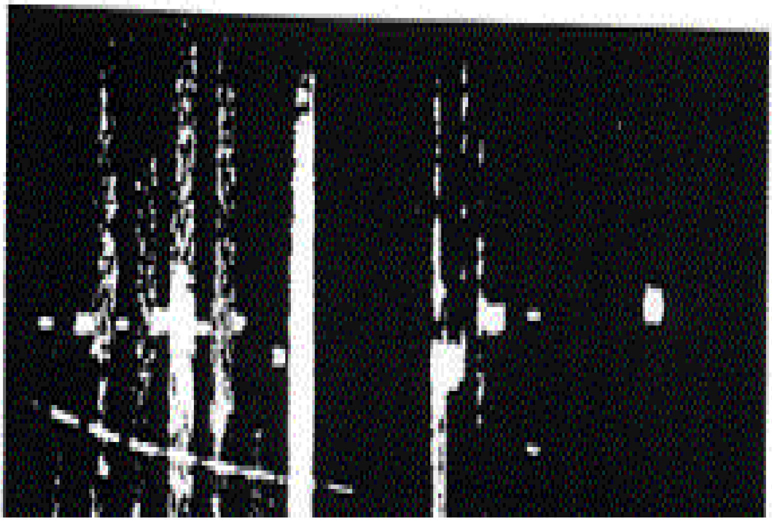


B

This is what electrons look like



A



B

Results of ν beam experiment

- 113 events total

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

- 22 vertex events

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

  e, γ
- 8 shower events
  6 with $p > 300$ 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

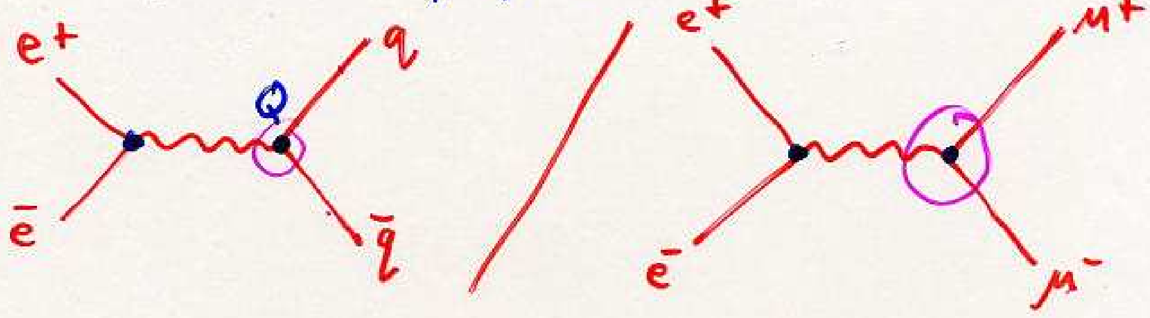
NOT ENOUGH SHOWER EVENTS $\Rightarrow$ NO ν_e
$\Rightarrow$ ν's from $\pi \to \mu\nu$ ARE DIFFERENT

e^+e^- colliders

One simple measurement R.

New kind of detector.

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



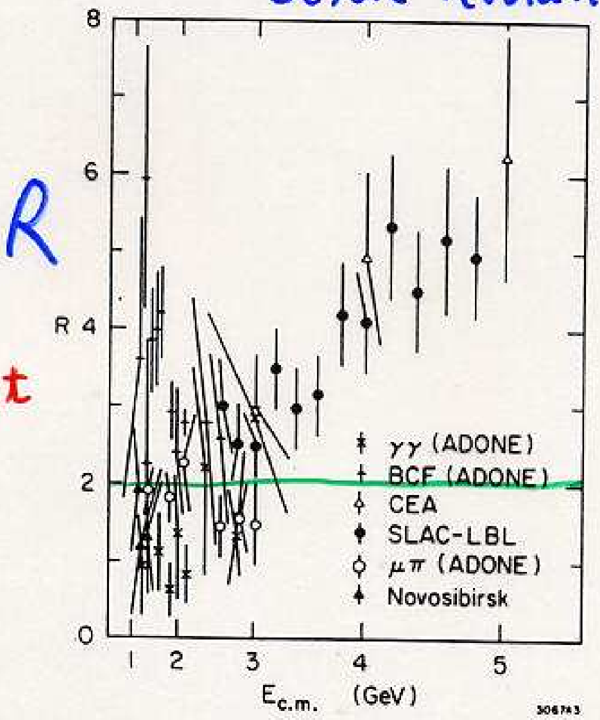
$$\sigma = \frac{\pi}{3}\left(\frac{\hbar Q c \alpha}{E}\right)^2 \quad \text{above threshold}$$

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

colour

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

Before revolutin

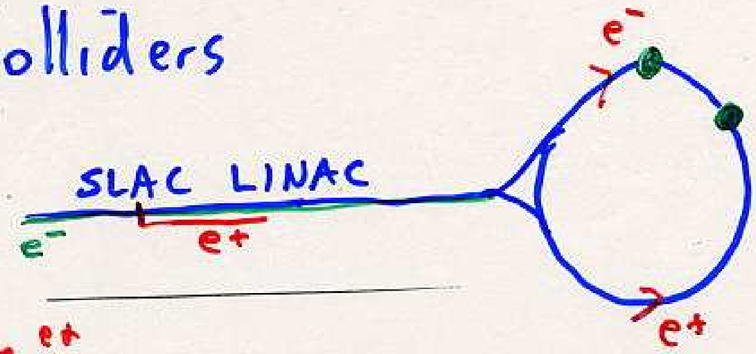


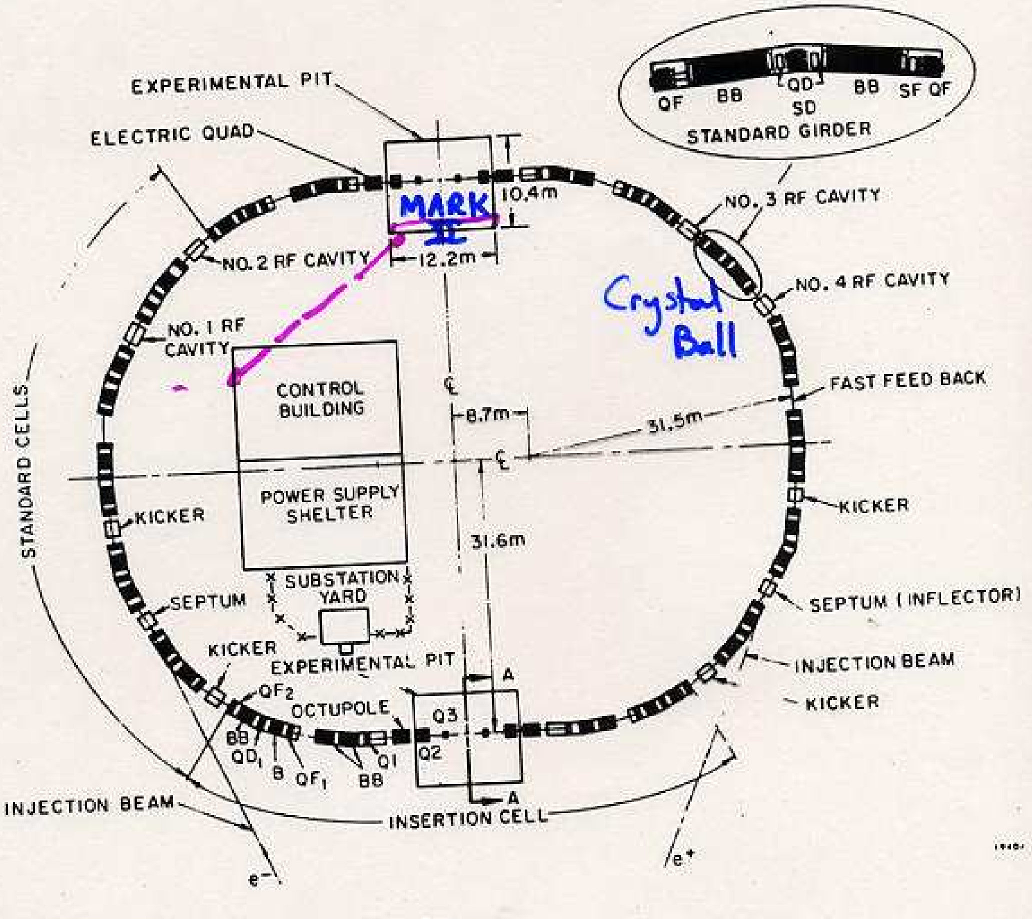
. The ratio *R* as of July 1974.

if only u, d, s $\quad R = 3\left(\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right)$

$= 2$

e^+e^- Colliders





1. Schematic of the SPEAR storage ring.

3.1

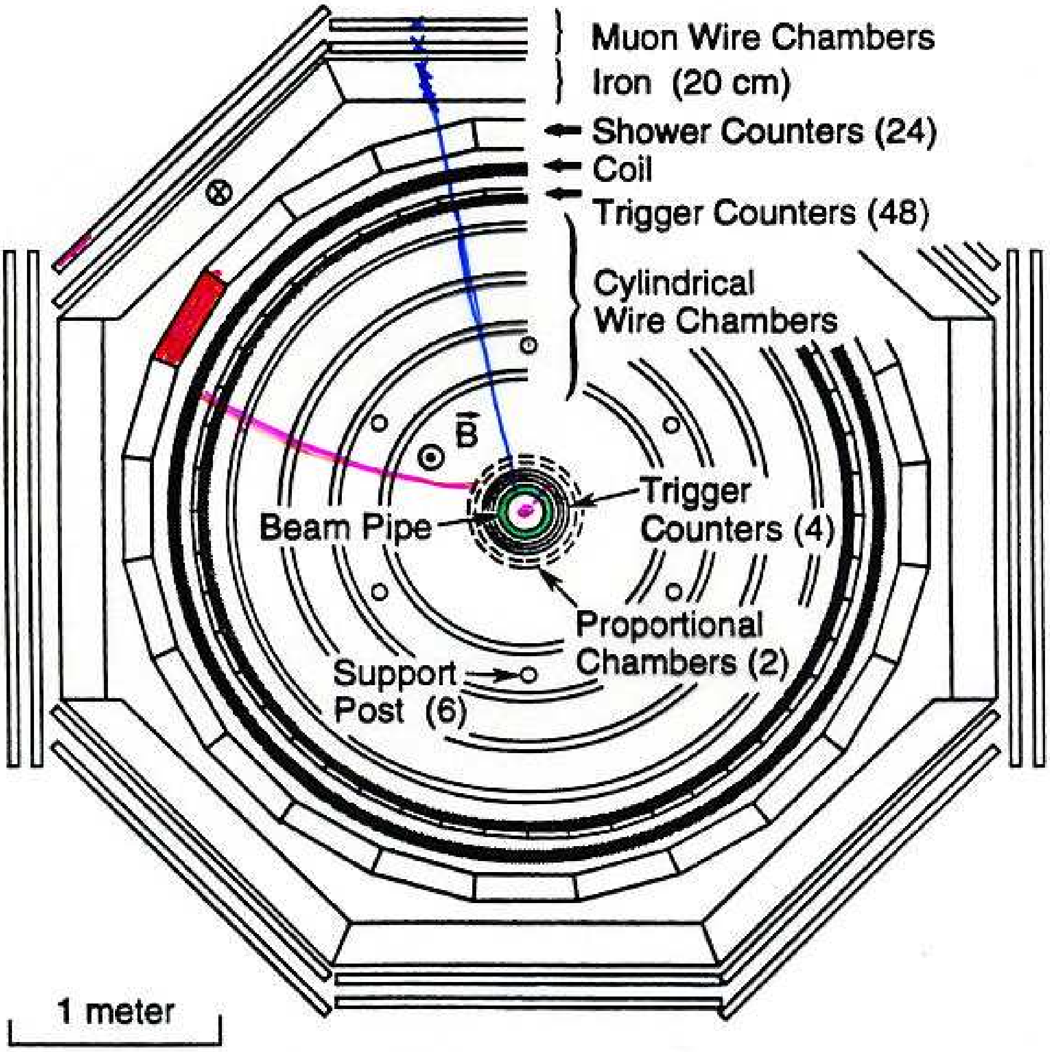


Figure 5. The initial form of the Mark I detector.

e^+e^- Mark I detector at SLAC

hermetic,

"Typical" J/ψ event
in tracking chamber

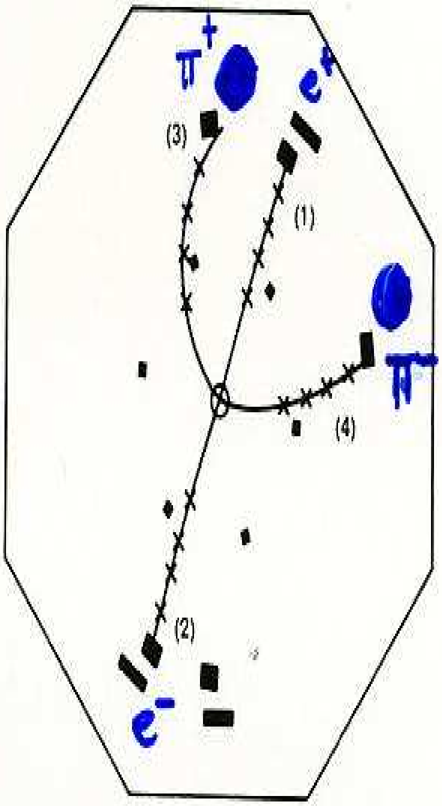
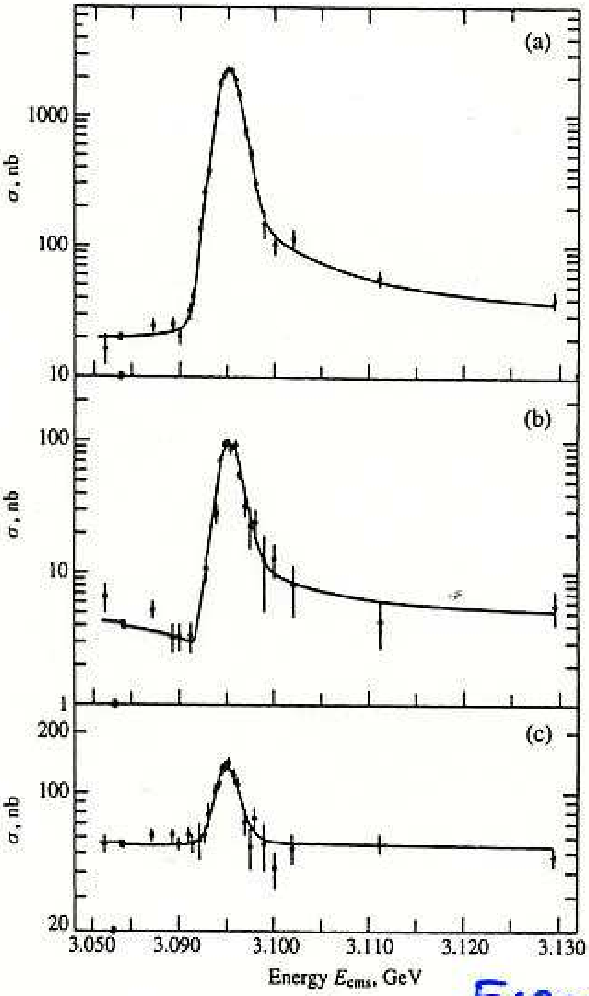


Fig. 4.4. Example of the decay $\psi(3.7) \rightarrow \psi(3.1)+\pi^{+}+\pi^{-}$ observed in a spark chamber detector. The $\psi(3.1)$ decays to $e^{+}+e^{-}$. Tracks (3) and (4) are due to the relatively low energy (150 MeV) pions, and (1) and (2) to the 1.5 GeV electrons. The magnetic field and the 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.)

$$\psi' \rightarrow \psi \, \pi^+ \pi^-$$
$$\hookrightarrow e^+ e^-$$

From e^+e^-



σ $e^+e^- \to$ hadrons

σ $e^+e^- \to \mu^+\mu^-$

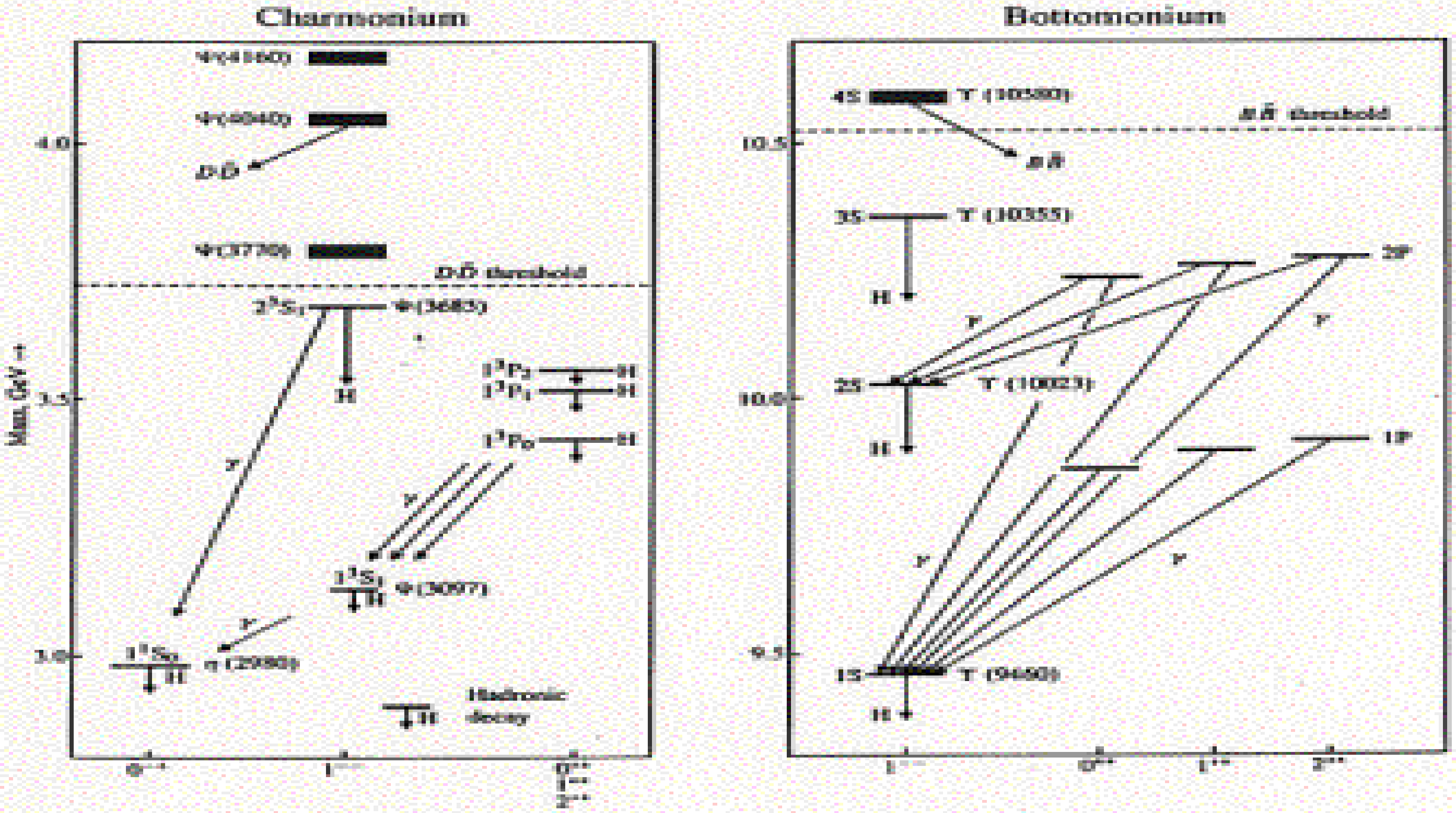
σ $e^+e^- \to e^+e^-$

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) $e^+e^- \to$ hadrons; (b) $e^+e^- \to \mu^+\mu^-$, $|\cos\theta| \leq 0.6$; (c) $e^+e^- \to e^+e^-$, $|\cos\theta| \leq 0.6$.

copy convinces us that there really are quarks.

$c\bar{c}$ $b\bar{b}$



sitronium, charmonium and bottomonium. Note the changes in scale for positronium. Only in e^+e^- annihilation experiments. Note that the atomic physics convention is to label the , while for the charmonium and bottomonium states the nuclear physics nomenclature 1P is

3.21

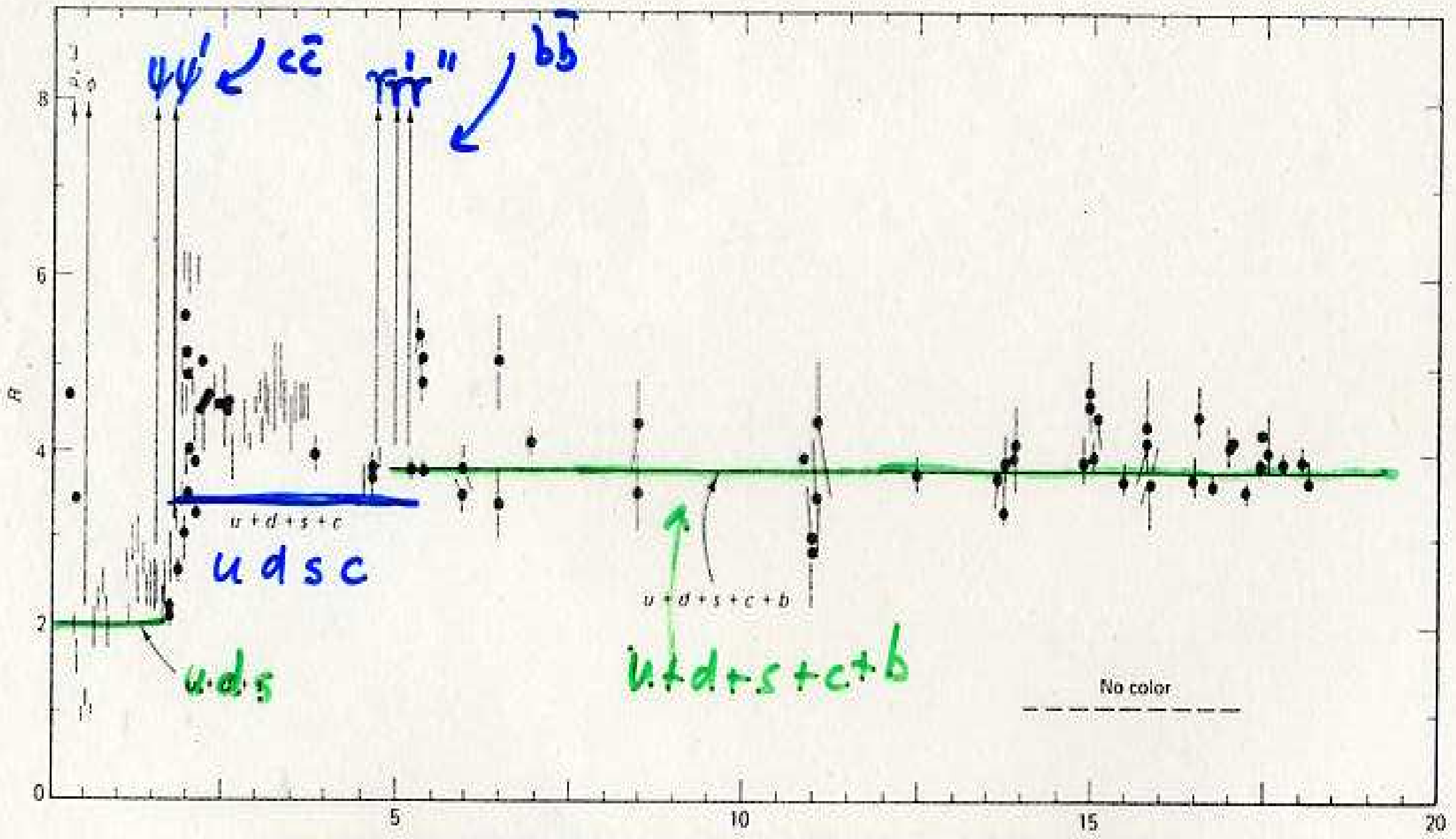
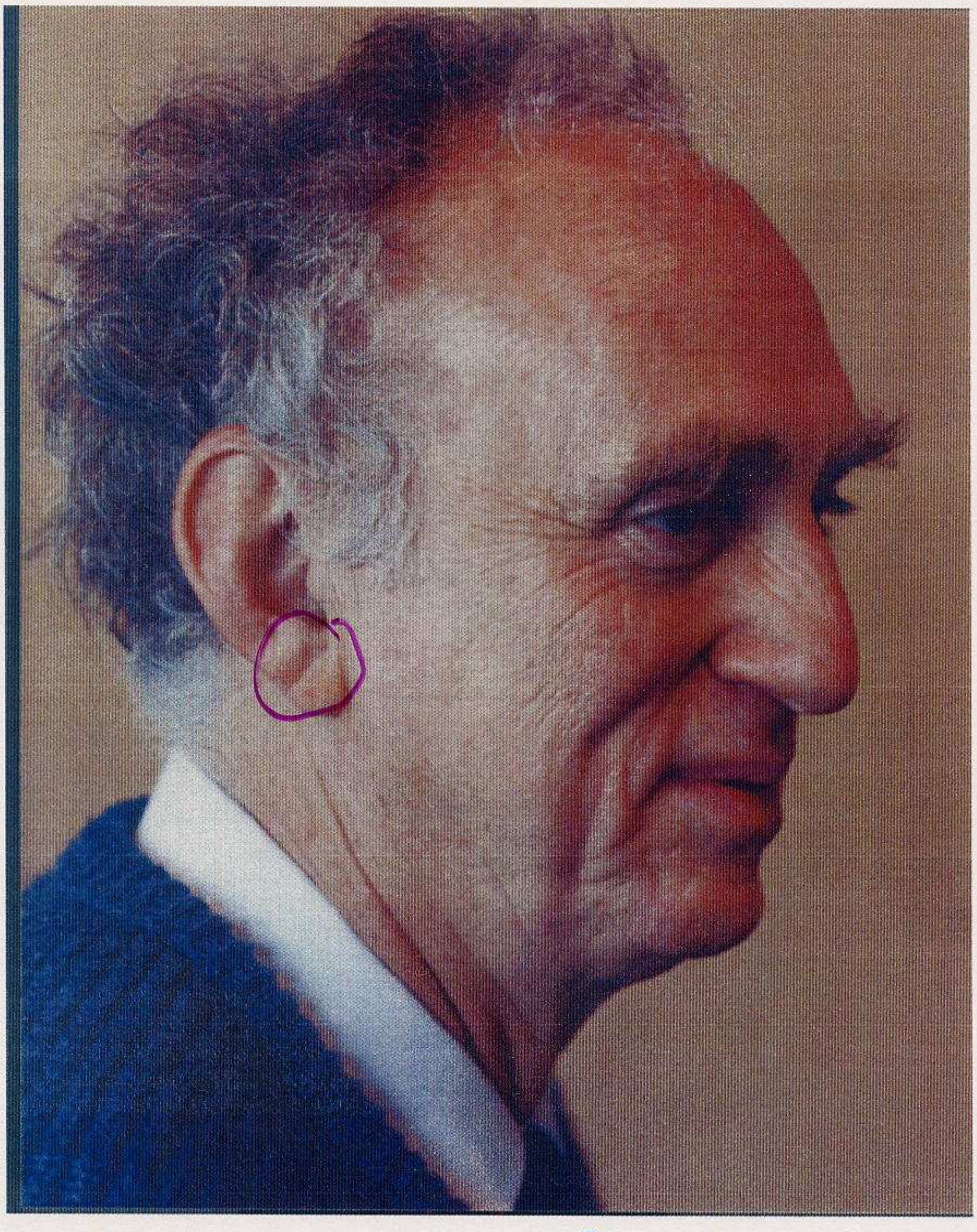


Figure 8.3 R is plotted against electron energy (in GeV). (*Source:* F. Halzen and A. D. Martin, *Quarks and Leptons* (New York: Wiley, copyright © 1984, p. 229. Reprinted by permission of John Wiley & Sons, Inc.)

3.24

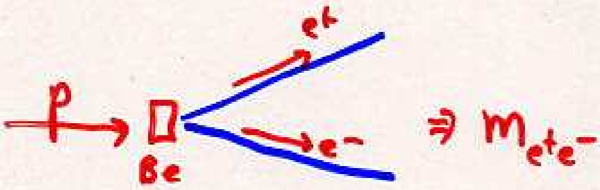
My advisor



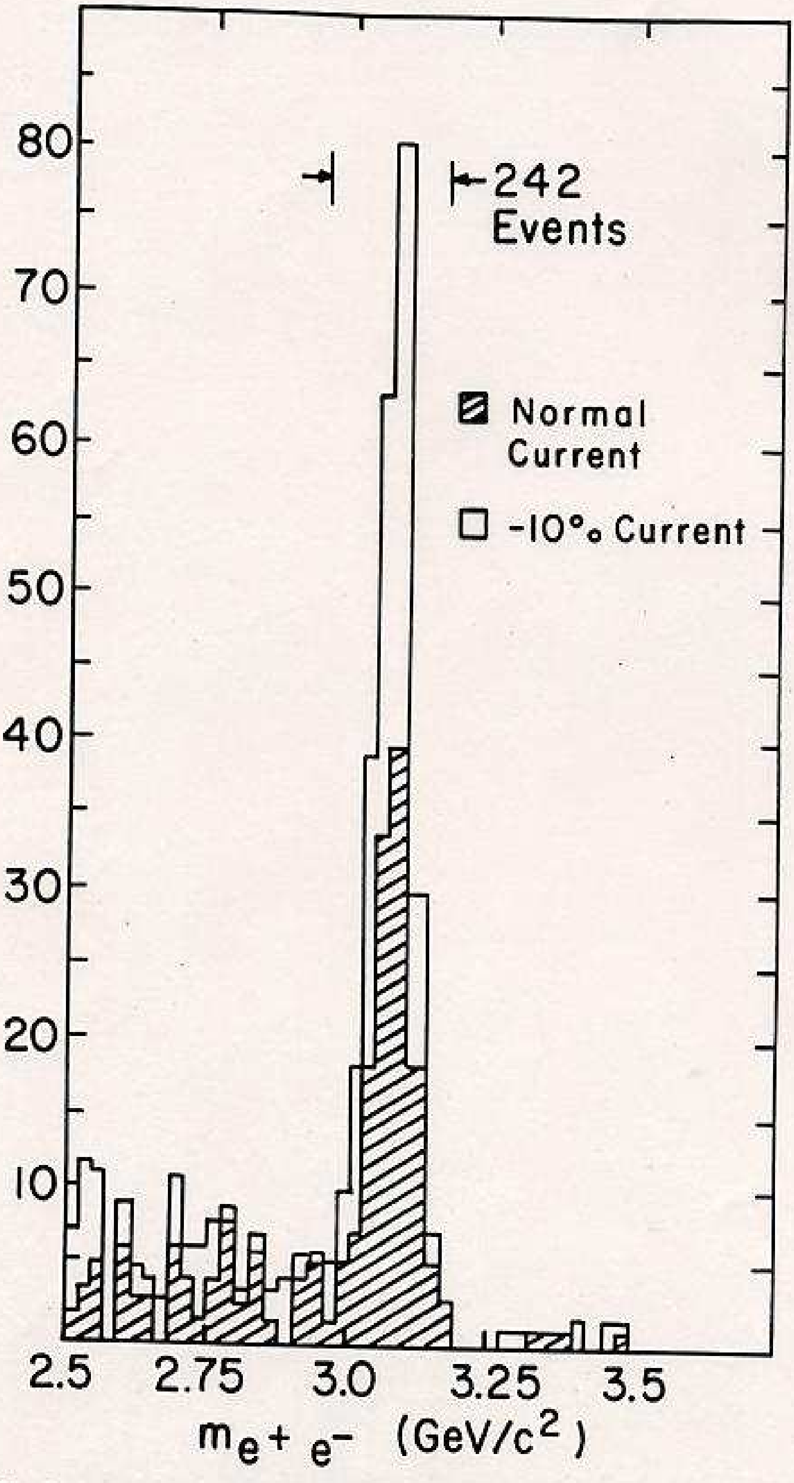
Martin Perl τ

ling @ Brookhaven

$p\,Be \to e^+e^- X$

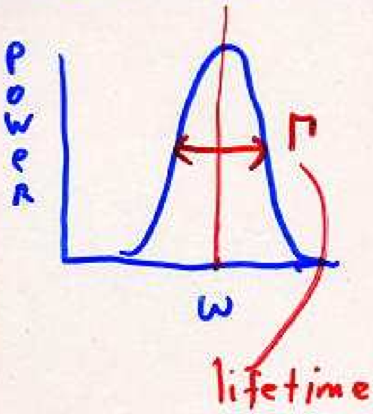


two arm spectrometer



7b. Dielectron data from the BNL experiment showing the peak at 3.1 GeV which was

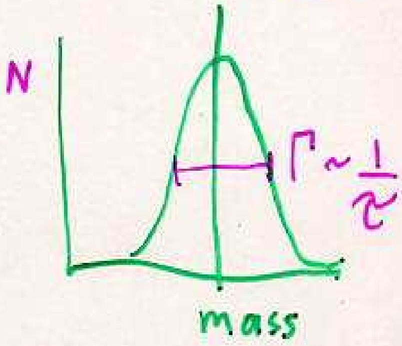
Classical "Resonance"



↓

quantum resonance

$c\bar{c}$



Try to understand $e - \mu$

What is different? Mass, Lepton #

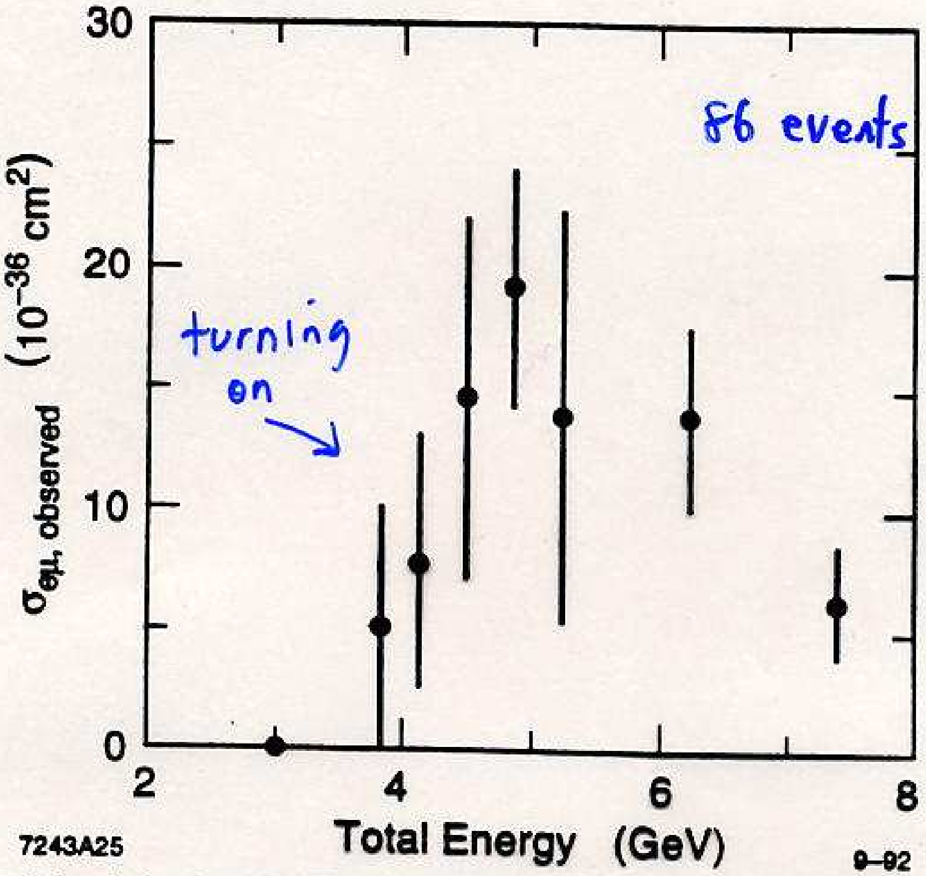


Figure 6. From Perl et al. (1975b): "The observed cross section for the signature eμ events from the Mark I experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events."

$\mu^- \to e^- \bar{\nu}_e \nu_\mu$ ⇒ Look for heavy μ

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

$e^+e^- \to \tau^+\tau^-$

$\hookrightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ Clean signature

$\hookrightarrow e^+ \nu_e \bar{\nu}_\tau$

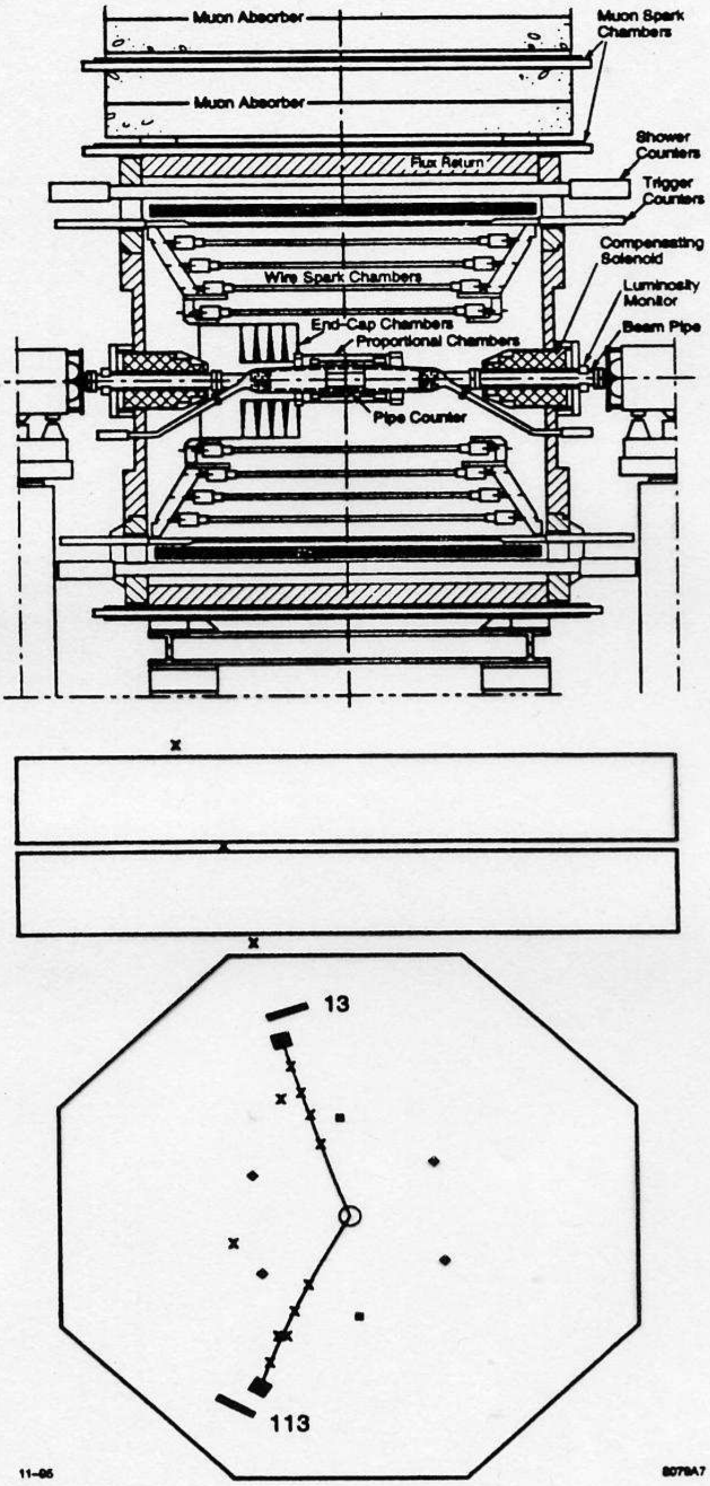
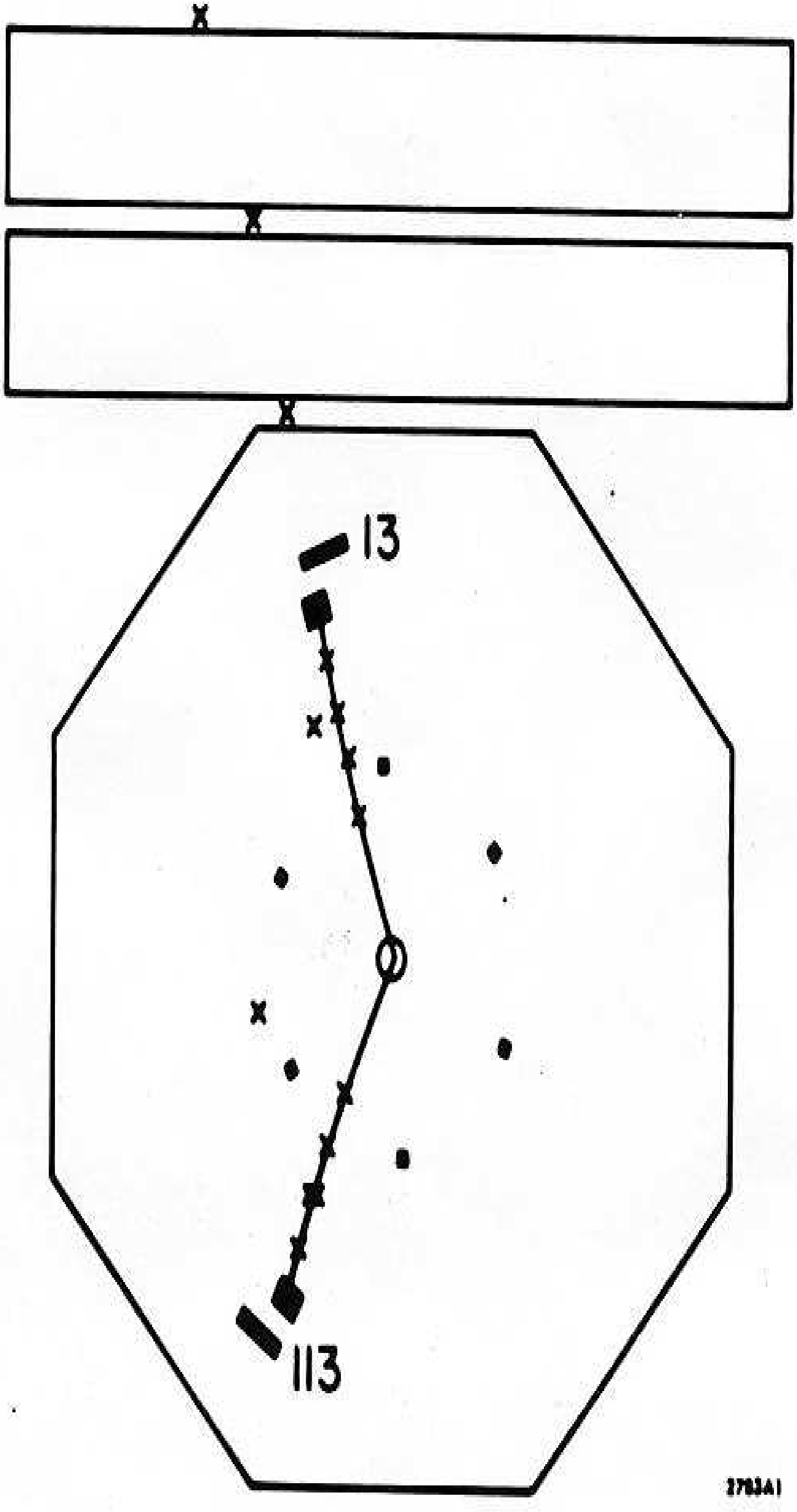


Figure 7. (a) The Mark I detector with the muon tower: (b) one of the first eμ events using the tower. The μ moves upward through the muon detector tower and the e moves downward. The numbers 13 and 113 give the relative amounts of electromagnetic shower energy deposited by the μ and e. The six square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


13
113
2783A1

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>

best mariAM '82 PRL <u>49</u>, 993

look it up in library

1.000024±0.000078	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^-

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

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

VALUE	*DOCUMENT ID*
(2±8) × 10^{-5} 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 85, KINOSHITA 84, COMBLEY 81, FARLEY 79, and CALMET 77.

VALUE (units 10^{-6})	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1165.9230±0.0084	COHEN	87	RVUE		1986 CODATA value

• • • We do not use the following data for averages, fits, limits, etc. • • •

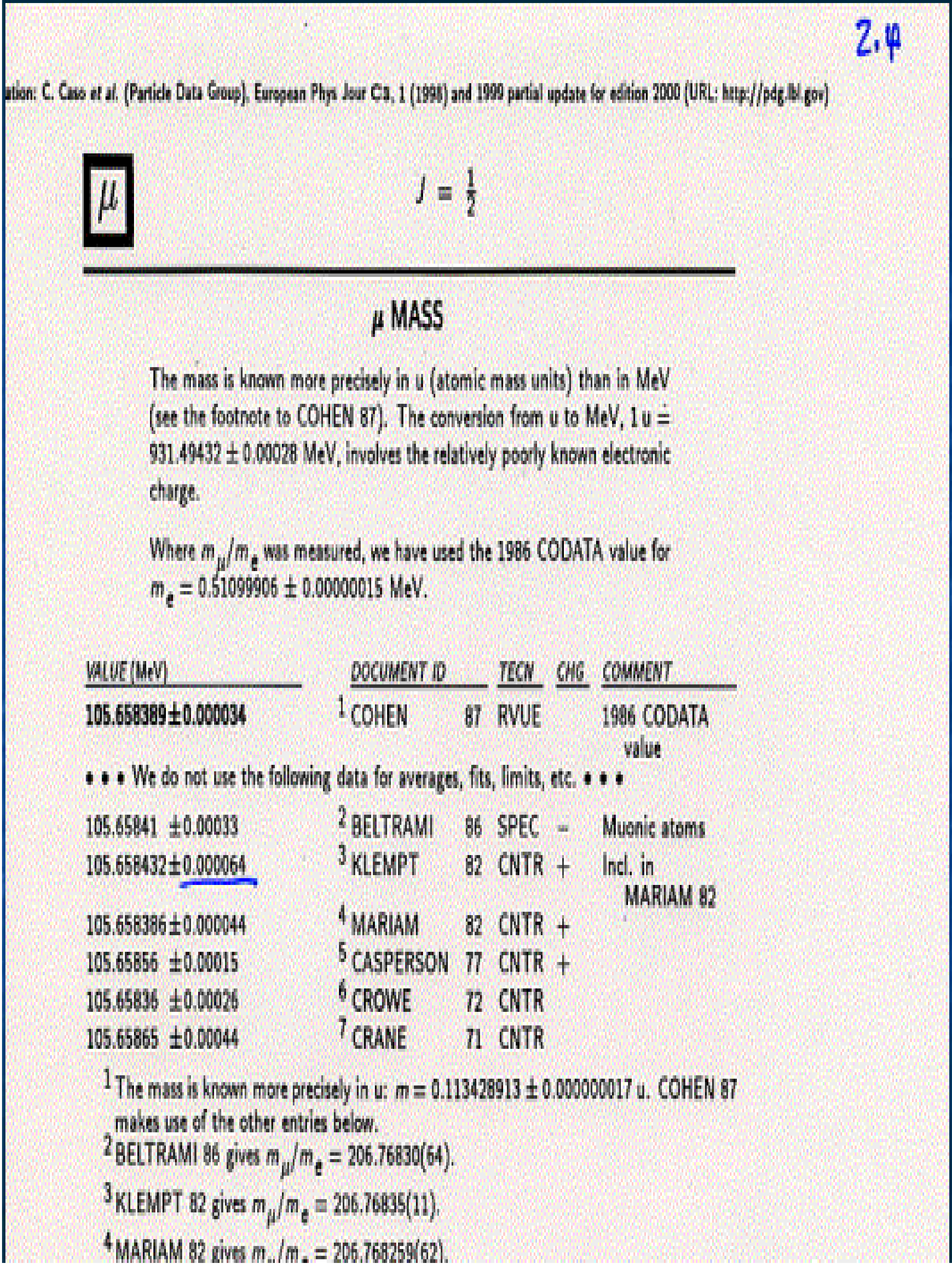
1165.910 ±0.011	[8] BAILEY	79	CNTR	+	Storage ring
1165.937 ±0.012	[8] BAILEY	79	CNTR	−	Storage ring
1165.923 ±0.0085	[8] BAILEY	79	CNTR	±	Storage ring
1165.922 ±0.009	[8] BAILEY	77	CNTR	±	Storage ring
1166.16 ±0.31	BAILEY	68	CNTR	±	Storage rings
1162.0 ±5.0	CHARPAK	62	CNTR	+	

[8] 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.

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

A test of *CPT* invariance.

VALUE (units 10^{-8})	*DOCUMENT ID*	
−2.6±1.6	BAILEY	79



2.4

ation: C. Caso *et al.* (Particle Data Group), European Phys Jour C3, 1 (1998) and 1999 partial update for edition 2000 (URL: http://pdg.lbl.gov)

μ

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

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, $1\ \mathrm{u} \doteq 931.49432 \pm 0.00028$ MeV, involves the relatively poorly known electronic charge.

Where m_μ/m_e was measured, we have used the 1986 CODATA value for $m_e = 0.51099906 \pm 0.00000015$ MeV.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*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] KLEMPT	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] KLEMPT 82 gives $m_\mu/m_e = 206.76835(11)$.

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

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 obselete pion mass are no longer shown; they were in any cass less restrive than ASSAMAGAN 96.

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.19	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] NATALE	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] GAEMERS	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 $\pi^\pm$ 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 FELDMAN 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, 0.29, and 0.19 MeV, respectively.

[2] ASSAMAGAN 96 measurement of p_μ from $\pi^+ \rightarrow \mu^+ \nu_\mu$ at rest combined with JECKELMANN 94 Solution B pion mass yields $m_\nu^2 = -0.016 \pm 0.023$ with corresponding Bayesian limit listed above. If Solution A is used, $m_2 = -0.143 \pm 0.024$ MeV^2. 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.

2.7

[5] MAYLE 93 recalculates 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] There 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] NATALE 91 published result multiplied by $\sqrt{8}\sqrt{4}$ at the advice of the author.

[10] GRIFOLS 90B estimated error is a factor of 3.

[11] GAEMERS 89 published result (< 0.03) corrected via the GANDHI 91 erratum.

[12] ANDERHUB 82 kinematics is insensitive to the pion mass.

$m_{\nu_2} - m_{\overline{\nu}_2}$

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	ν_μ, $\overline{\nu}_\mu$ at LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
			[14] BILLER 98	ASTR	m_ν= 0.05–1 eV
$> 2.8 \times 10^{15}$			[15,16] BLUDMAN 92	ASTR	$m_\nu < 50$ eV
none 10^{-12} – 5×10^4			[17] DODELSON 92	ASTR	m_ν=1–300 keV
$> 6.3 \times 10^{15}$			[16,18] CHUPP 89	ASTR	$m_\nu < 20$ eV
$> 1.7 \times 10^{15}$			[16] KOLB 89	ASTR	$m_\nu < 20$ eV
$> 3.3 \times 10^{14}$			[19,20] VONFEILIT... 88	ASTR	
> 0.11	90	0	[21] FRANK 81	CNTR	$\nu\overline{\nu}$ LAMPF
			[22] HENRY 81	ASTR	m_ν= 16–20 eV
			[23] KIMBLE 81	ASTR	m_ν= 10–100 eV
			[24] REPHAELI 81	ASTR	m_ν= 30–150 eV
			[25] DERUJULA 80	ASTR	m_ν= 10–100 eV
$> 2 \times 10^{21}$			[26] STECKER 80	ASTR	m_ν= 10–100 eV
$> 1.0 \times 10^{-2}$	90	0	[21] BLIETSCHAU 78	HLBC	ν_μ, CERN GGM
$> 1.7 \times 10^{-2}$	90	0	[21] BLIETSCHAU 78	HLBC	$\overline{\nu}_\mu$, CERN GGM
$> 2.2 \times 10^{-3}$	90	0	[21] BARNES 77	DBC	ν, ANL 12-ft
$> 3. \times 10^{-3}$	90	0	[21] BELLOTTI 76	HLBC	ν, CERN GGM
$> 1.3 \times 10^{-2}$	90	1	[21] BELLOTTI 76	HLBC	$\overline{\nu}$, CERN GGM

[13] KRAKAUER 91 quotes the limit $\tau/m_{\nu_1} > (0.75a^2 + 21.65a + 26.3)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta$

$= (1/2)(1 + a\cos\theta)$ The parameter $a = 0$ 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 $a = -1$).

[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, $> 1.2 \times 10^{21}$ 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 $\overline{\nu}_\mu \rightarrow \overline{\nu}_e \gamma$.

[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] REPHAELI 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*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<0.4	95	9800	KALBFLEISCH	79	SPEC		
<2.0	99	77	ALSPECTOR	76	SPEC	0	>5 GeV ν
<4.0	99	26	ALSPECTOR	76	SPEC	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)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.2 \times 10^{-19}) m_\nu \mu_B$ 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, $\mu(\nu_2) < 0.51 \times 10^{-13}\ \mu_B$.

VALUE ($10^{-10}\ \mu_B$)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<$ 8.5	90	AHRENS	90	CNTR	$\nu_\mu e \rightarrow \nu_\mu e$
$<$ 7.4	90	[27] KRAKAUER	90	CNTR	LAMPF $(\nu_\mu, \overline{\nu}_\mu)e$ elast.

Good reference in LIBRARY here: Particle physics : One hundred years of discovery.

Points to all the classic experiments.