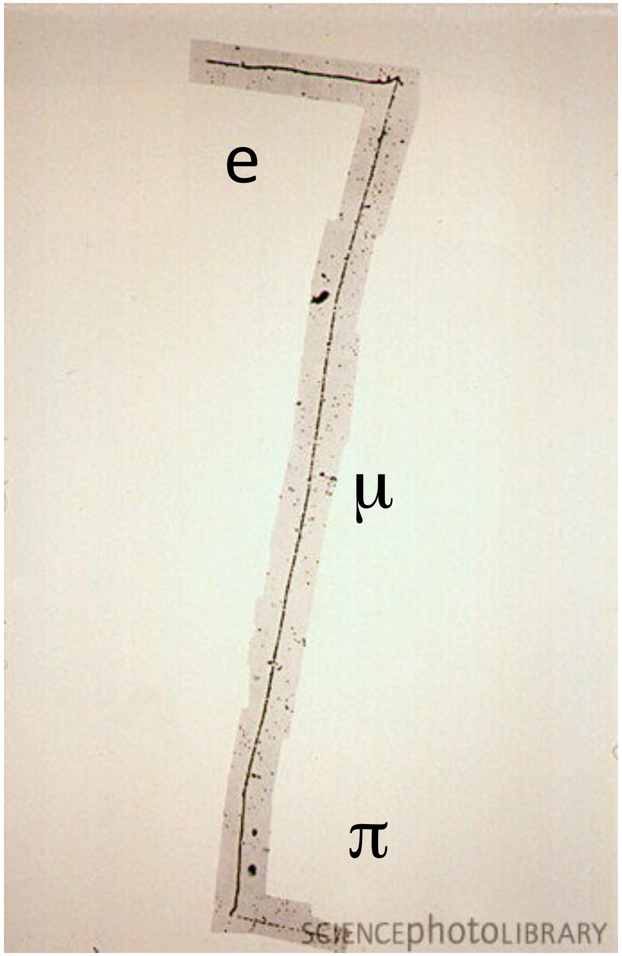
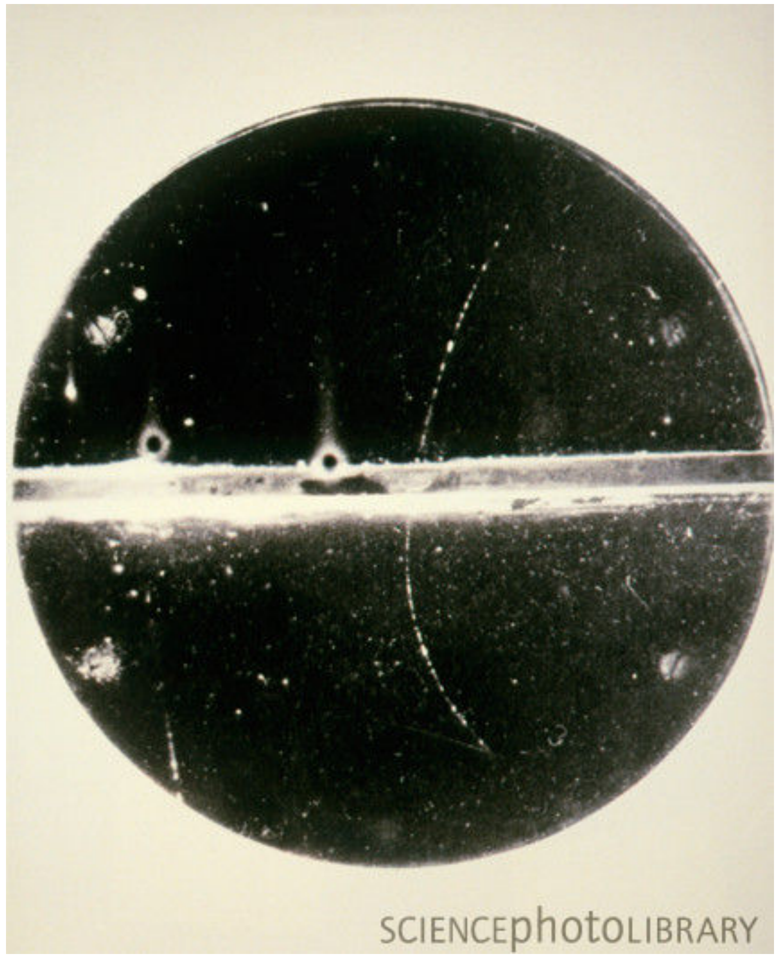
Discovery of pion



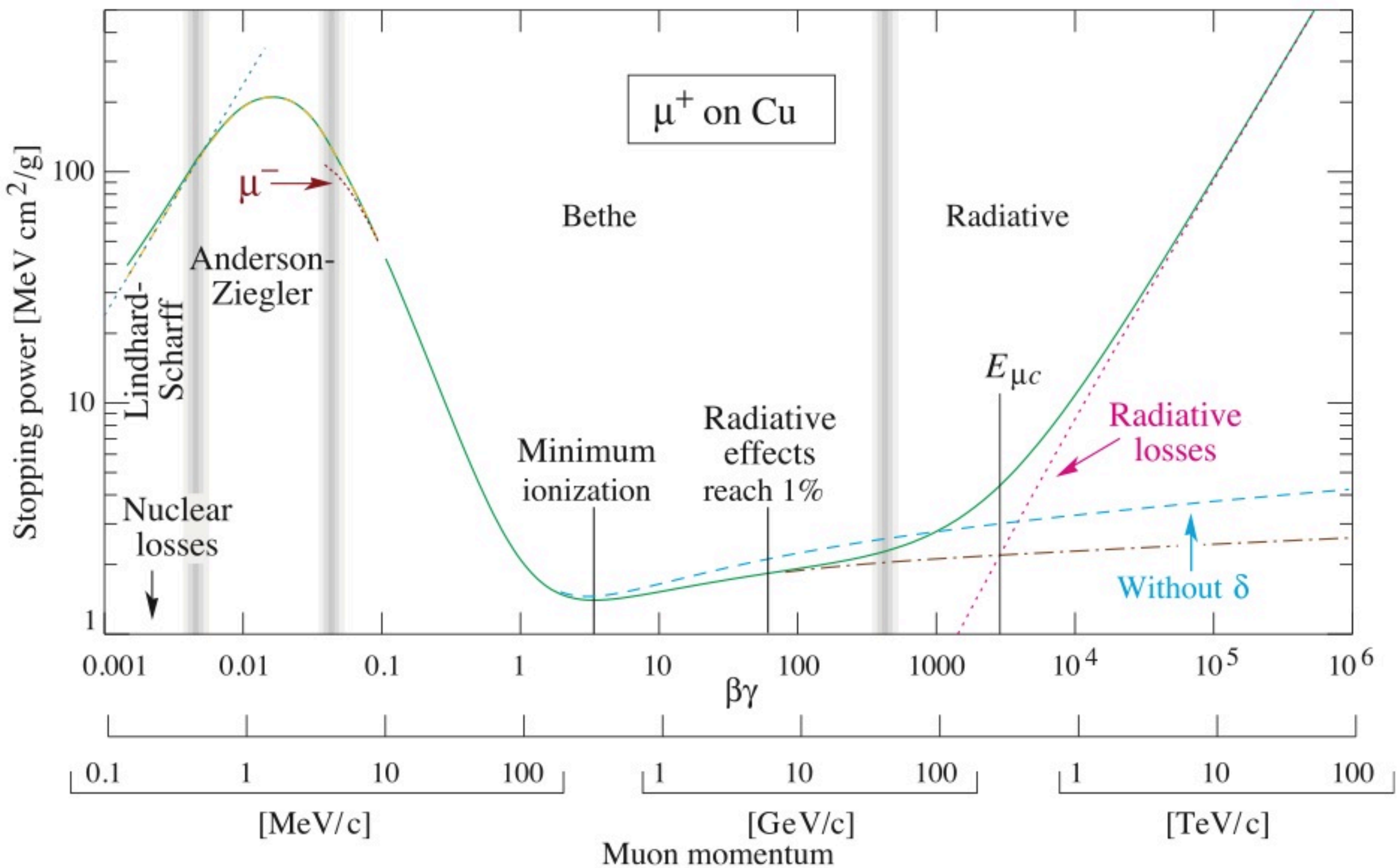
Cosmic rays
Photographic plate
Powell, 1947

Discovery of positron



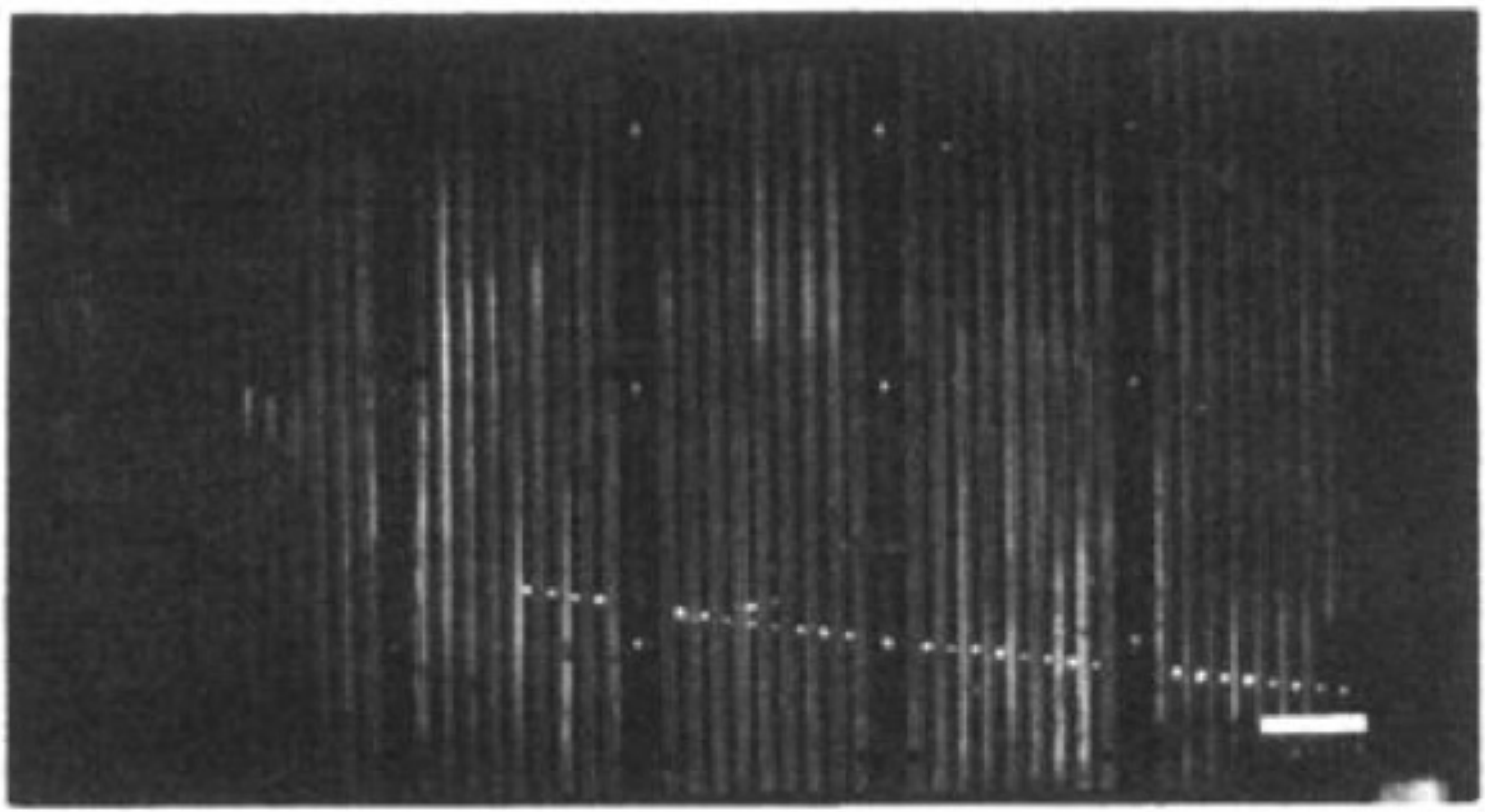
Cosmic rays
Cloud chamber photograph
Anderson, 1932

Stopping Power



J. Beringer *et al.* (Particle Data Group), Phys. Rev. D**86**, 010001 (2012)

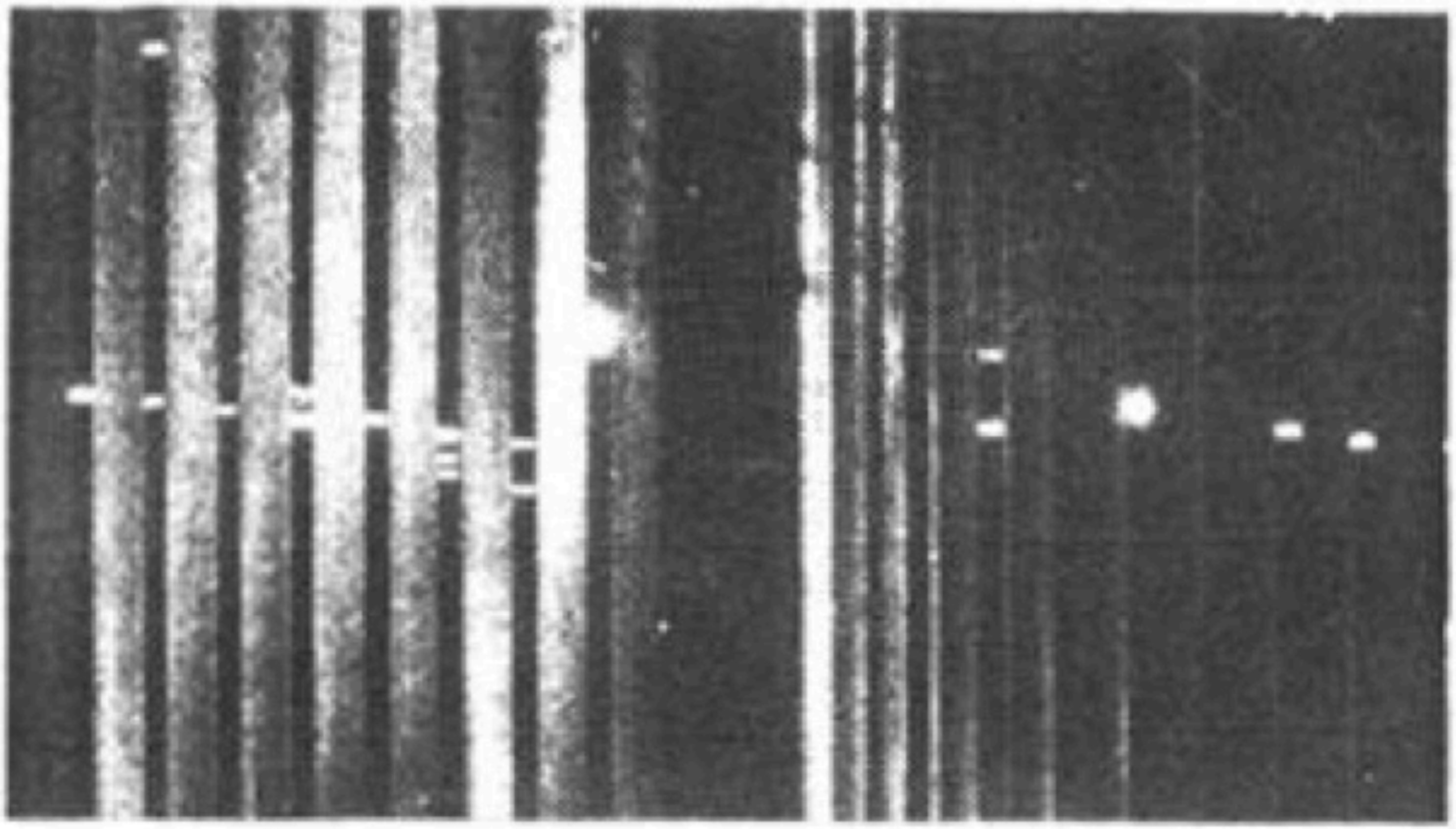
Muon



A

Danby, G., et al., Phys.Rev.Lett,9,36(1962)

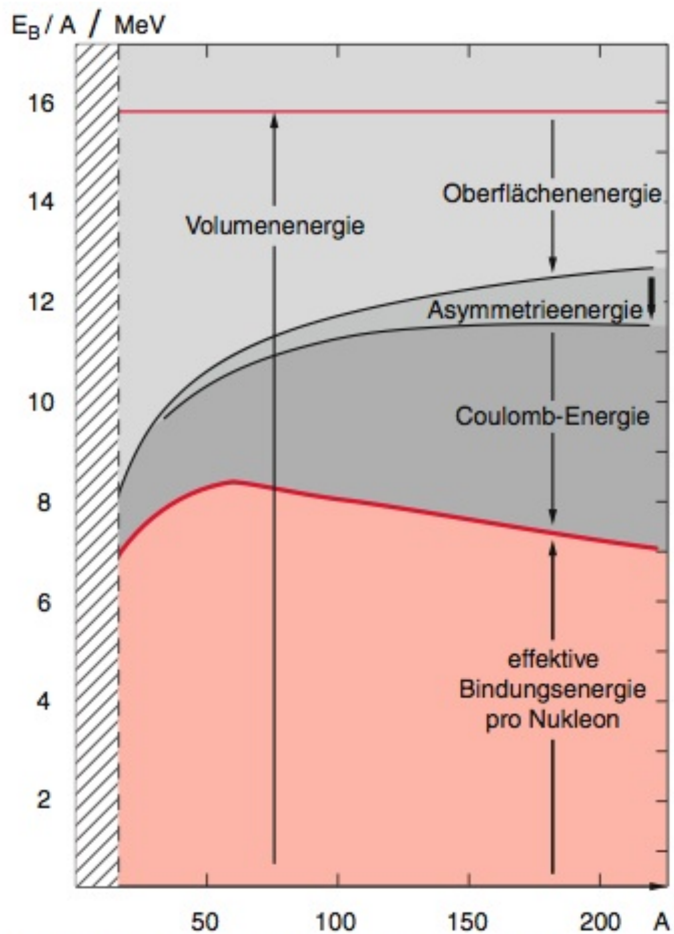
Electron



A

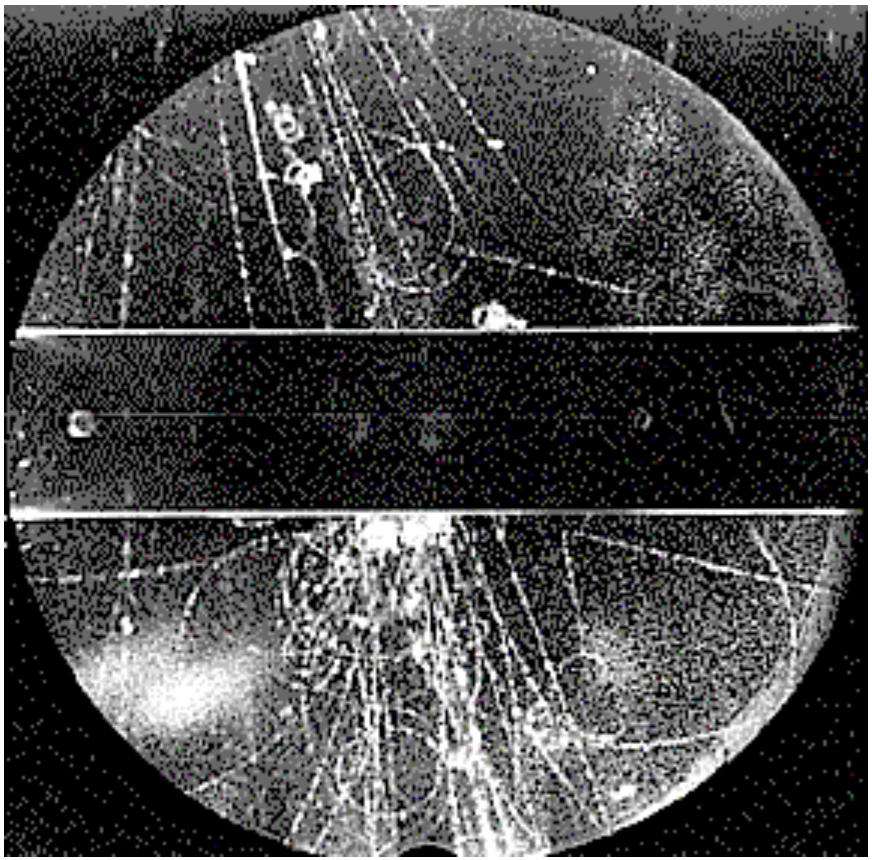
Danby, G., et al., Phys.Rev.Lett,9,36(1962)

Binding Energy



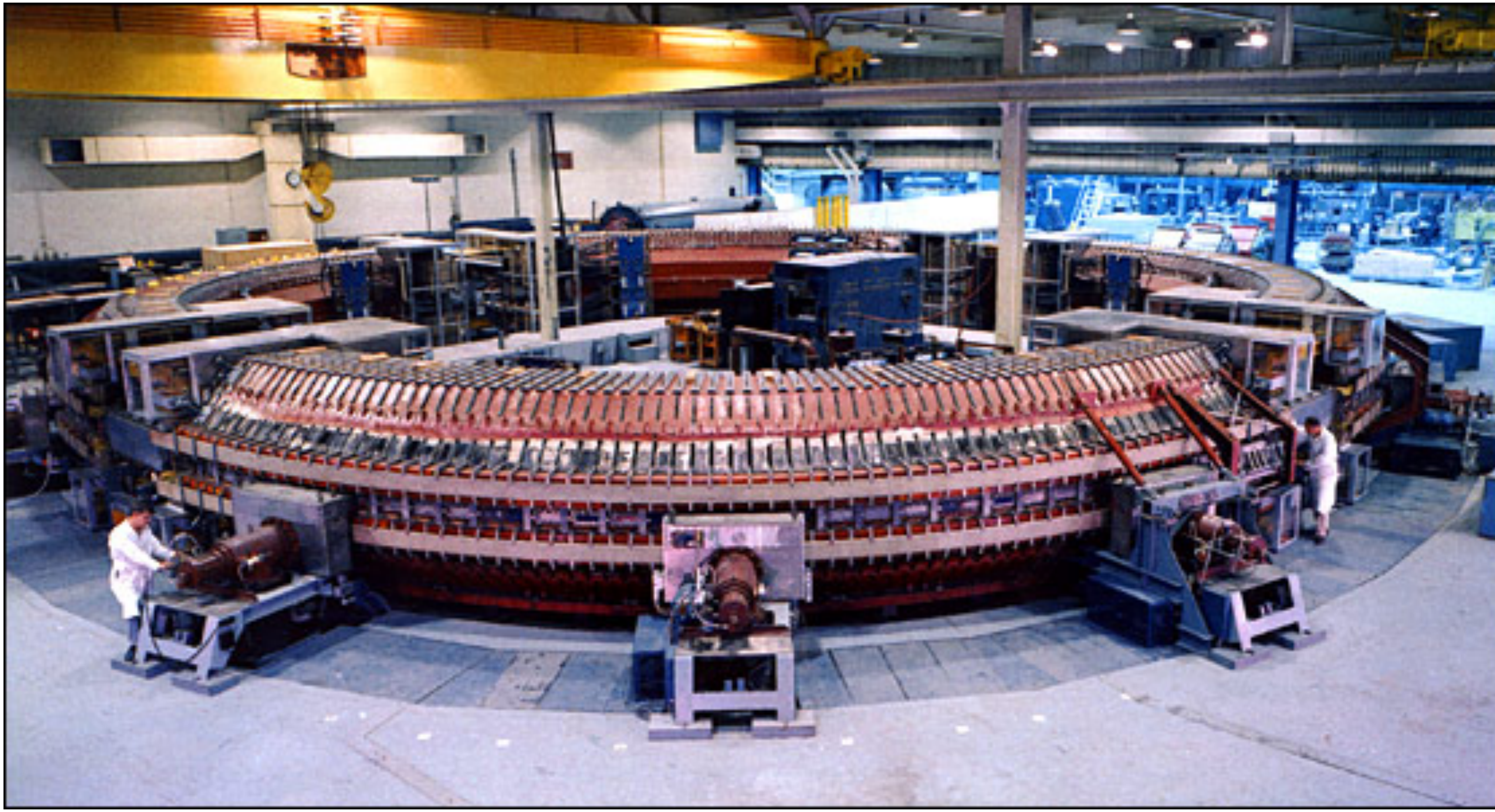
Demtroeder, Experimentalphysik, Springer

Discovery of strange particles



Cosmic rays
Cloud chamber photograph
Rochester, Butler, 1947

Cosmotron, BNL, 1952



First BeV accelerator

Discovery of Ω^-

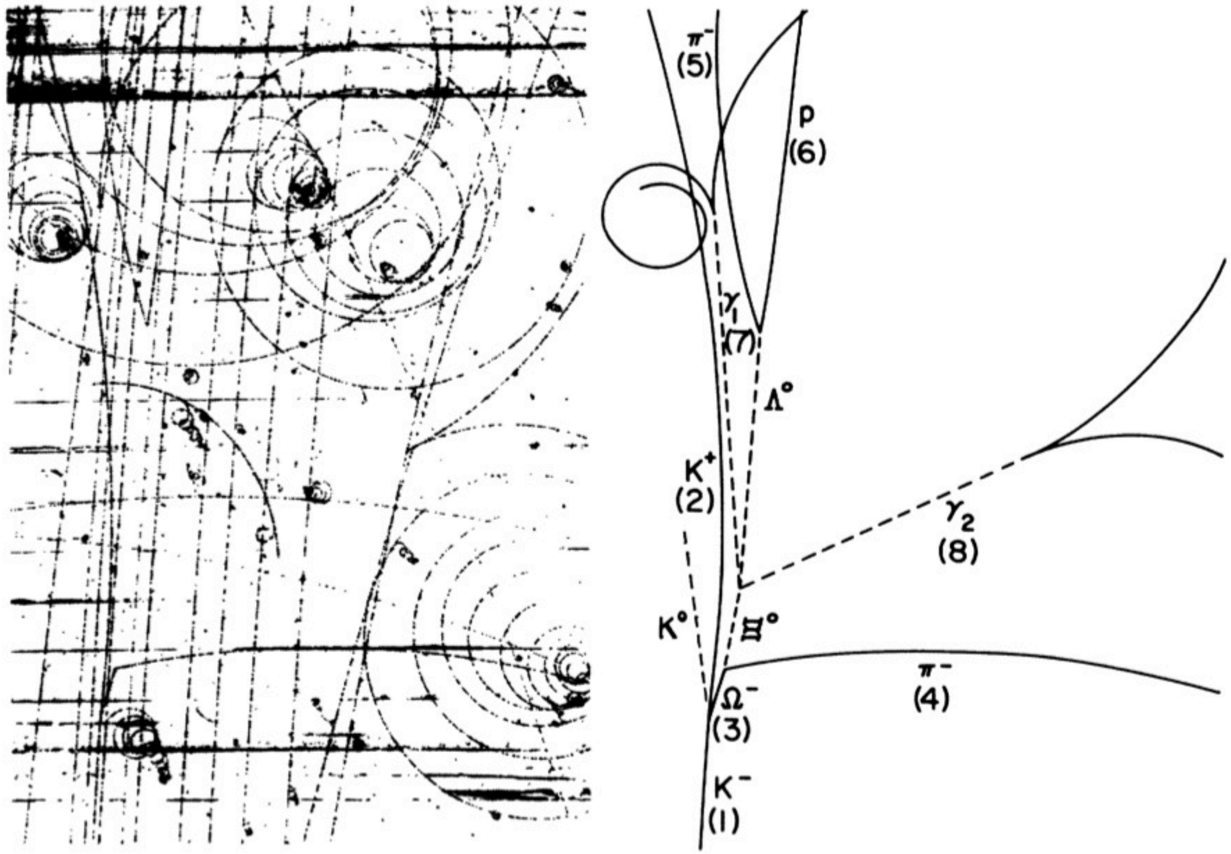
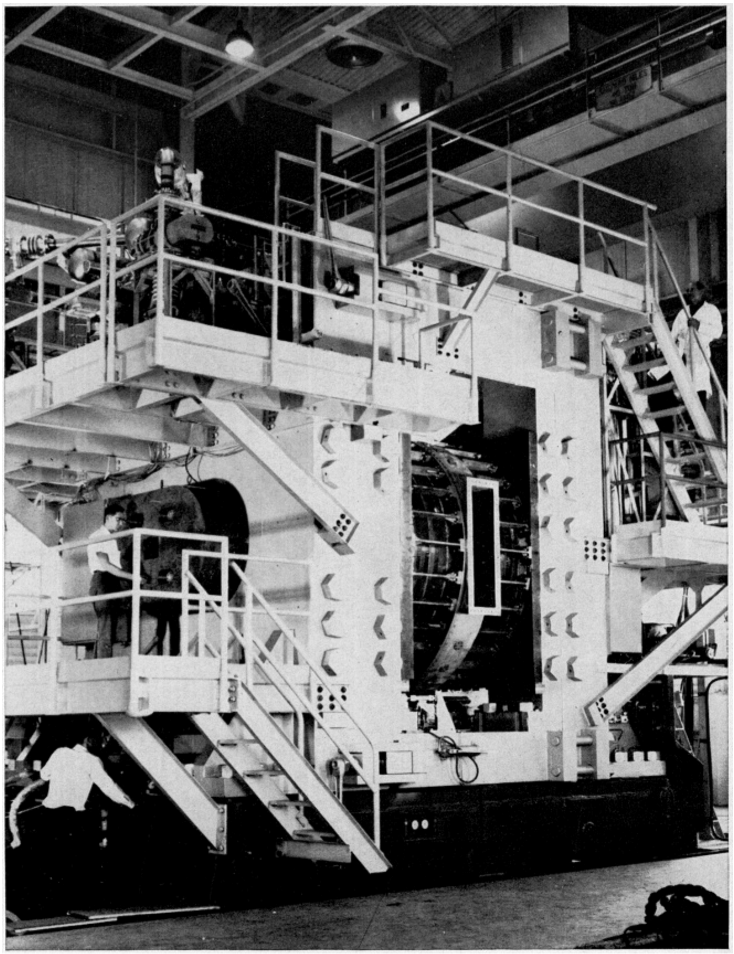


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

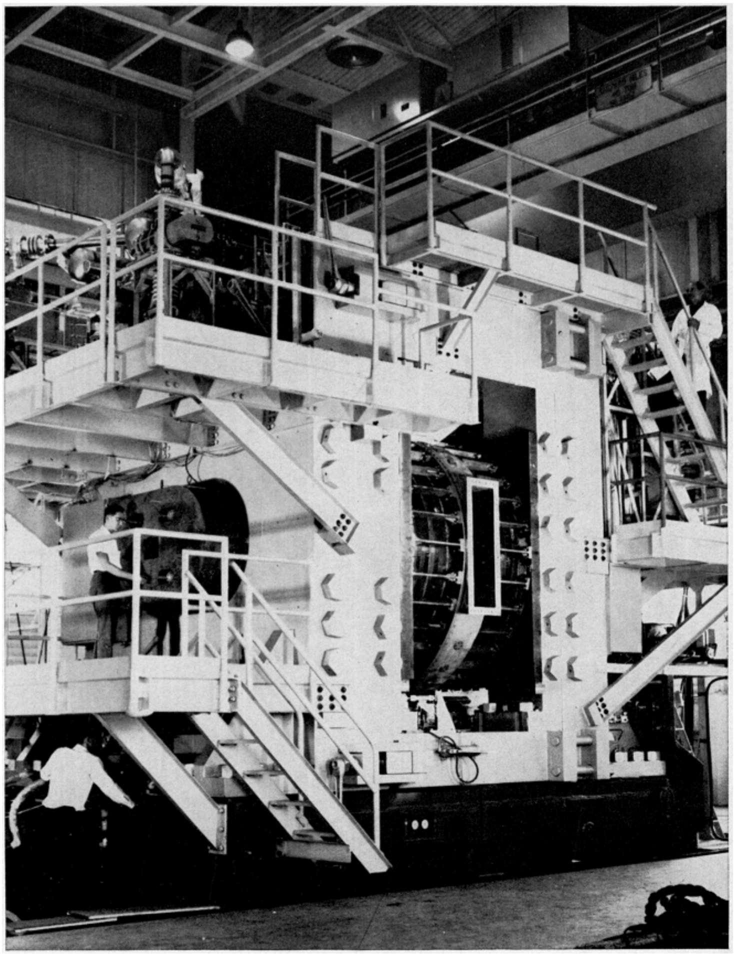
Barnes et al., Phys. Rev. Lett., 12, 204 (1964)

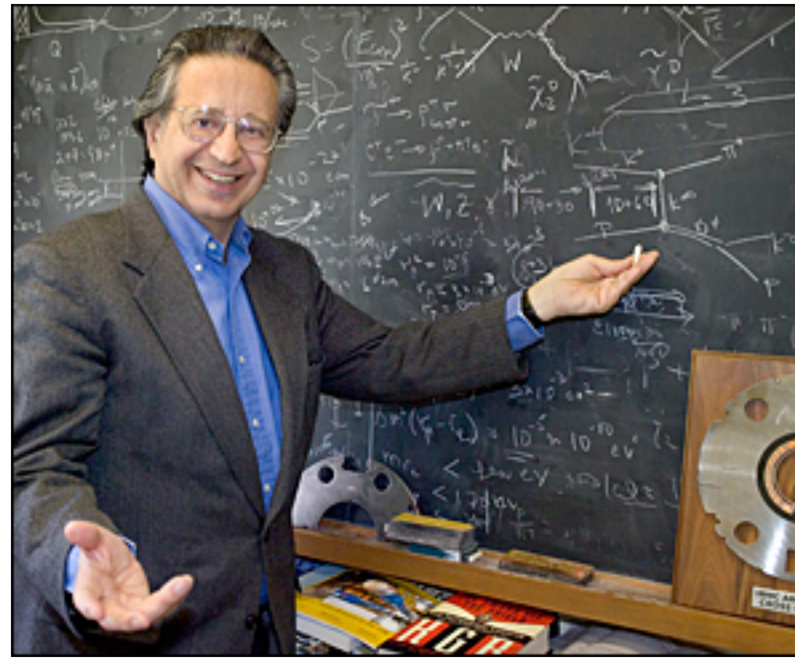
BNL 80 inch Bubble Chamber, 1964



Fowler, Samios, Scientific American, 211, 36 (1964)

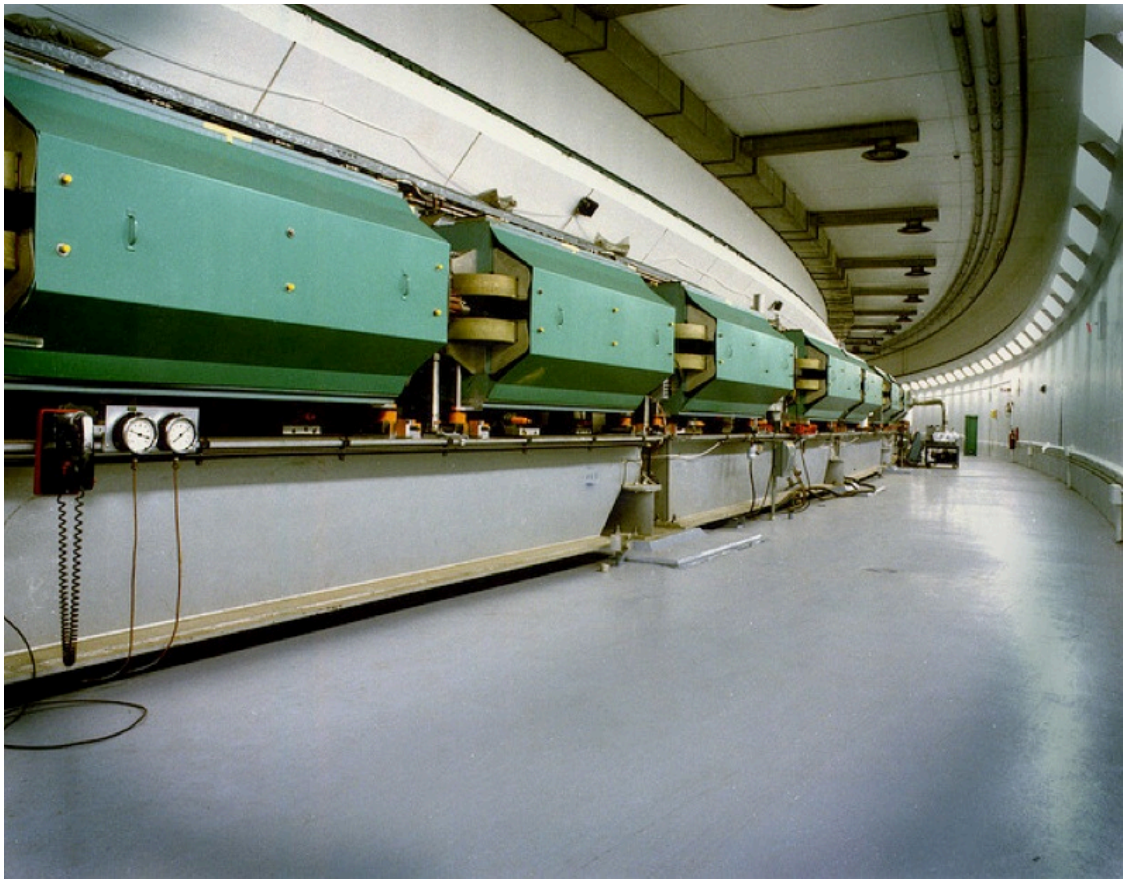
BNL 80 inch Bubble Chamber, 1964



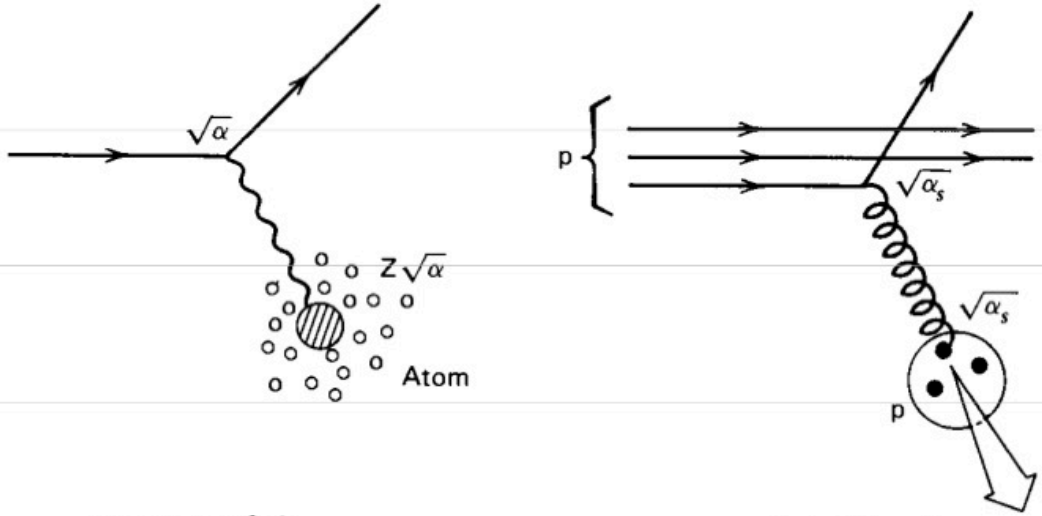


Fowler, Samios, Scientific American, 211, 36 (1964)

AGS, BNL, 1960



- Strong focusing through alternating gradient magnets (Courant, Livingston, Snyder)
- 33 GeV
- not 100 times more steel (200,000 tons) than 3.3 GeV Cosmotron, only twice



Probability $Z^2\alpha^2$
(a)

Probability α_s^2
(b)

DIS

DIS

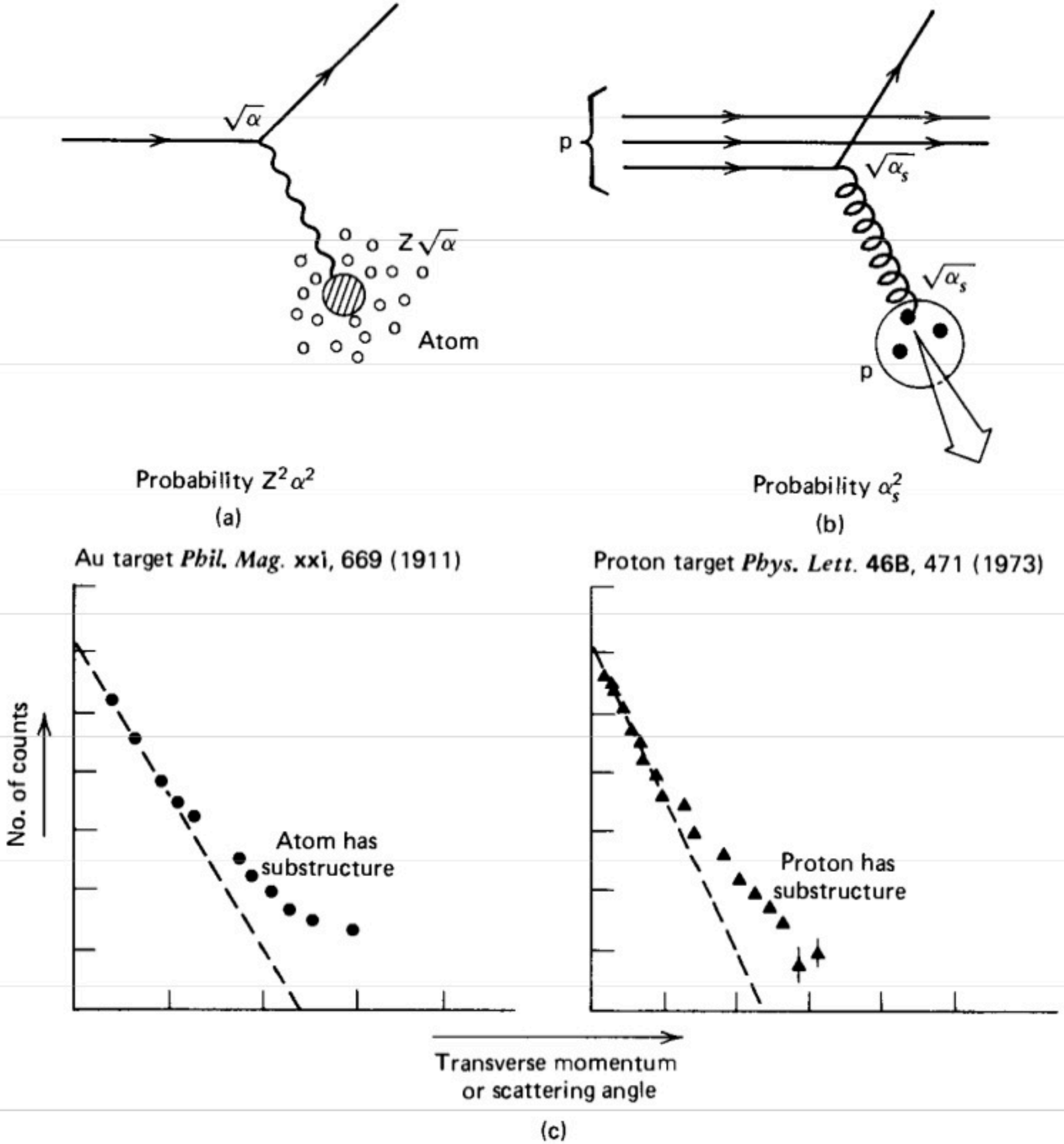
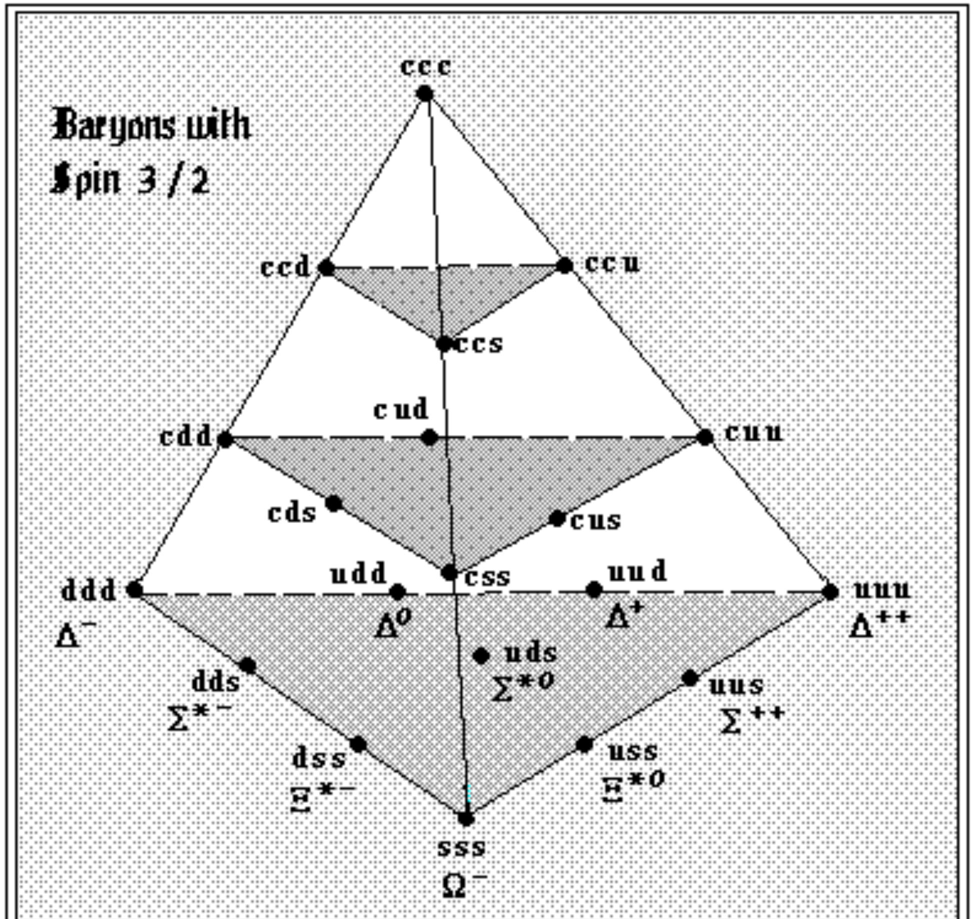


Fig. 1.10 (a) Inelastically scattered charged particle beam reveals the substructure of the atom. (b) Inelastically scattered proton beam reveals the quark structure of the proton target. (c) Experimental results.

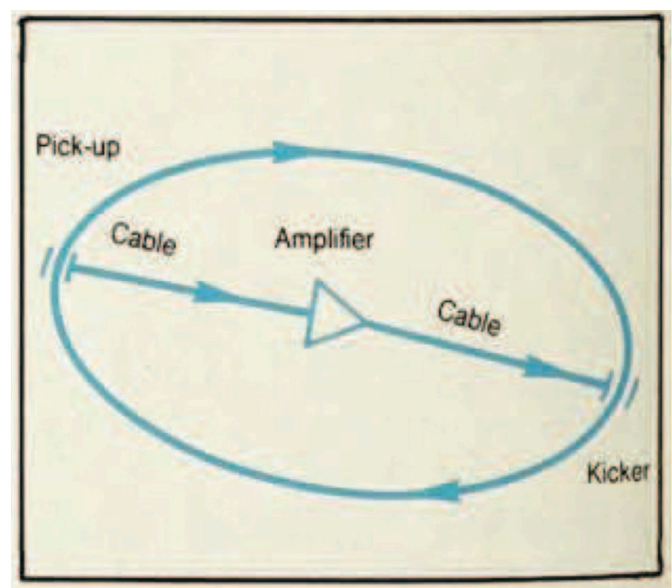
Halzen, Martin, Quarks and Leptons, Wiley, 1984

Supermultiplets



CERN ISR: Intersecting Storage Rings, 1971

- 62.4 GeV com E
- Fed by PS (Proton Synchrotron) with 25 GeV p
- DIS
- Simon van der Meer's stochastic cooling



Rubbia, Cline, Physics Today, 33, 44 (1980)

CERN SPS (Super Proton Synchrotron), 1981

- 450 GeV
- Also ppbar with 540 GeV com E
- Discovery of W, 1983
- Nobel Prize: Rubbia, van der Meer, 1984
- Still in use for experiments and as pre-accelerator for LHC

W discovery

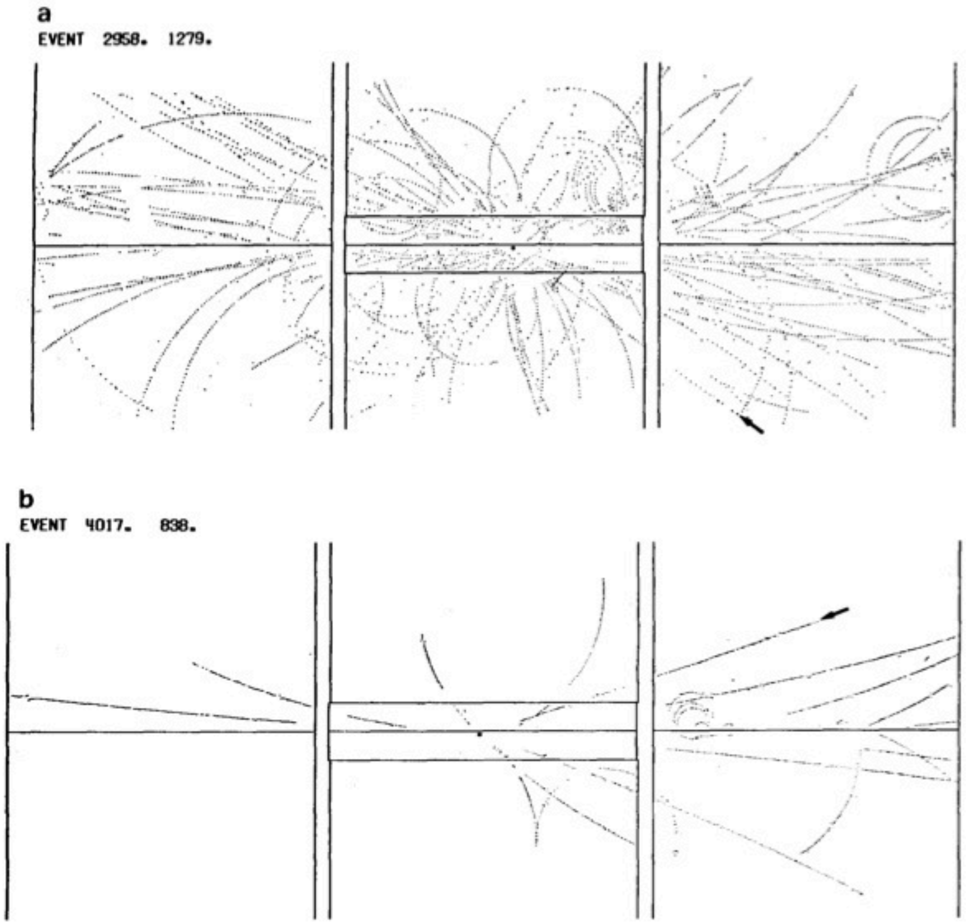


Fig. 6. The digitization from the central detector for the tracks in two of the events which have an identified, isolated, well-measured high-p_T electron: (a) high-multiplicity, 65 associated tracks; (b) low-multiplicity, 14 associated tracks.

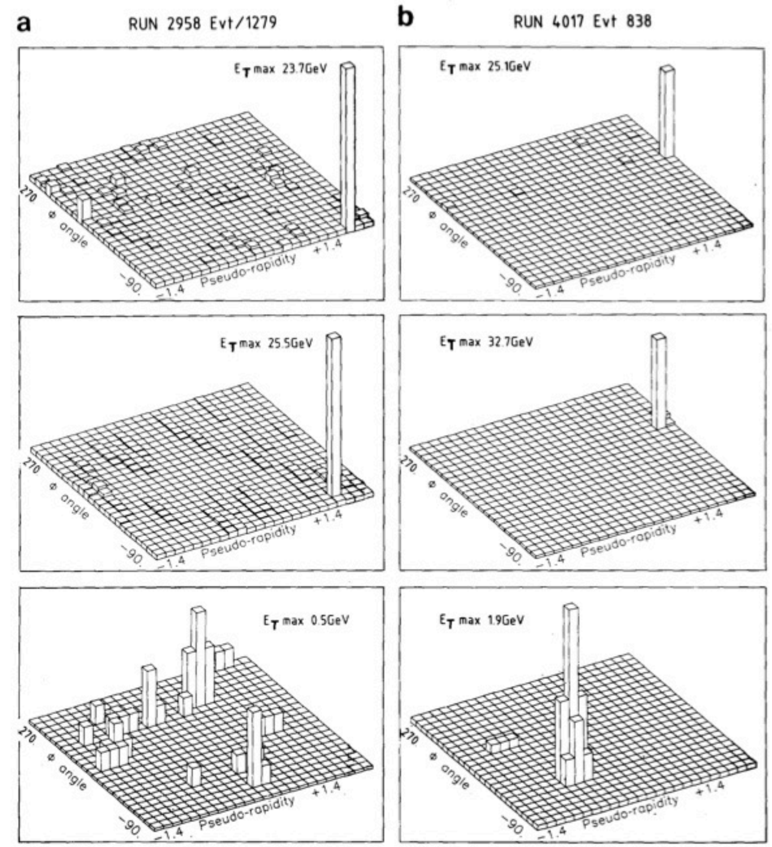
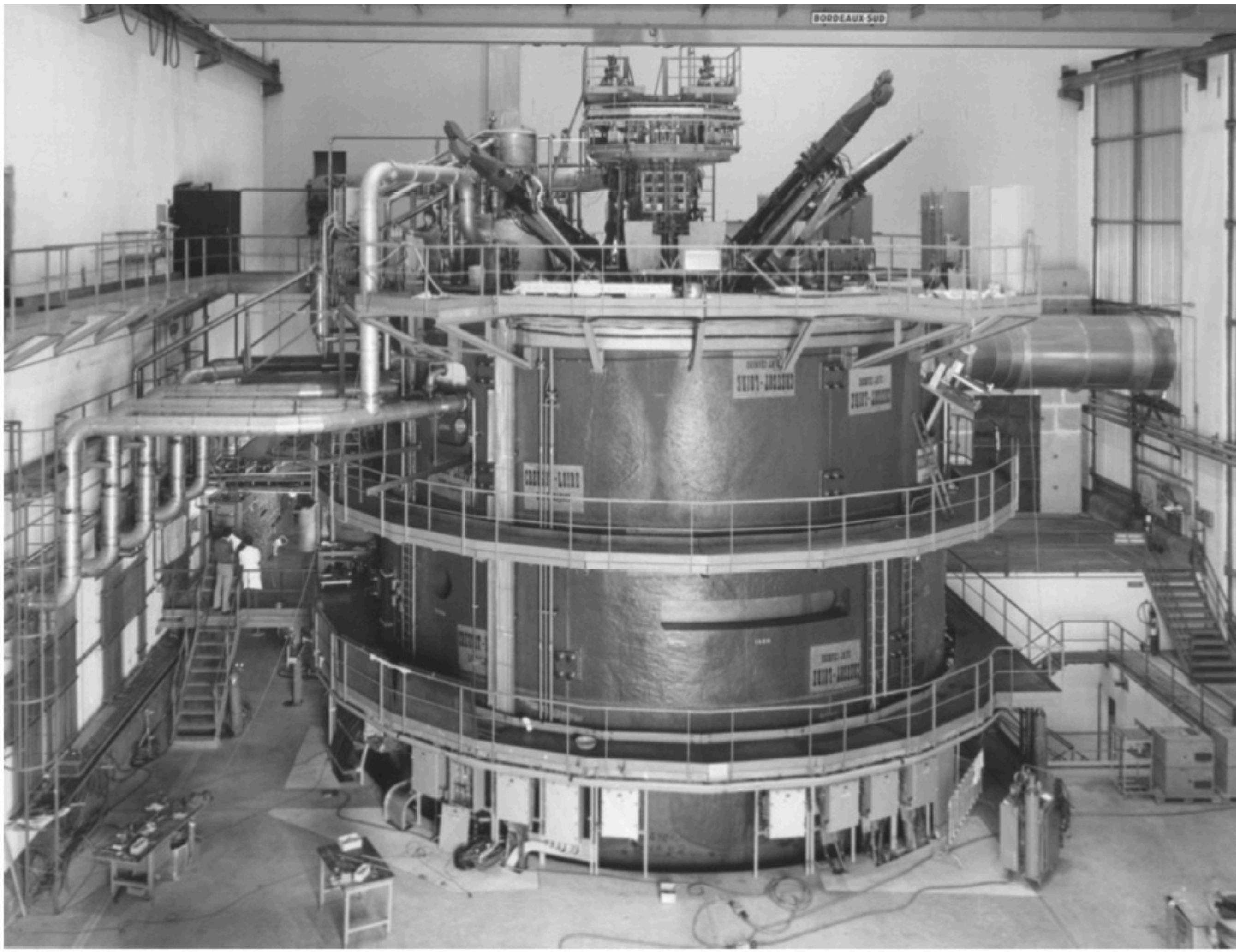


Fig. 7. The energy deposited in the cells of the central calorimetry and the equivalent plot for track momenta in the central detector for the two events of fig. 6. The top diagram shows the electromagnetic cells, the middle shows the central detector tracks, and the bottom plot, with a very much increased sensitivity, shows the energy in the hadron calorimeter. The plots reveal no hadronic energy behind the electron and no jet structure; (a) high-multiplicity; (b) low-multiplicity.

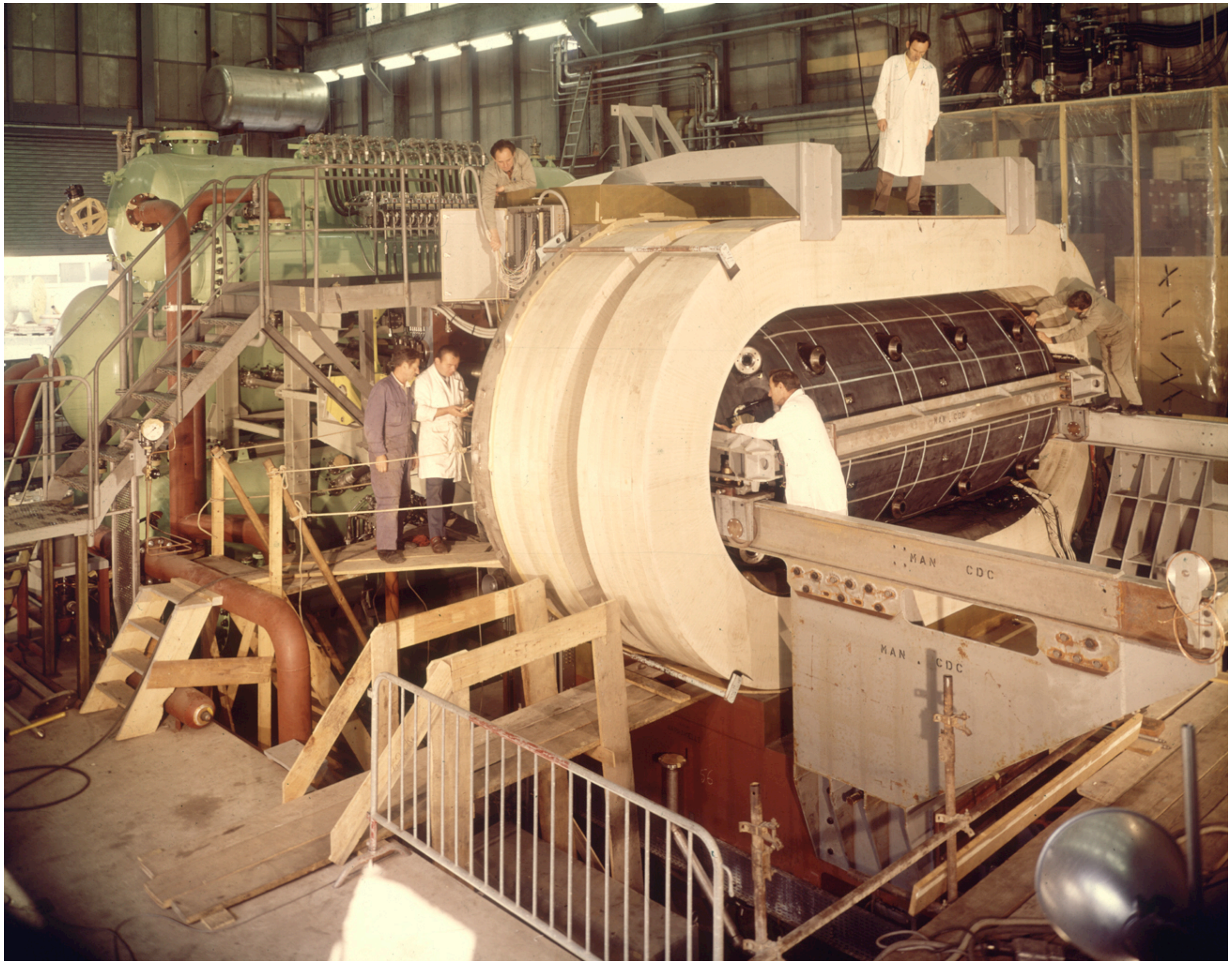
Arnison et al., Phys. Lett., 122B, 103 (1983)

Big European Bubble Chamber (BEBC)



- CERN
- 35 m^3 of liquid hydrogen
- 1973: PS
- 1977: SPS
- νDIS

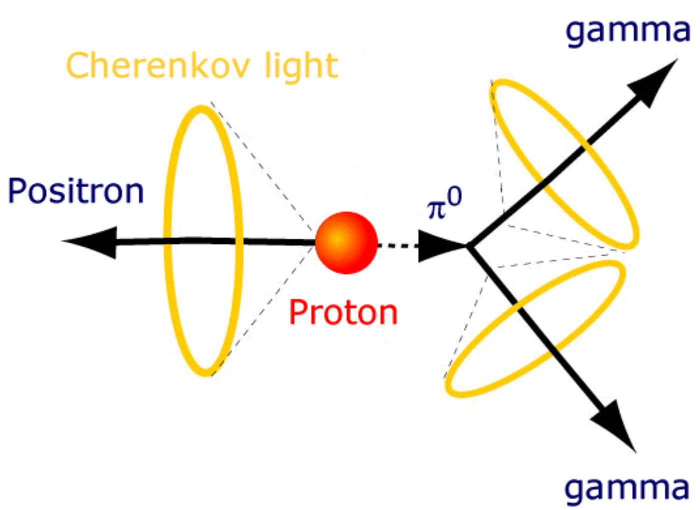
Gargamelle Bubble Chamber

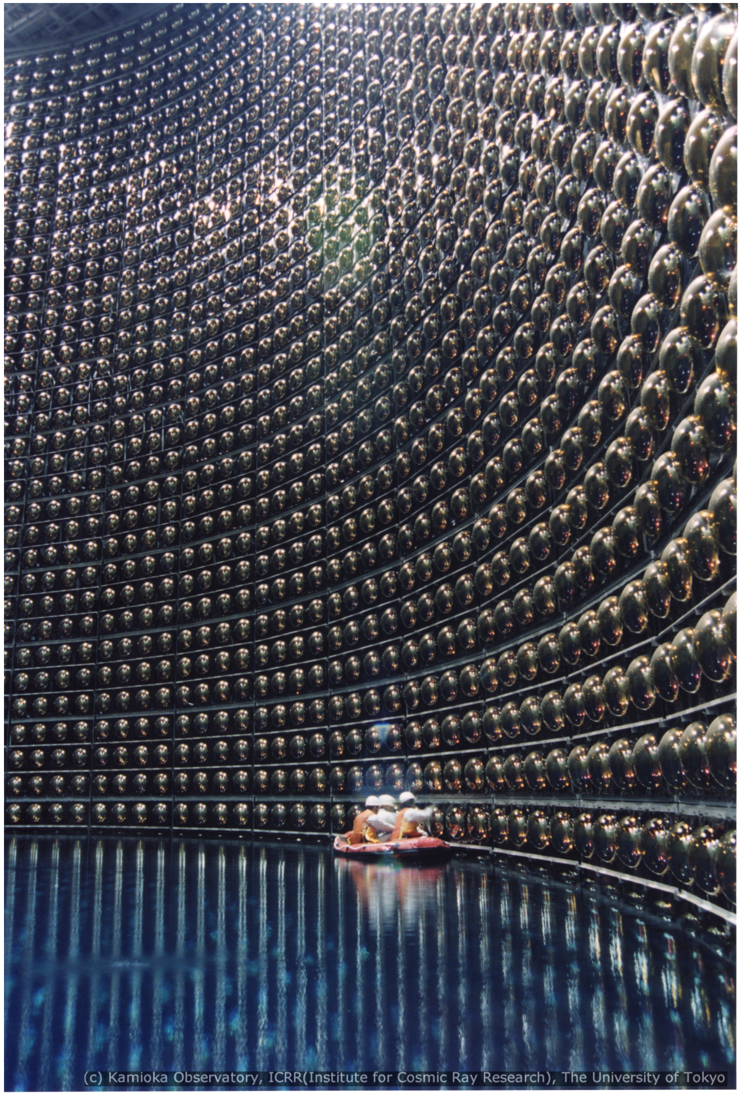


- Discovery of Neutral Current, 1973
- $\nu + N \to \nu +$ hadrons
- Hasert et al., Phys. Lett., B46, 138 (1973)
- 18 t liquid Freon (denser)
- PS beam

Super-Kamiokande

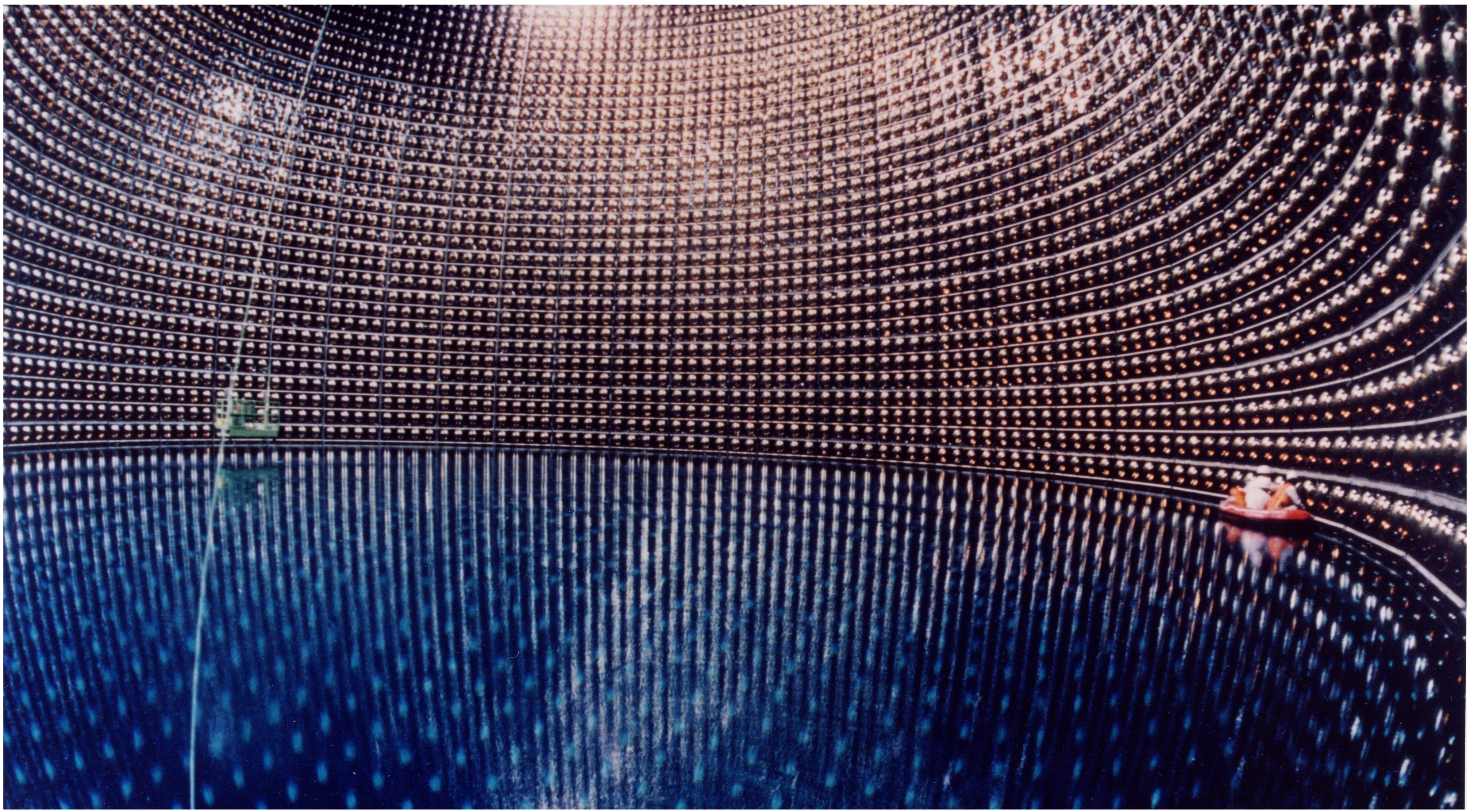
- 50,000 t of pure water
- Cylindrical tank: d = 40 m, h = 40 m
- 11,000 20 inch + 2,000 8 inch PMT's
- 1,000 m underground in Kamioka mine, Japan
- Started 1996
- First evidence for ν oscillations in 1998





Super-Kamiokande

- 2001 accident: $7,000 of 11,000 PMT's imploded (each tube costs $3,000)
- During refilling after tube replacement worker broke tube → chain reaction
- Restored in 2006



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Note: A square-root sign is to be understood over *every* coefficient, *e.g.*, for $-8/15$ read $-\sqrt{8/15}$.

Notation:

		J	J	...
		M	M	...
m_1	m_2	Coefficients		
m_1	m_2			
.	.			
.	.			

$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\sin\theta\, e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}}\Big(\frac{3}{2}\cos^2\theta - \frac{1}{2}\Big)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta\, e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\phi}$$

1/2×1/2

m_1	m_2	J=1, M=+1
+1/2	+1/2	1

m_1	m_2	J=1, M=0	J=0, M=0
+1/2	−1/2	1/2	1/2
−1/2	+1/2	1/2	−1/2

m_1	m_2	J=1, M=−1
−1/2	−1/2	1

1×1/2

m_1	m_2	J=3/2, M=+3/2
+1	+1/2	1

m_1	m_2	J=3/2, M=+1/2	J=1/2, M=+1/2
+1	−1/2	1/3	2/3
0	+1/2	2/3	−1/3

m_1	m_2	J=3/2, M=−1/2	J=1/2, M=−1/2
0	−1/2	2/3	1/3
−1	+1/2	1/3	−2/3

m_1	m_2	J=3/2, M=−3/2
−1	−1/2	1

2×1

m_1	m_2	J=3, M=+3
+2	+1	1

m_1	m_2	J=3, M=+2	J=2, M=+2
+2	0	1/3	2/3
+1	+1	2/3	−1/3

m_1	m_2	J=3, M=+1	J=2, M=+1	J=1, M=+1
+2	−1	1/15	1/3	3/5
+1	0	8/15	1/6	−3/10
0	+1	2/5	−1/2	1/10

m_1	m_2	J=3, M=0	J=2, M=0	J=1, M=0
+1	−1	1/5	1/2	3/10
0	0	3/5	0	−2/5
−1	+1	1/5	−1/2	3/10

m_1	m_2	J=3, M=−1	J=2, M=−1	J=1, M=−1
0	−1	2/5	1/2	1/10
−1	0	8/15	−1/6	−3/10
−2	+1	1/15	−1/3	3/5

m_1	m_2	J=3, M=−2	J=2, M=−2
−1	−1	2/3	1/3
−2	0	1/3	−2/3

m_1	m_2	J=3, M=−3
−2	−1	1

1×1

m_1	m_2	J=2, M=+2
+1	+1	1

m_1	m_2	J=2, M=+1	J=1, M=+1
+1	0	1/2	1/2
0	+1	1/2	−1/2

m_1	m_2	J=2, M=0	J=1, M=0	J=0, M=0
+1	−1	1/6	1/2	1/3
0	0	2/3	0	−1/3
−1	+1	1/6	−1/2	1/3

m_1	m_2	J=2, M=−1	J=1, M=−1
0	−1	1/2	1/2
−1	0	1/2	−1/2

m_1	m_2	J=2, M=−2
−1	−1	1

3/2×1

m_1	m_2	J=5/2, M=+5/2
+3/2	+1	1

m_1	m_2	J=5/2, M=+3/2	J=3/2, M=+3/2
+3/2	0	2/5	3/5
+1/2	+1	3/5	−2/5

m_1	m_2	J=5/2, M=+1/2	J=3/2, M=+1/2	J=1/2, M=+1/2
+3/2	−1	1/10	2/5	1/2
+1/2	0	3/5	1/15	−1/3
−1/2	+1	3/10	−8/15	1/6

m_1	m_2	J=5/2, M=−1/2	J=3/2, M=−1/2	J=1/2, M=−1/2
+1/2	−1	3/10	8/15	1/6
−1/2	0	3/5	−1/15	−1/3
−3/2	+1	1/10	−2/5	1/2

m_1	m_2	J=5/2, M=−3/2	J=3/2, M=−3/2
−1/2	−1	3/5	2/5
−3/2	0	2/5	−3/5

m_1	m_2	J=5/2, M=−5/2
−3/2	−1	1

2×1/2

m_1	m_2	J=5/2, M=+5/2
+2	+1/2	1

m_1	m_2	J=5/2, M=+3/2	J=3/2, M=+3/2
+2	−1/2	1/5	4/5
+1	+1/2	4/5	−1/5

m_1	m_2	J=5/2, M=+1/2	J=3/2, M=+1/2
+1	−1/2	2/5	3/5
0	+1/2	3/5	−2/5

m_1	m_2	J=5/2, M=−1/2	J=3/2, M=−1/2
0	−1/2	3/5	2/5
−1	+1/2	2/5	−3/5

m_1	m_2	J=5/2, M=−3/2	J=3/2, M=−3/2
−1	−1/2	4/5	1/5
−2	+1/2	1/5	−4/5

m_1	m_2	J=5/2, M=−5/2
−2	−1/2	1

3/2×1/2

m_1	m_2	J=2, M=+2
+3/2	+1/2	1

m_1	m_2	J=2, M=+1	J=1, M=+1
+3/2	−1/2	1/4	3/4
+1/2	+1/2	3/4	−1/4

m_1	m_2	J=2, M=0	J=1, M=0
+1/2	−1/2	1/2	1/2
−1/2	+1/2	1/2	−1/2

m_1	m_2	J=2, M=−1	J=1, M=−1
−1/2	−1/2	3/4	1/4
−3/2	+1/2	1/4	−3/4

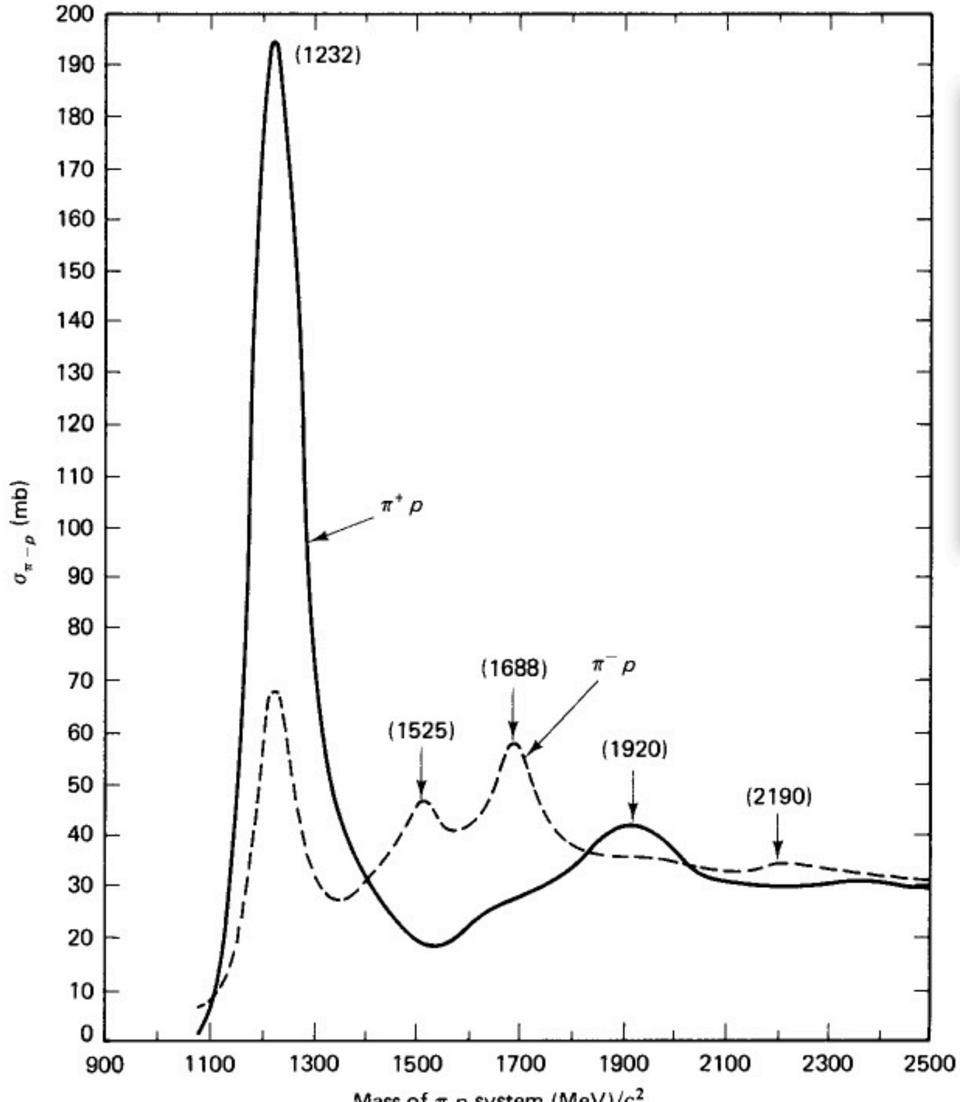
m_1	m_2	J=2, M=−2
−3/2	−1/2	1

$$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$$

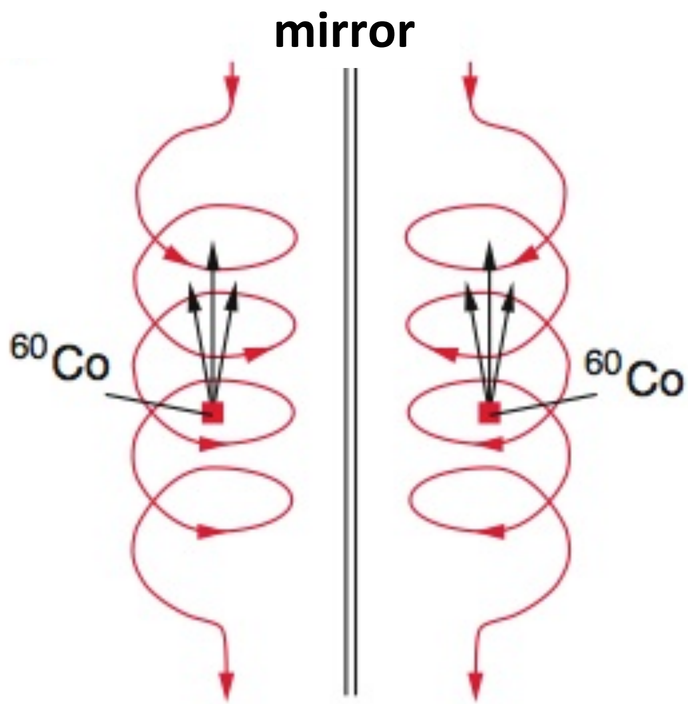
$$d^{\,\ell}_{m,0} = \sqrt{\frac{4\pi}{2\ell+1}}\, Y_\ell^m\, e^{-im\phi}$$

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M\rangle = (-1)^{J-j_1-j_2}\langle j_2 j_1 m_2 m_1 | j_2 j_1 J M\rangle$$

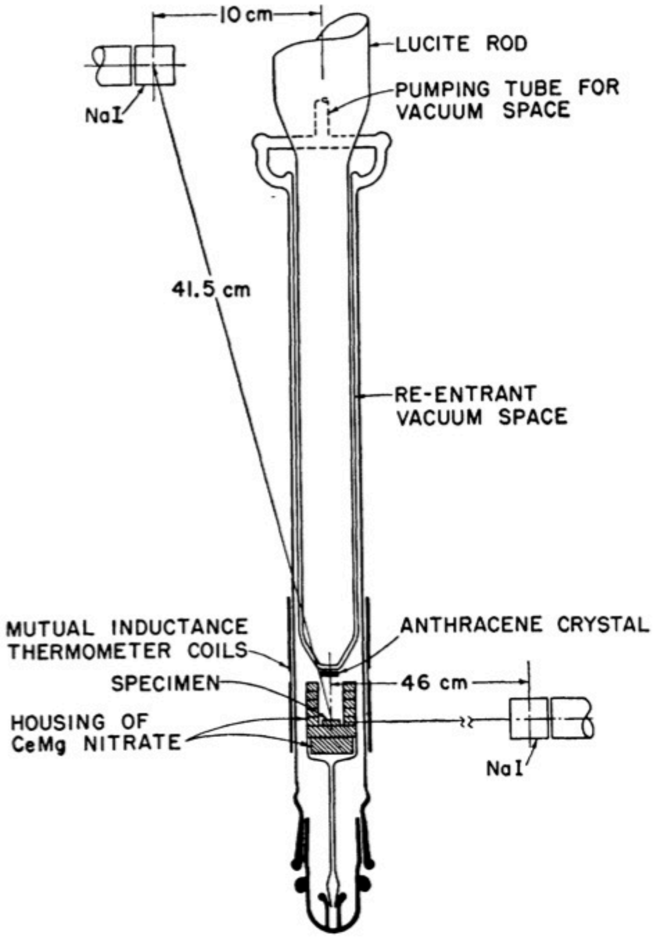
π *p* elastic scattering

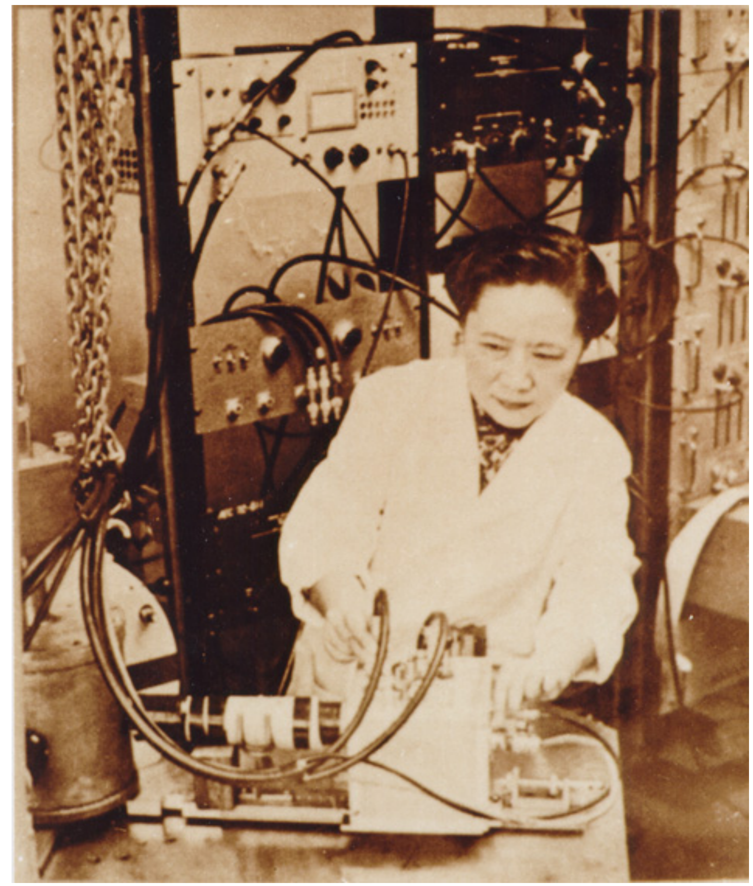


Wu Experiment



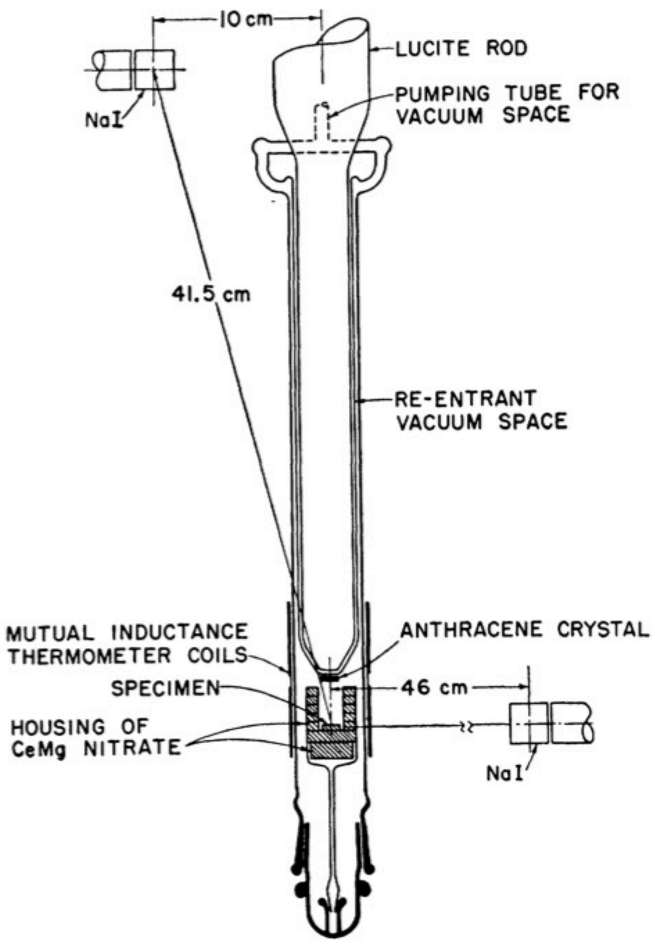
Wu Experiment

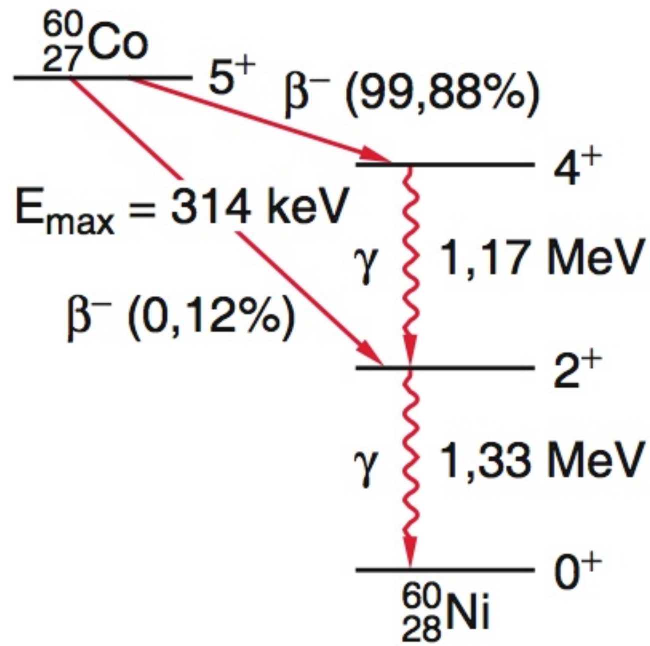




C. S. Wu et al., Phys. Rev., 105, 1413 (1957)

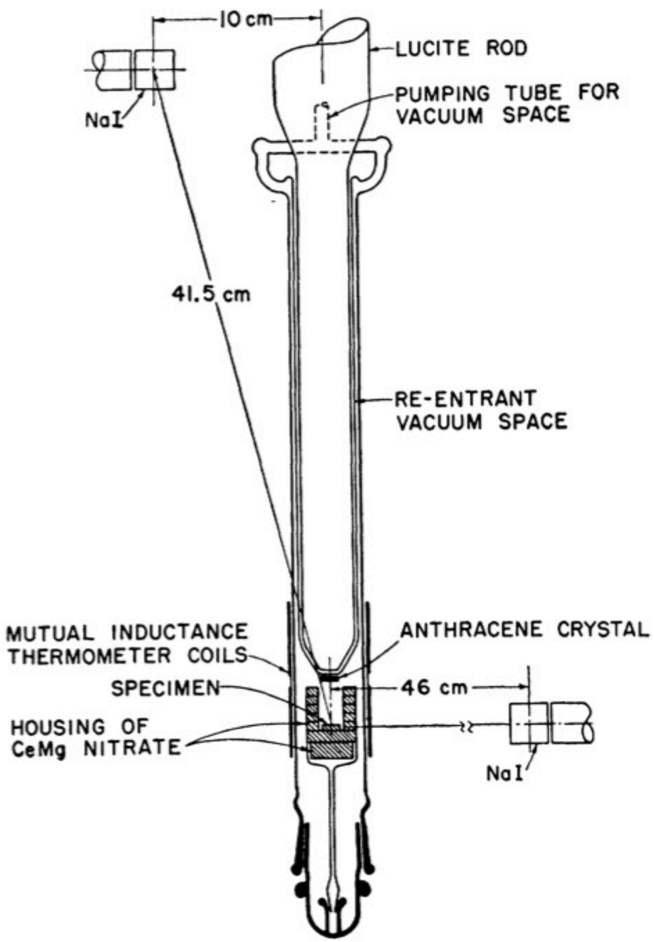
Wu Experiment

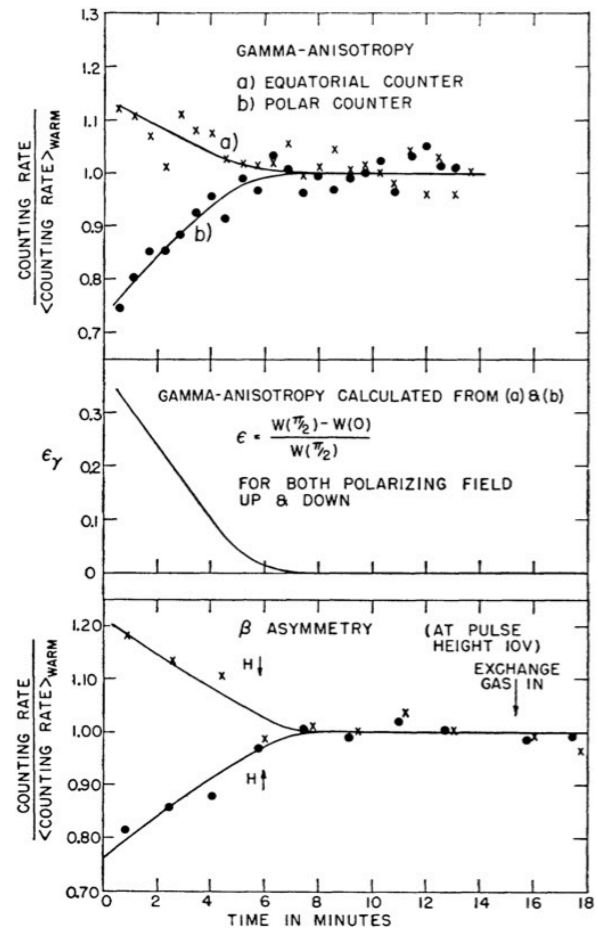




C. S. Wu et al., Phys. Rev., 105, 1413 (1957)

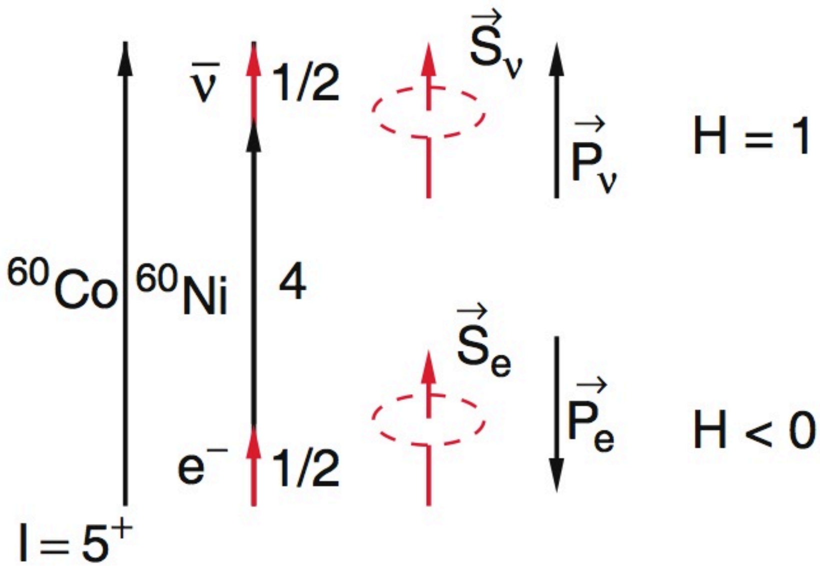
Wu Experiment





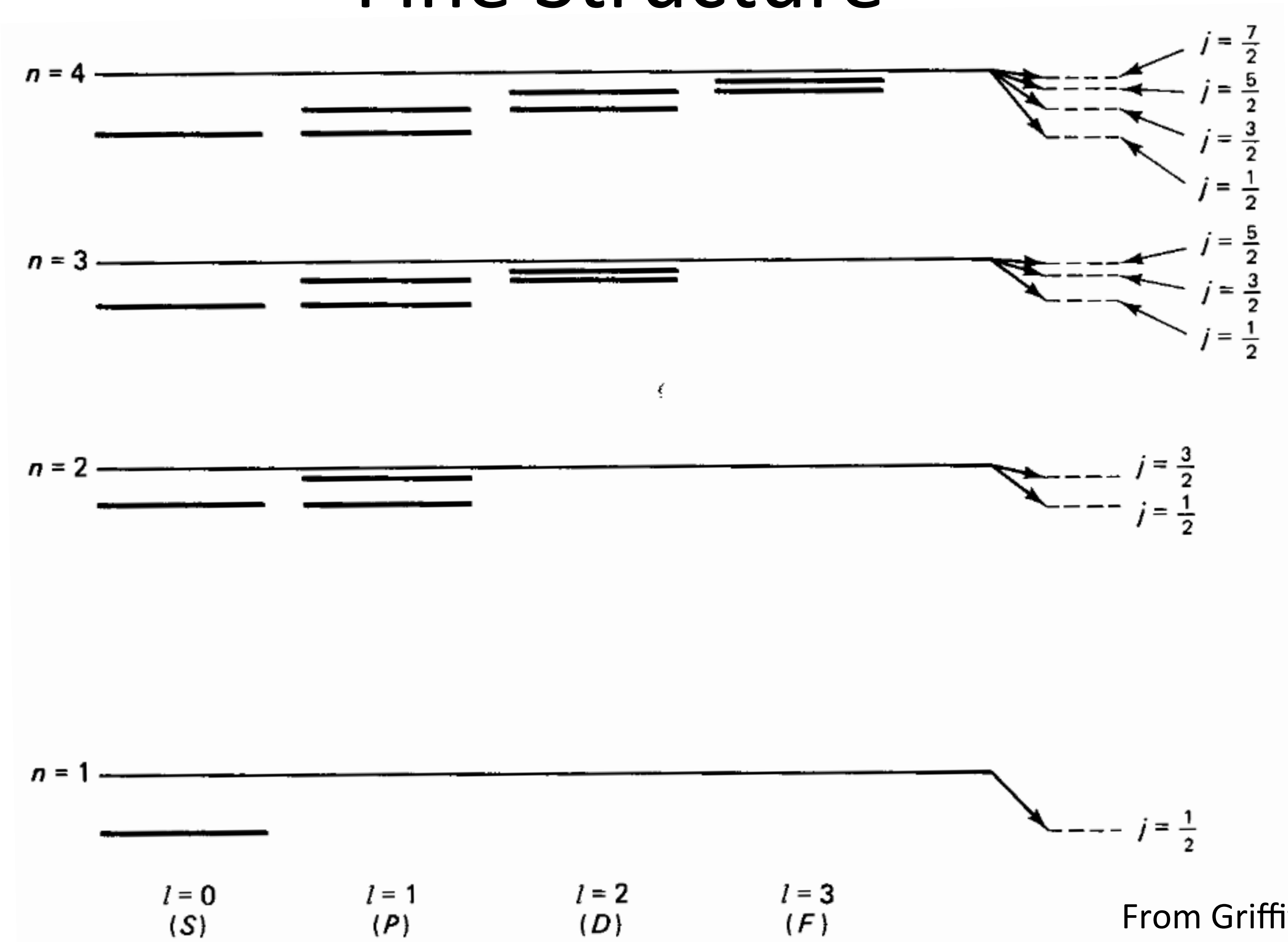
C. S. Wu et al., Phys. Rev., 105, 1413 (1957)

Wu Experiment



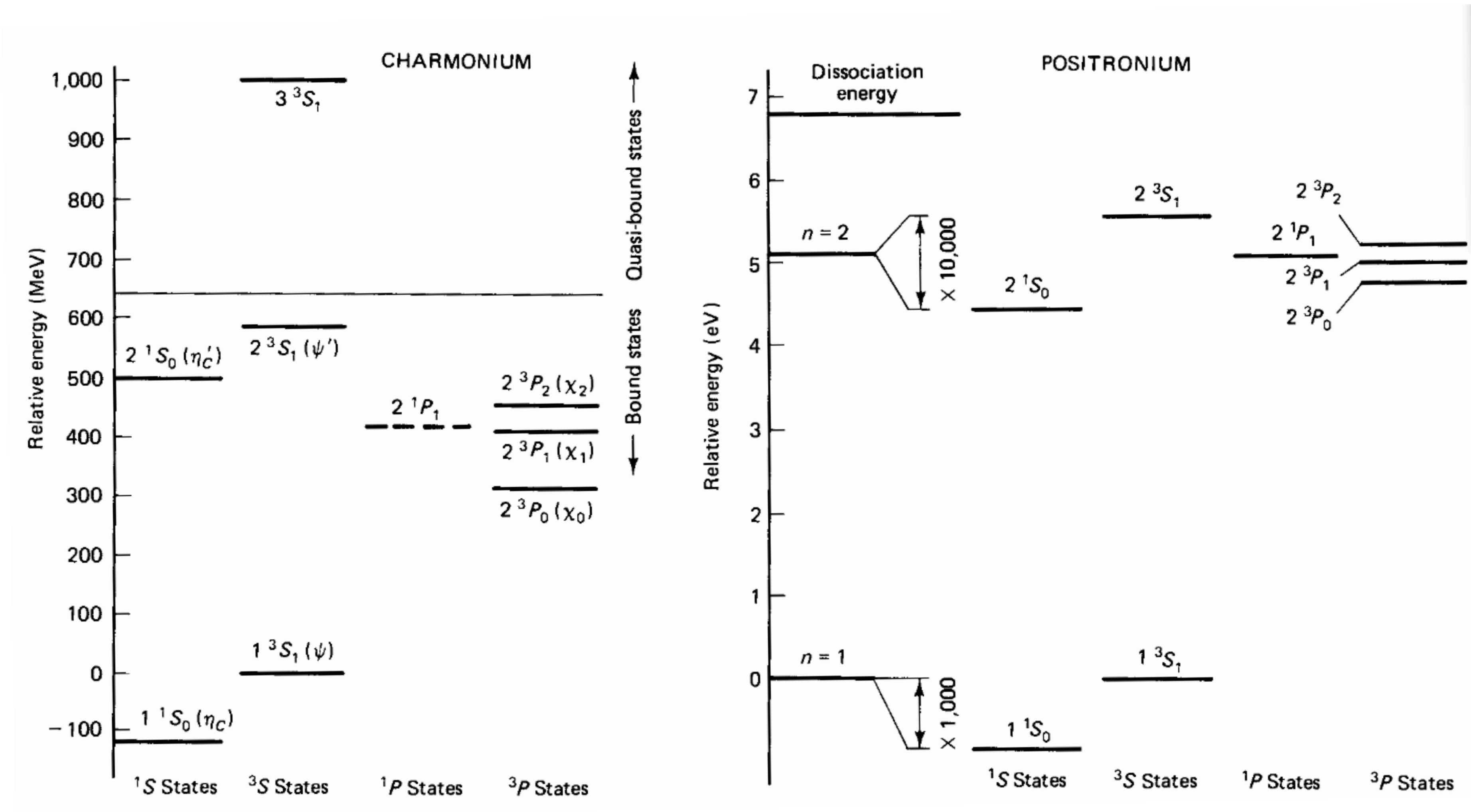
Wu Experiment

Fine Structure



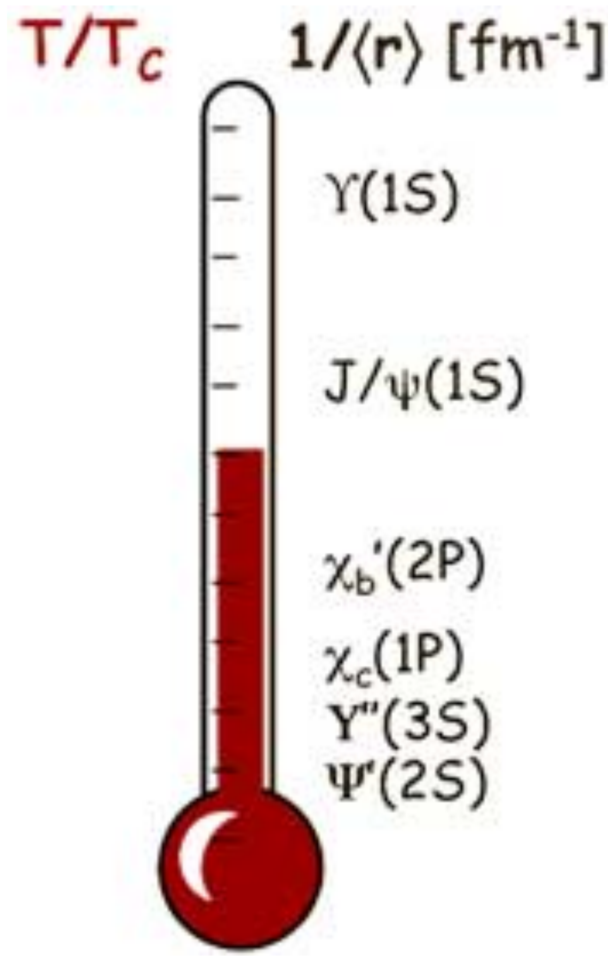
From Griffith

Charmonium/Positronium



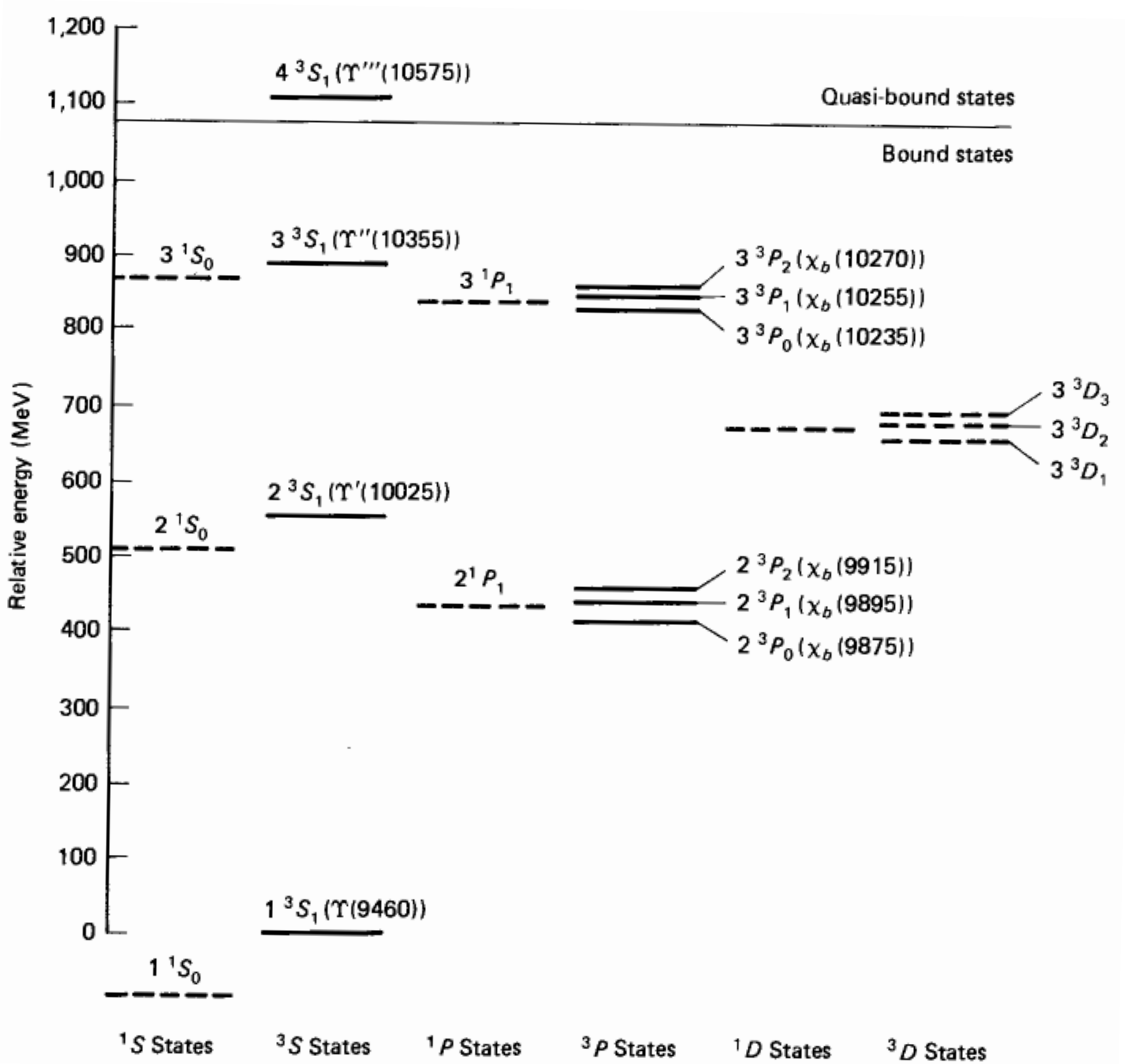
from Bloom, Feldman (1982) ‘Quarkonium’, Sci.Am., p.66

Charmonium QGP thermometer

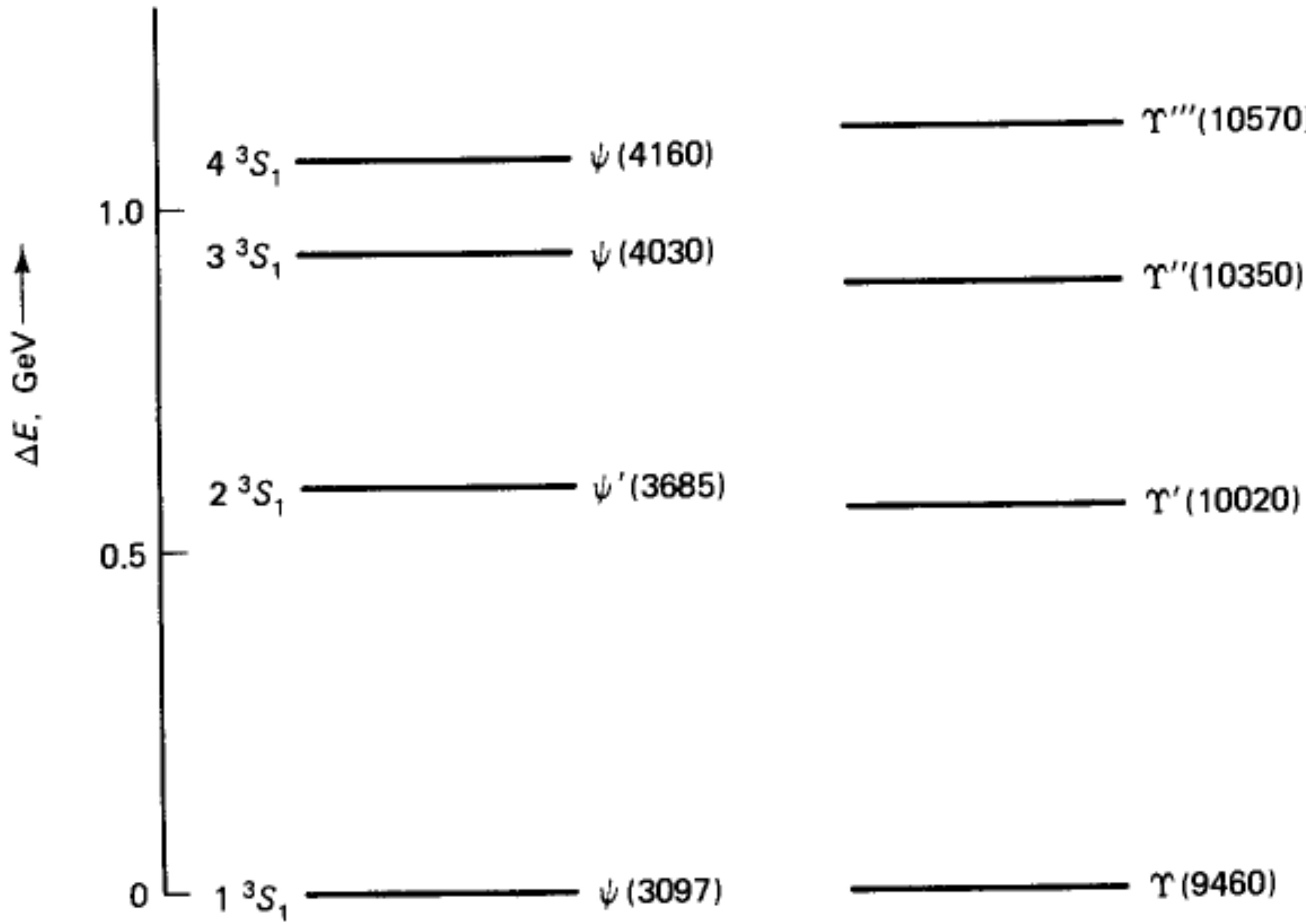


From Agnes Mocsy

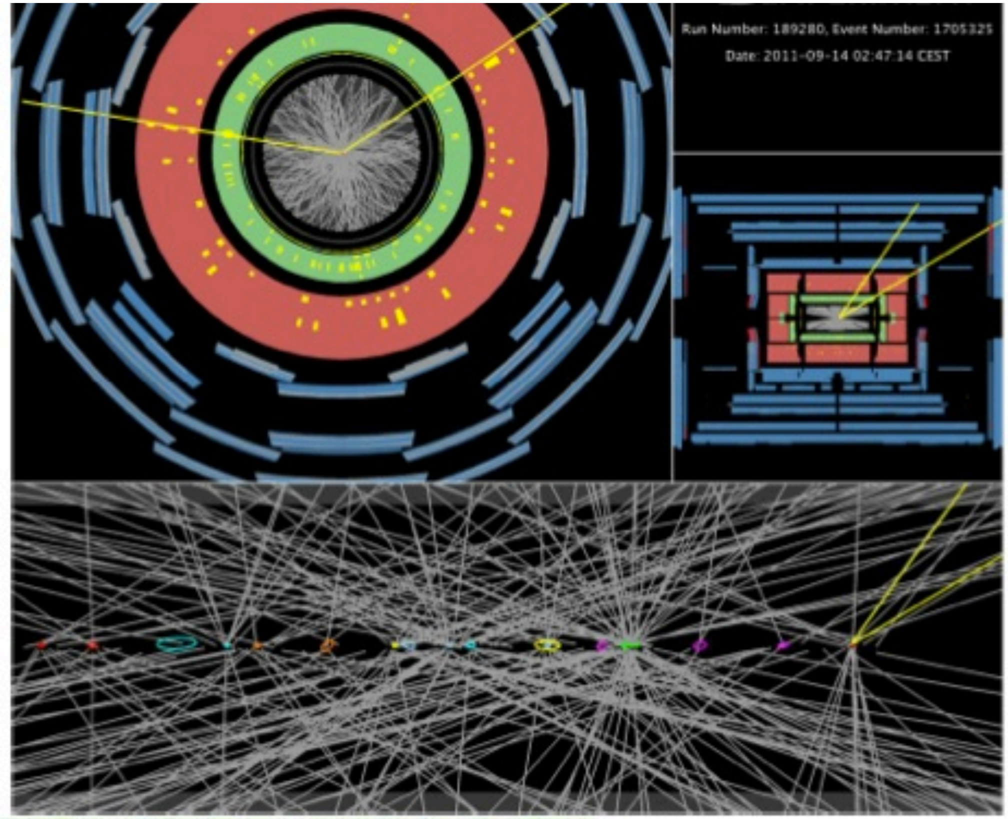
Bottomonium



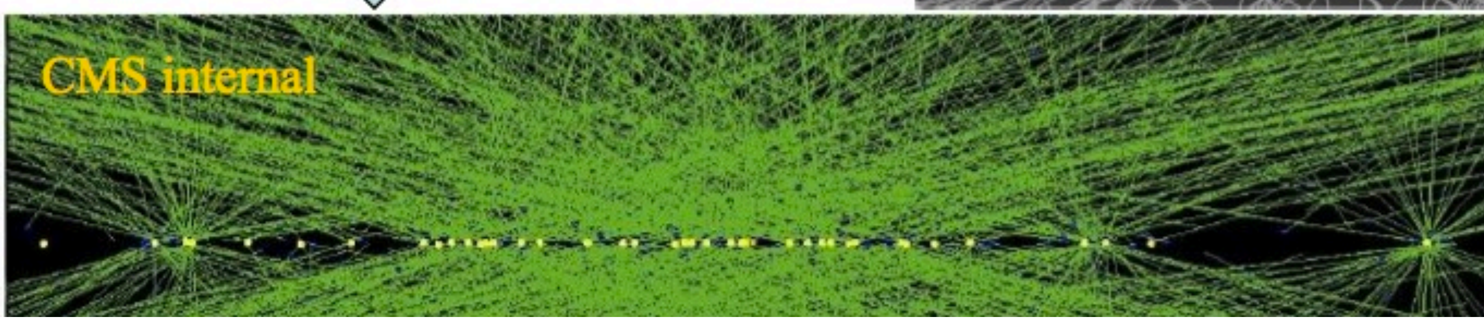
Charmonium/Bottomonium

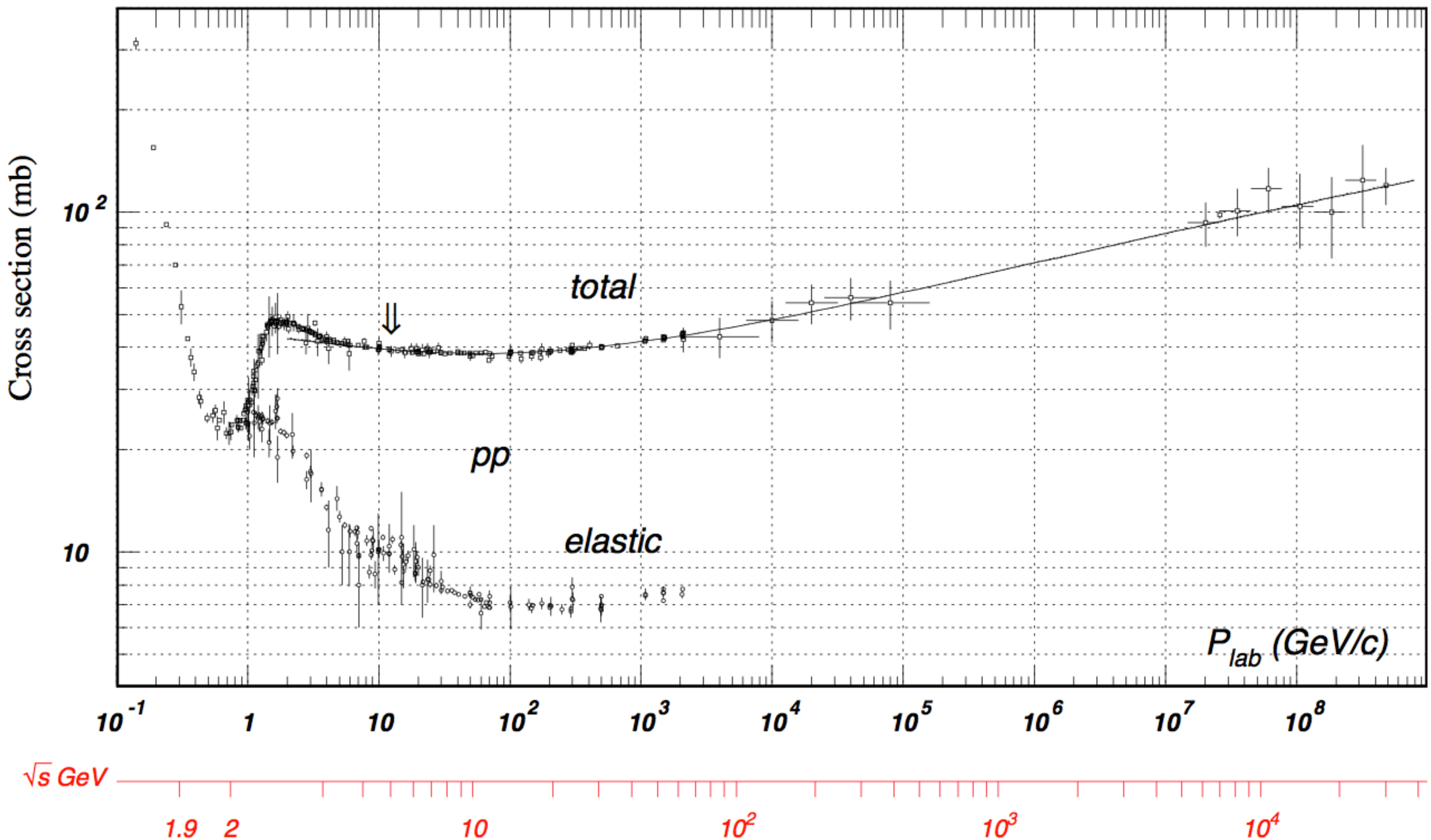


- Z→μμ candidate with 20 reconstructed vertices



- Event with 40 reconstructed vertices





Cross section (mb)
10^2
10
total
pp
elastic
P_{lab} (GeV/c)
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
$\sqrt{s}$ GeV
1.9
2
10
10^2
10^3
10^4