GLORIOUS EXPERIMENTS IN PHYSICS

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WARNING

The experiments discussed in these lectures represent only a small sample of "glorious experiments".

This is a personal choice based on the following criteria:

- **Impact on the understanding of Weak Interactions and Neutrinos**
- **Clever experimental ideas and methods**

24th Indian - Summer School of Physics, Prague, September 2012

Experiments discussed in these lectures:

- **First direct neutrino detection at a location far from production**
- **Observation of parity violation in the $\pi \rightarrow \mu \rightarrow$ e decay chain**
- **Precise measurements of the muon magnetic anomaly (g – 2)**
- **Measurement of the neutrino helicity**
- **Discovery of the second neutrino**
- **Discovery of the violation of CP symmetry**
- **First observation of neutrino Neutral-Current interactions**
- **First observation of production and decay of the weak intermediate bosons $W^{\pm}$ and Z**

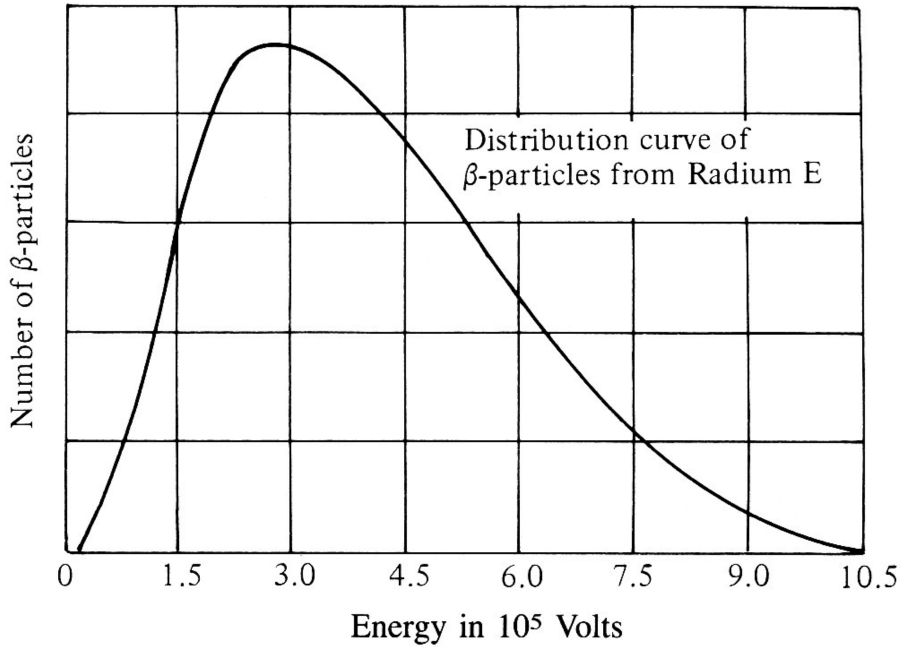
A short historical introduction to each experiment will be included.

First neutrino detection

Historical introduction

A puzzle in β – decay: the continuous electron energy spectrum

First measurement by Chadwick (1914)



Radium E: $^{210}Bi_{83}$ (a radioactive isotope produced in the decay chain of ^{238}U)

[If β – decay is $(A, Z) \to (A, Z+1) + e^-$, then the emitted electron is mono-energetic]

Several solutions to the puzzle proposed before the 1930's (all wrong), including violation of energy conservation in β – decay

December 1930: public letter sent by W. Pauli to a physics meeting in Tübingen

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

...because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous β-spectrum, I have hit upon a desperate remedy to save the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin ½ and obey the exclusion principle ..... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous β-spectrum would then become understandable by the assumption that in β-decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant.

.... For the moment, however, I do not dare to publish anything on this idea ......

So, dear Radioactives, examine and judge it. Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zürich because of a ball on the night of 6/7 December. ....

W. Pauli

- "Wrong" statistics of the $^{14}N_7$ and $^{6}Li_3$ nuclei: in 1930 (before the neutron discovery by Chadwick in 1932) nuclei (*A*,*Z*) were believed to consist of *A* protons and *A-Z* electrons
  → $^{14}N_7$ and $^{6}Li_3$ nuclei were believed to consist of 21 and 9 fermions, respectively
  → expect half – integer spin but measure integer value
- Pauli's "neutron" is a light particle
- As everybody else at that time, Pauli believed that if radioactive nuclei emit particles, these particles must exist in the nuclei before emission

Theory of β-decay (E. Fermi, 1932-33)

β^- decay: $n \to p + e^- + \bar{\nu}$

β^+ decay: $p \to n + e^+ + \nu$ (e.g., $^{14}O_8 \to {}^{14}N_7 + e^+ + \nu$)

ν: the particle proposed by Pauli (named "neutrino" by Fermi)

$\bar{\nu}$: its antiparticle (antineutrino)

Fermi's theory: a point interaction among four spin ½ particles, using the mathematical formalism of creation and annihilation operators invented by Jordan

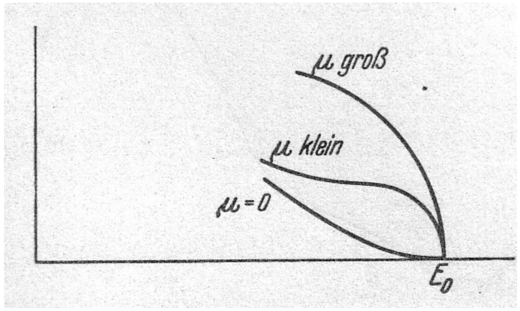
$\Rightarrow$ particles emitted in β – decay need not exist before emission – they are "created" at the instant of decay

Prediction of β – decay rates and electron energy spectra as a function of only one parameter: Fermi coupling constant G_F (determined from experiments)

Energy spectrum dependence on neutrino mass μ

(from Fermi's original article, published in German in Zeitschrift für Physik, following rejection of the English version by Nature)

Measurable distortions for $\mu > 0$ near the end-point (E_0: max. allowed electron energy)



1934: Bethe and Peierls use Fermi's theory to estimate the cross-section for processes in which "a neutrino hits a nucleus and a positive or negative electron is created while the neutrino disappears and the charge of the nucleus changes by 1" (Nature **133**, 532)

$$\sigma \approx 10^{-44}\ \mathrm{cm}^2$$

"corresponding to a penetrating power of 10^{16} km in solid matter.
It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.
With increasing energy, σ increases (in Fermi's model for large energies as E^2) but even if one assumes a very steep increase, it seems highly improbable that, even for cosmic ray energies, σ becomes large enough to allow the process to be observed.
.... One can conclude that there is no practically possible way of observing the neutrino."

H. BETHE, R. PEIERLS
Physical Laboratory,
University, Manchester
February 20th, 1934

Late 1930s: discovery of Uranium fission
1940 - : applications (mostly military)

1952: Frederick Reines and Clyde Cowan (Los Alamos) begin thinking of methods of neutrino detection using large volumes of liquid scintillator

First idea: install detector near a test atomic explosion.
Expect detection of few events before detector destruction.

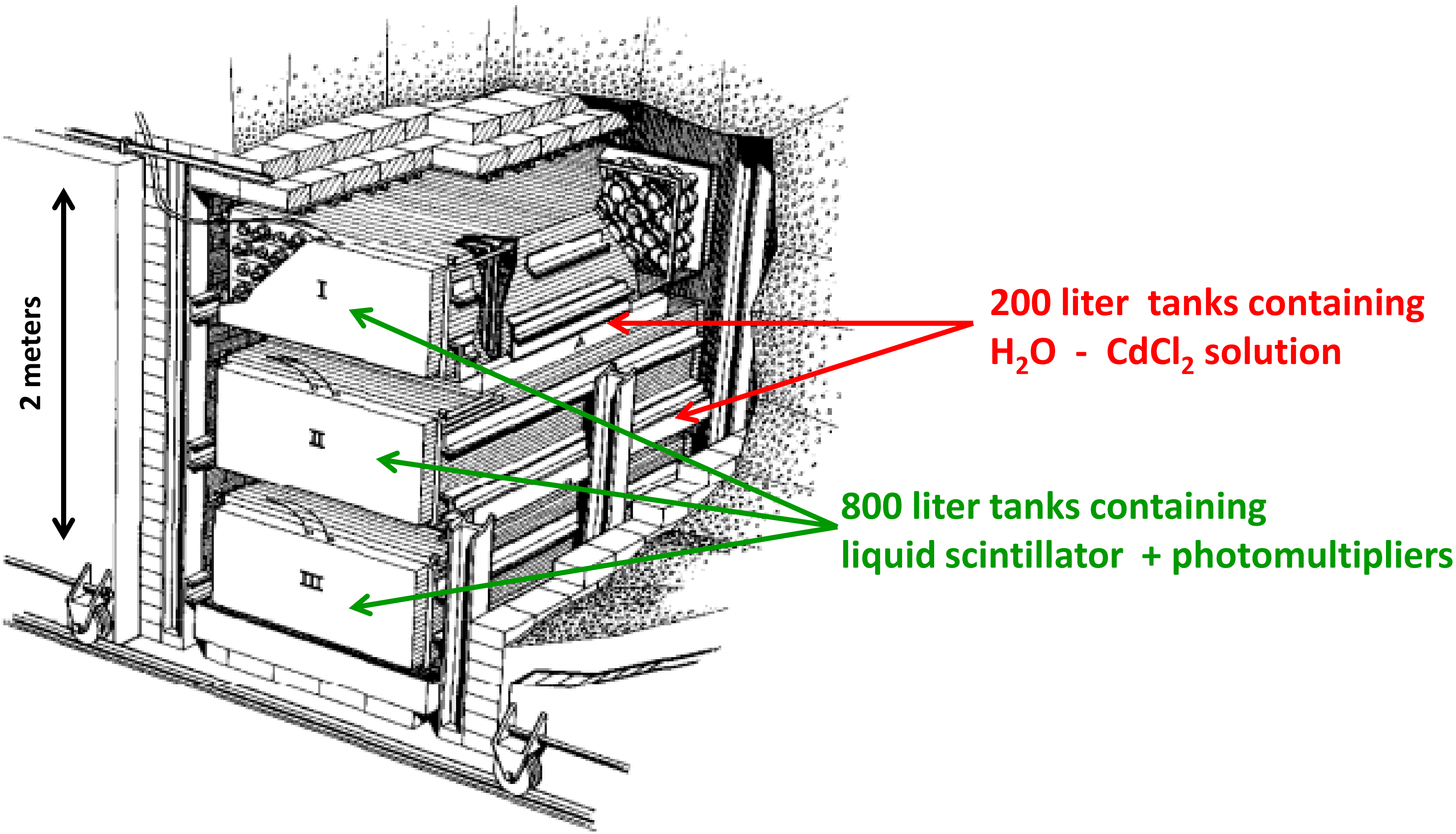
Second idea: install detector near a nuclear reactor (a strong isotropic source of $\bar{\nu}$ from β – decay of fission fragments)

1954: Install a 300 liter liquid scintillator detector near one of the Hanford reactors (a military reactor used for Plutonium production)
Observe a reactor – independent background signal from cosmic rays

→ **DESIGN A NEW DETECTOR TO BE INSTALLED IN AN UNDERGROUND LOCATION 11 m FROM THE CENTER OF THE SAVANNAH RIVER 700 MW REACTOR**

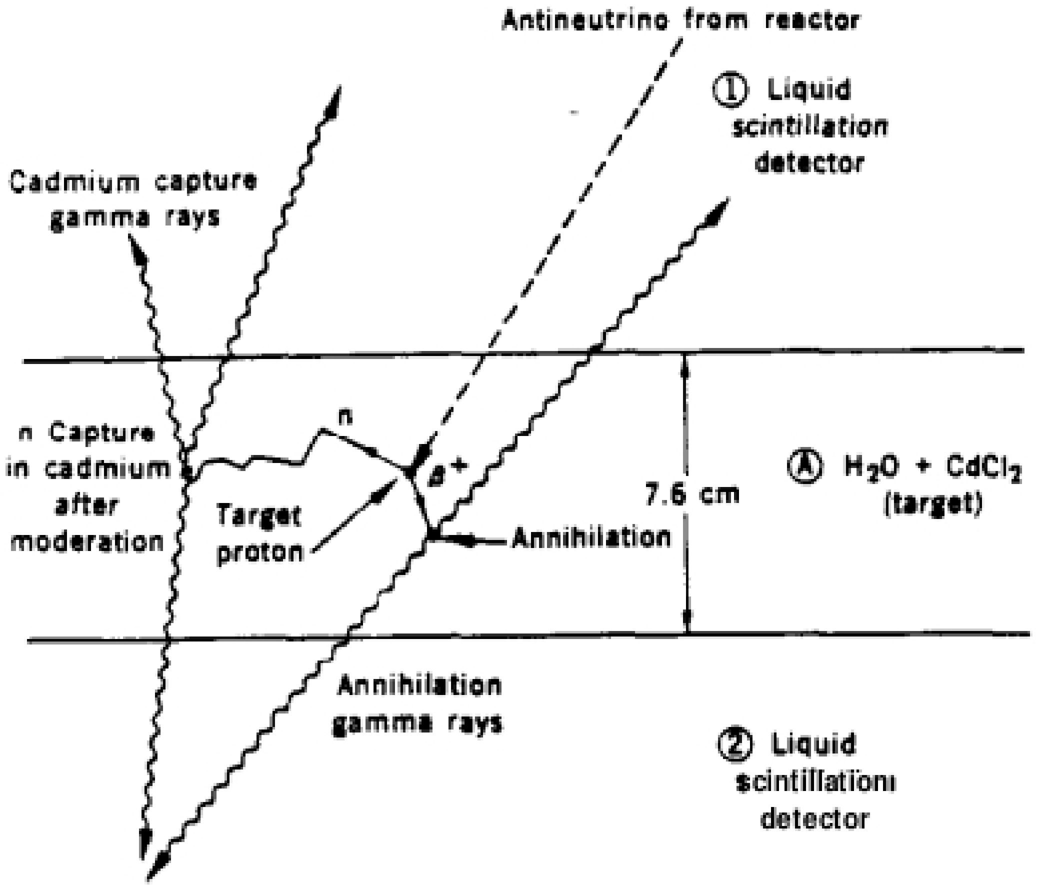
THE ANTINEUTRINO DETECTOR AT THE SAVANNAH RIVER REACTOR

(Autumn 1955)



ANTINEUTRINO DETECTION METHOD

$\bar{\nu} + p \rightarrow e^+ + n$ on the free protons of H_2O



- Detect two simultaneous γ – rays from e^+ annihilation at rest
- Detect the late (~ 10 μs) γ – rays from neutron capture in Cadmium

First results published in July 1956 (Science **124**, 103**)**

Final results: Reines, Cowan, Harrison, McGuire, Kruse, Phys. Rev. 117 (1960) 159

Reactor – associated event rate : 2.9 ± 0.2 events / hour

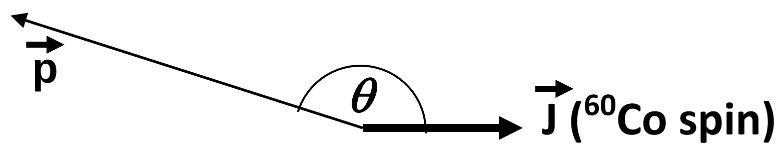
Demonstration that signal is due to $\bar{\nu} + p \rightarrow e^+ + n$:

- **Insert Pb layers of variable thickness between H_2O + $CdCl_2$ target and scintillator tanks → signal is reduced as expected for 0.5 MeV γ – rays produced inside target;**
- **Remove $CdCl_2$ from target → signal from late neutron capture in Cd disappears;**
- **Replace 47% of the target protons by deuterons using the appropriate mixture of heavy and ordinary water in the target:**
  [Expect $\sigma(\bar{\nu} + d \rightarrow e^+ + n + n) \approx \frac{1}{15}\,\sigma(\bar{\nu} + p \rightarrow e^+ + n)$ for reactor antineutrinos]
  measure reduction of reactor – associated signal as expected

Violation of Parity (P) Invariance in the $\pi \rightarrow \mu \rightarrow e$ Decay Chain

Historical introduction

- In the early 1950s, two mesons with strangeness +1 were discovered:
  $\tau^+ \rightarrow \pi^+\pi^+\pi^-$ (final state P = -1) ; $\theta^+ \rightarrow \pi^+\pi^0$ (final state P = +1)
  with equal mass and mean lifetime values → the $\tau - \theta$ puzzle
- Following a critical review of all experimental data then available, Lee and Yang proposed that the weak interactions may not be invariant under Parity (T.D. Lee and C.N. Yang, Phys. Rev. 104 (1956) 254) and suggested experiments to test this hypothesis
- The first experiment to observe the violation of P symmetry in β – decay was a study of the decay $^{60}Co \rightarrow {}^{60}Ni^* + e^- + \bar{\nu}$ using polarized ^{60}Co nuclei (C.S. Wu et al., Phys. Rev. 105 (1957) 1413)



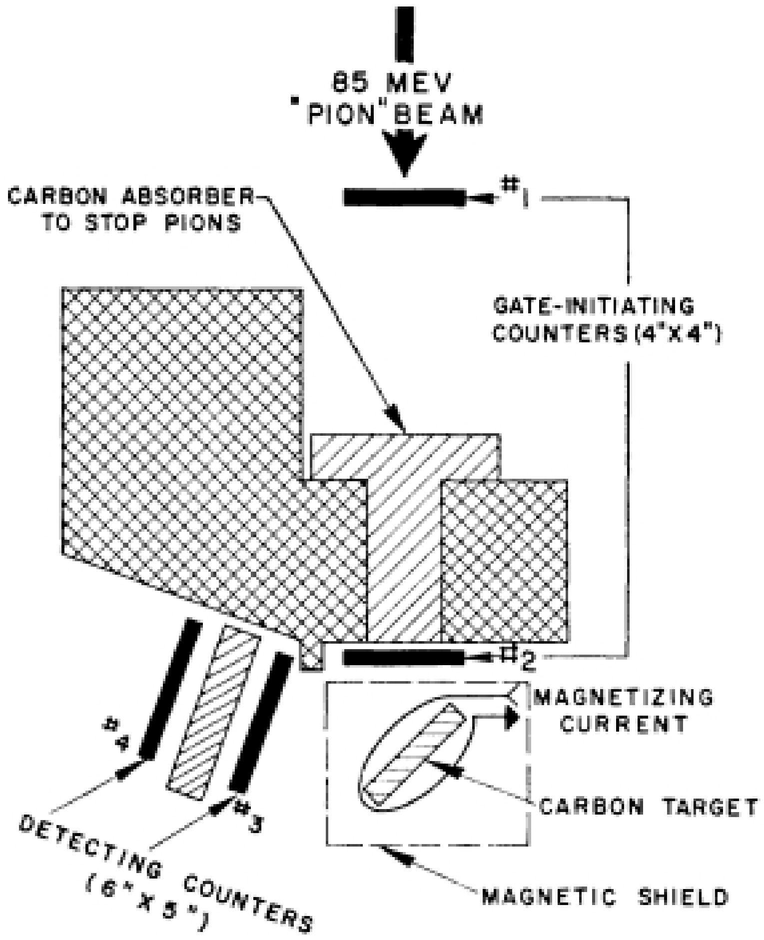
Measured electron angular distribution consistent with the form

$$I(\theta) \propto 1 + \alpha \frac{\vec{\sigma} \cdot \vec{p}}{E} = 1 + \alpha \frac{|\vec{p}|}{E} \cos\theta \qquad \text{with } \alpha = -1$$

$\vec{\sigma}$: unit vector along $\vec{J}$; $\vec{p}$, E : electron momentum, energy

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon

R.L. Garwin, L.M. Lederman and. M. Weinrich, Phys. Rev. **105** (1957) 1415



176 MeV/c beam from the Nevis synchrocyclotron contains 10% muons from $\pi \rightarrow \mu$ decay in flight

Pions stop in Carbon absorber

Muons stop in the Carbon target;

Magnetic field *B* perpendicular to figure induces muon spin precession with angular precession rate

$$\omega_s = g_\mu \frac{e}{2m_\mu c} B$$

***g_μ* : gyromagnetic ratio**
(*g* = 2 to lowest order
for a spin ½ fermion)

***m_μ* :**
muon mass

If Parity is not conserved in the $\pi \rightarrow \mu \rightarrow e$ decay chain one may expect:

- muon polarization (P_μ) along momentum;
- electron angular asymmetry with respect to the P_μ direction: $I(\theta) = 1 + \alpha P_\mu \cos\theta$

Muon spin precession ➡ *B* – dependent modulation of the electron time distribution :

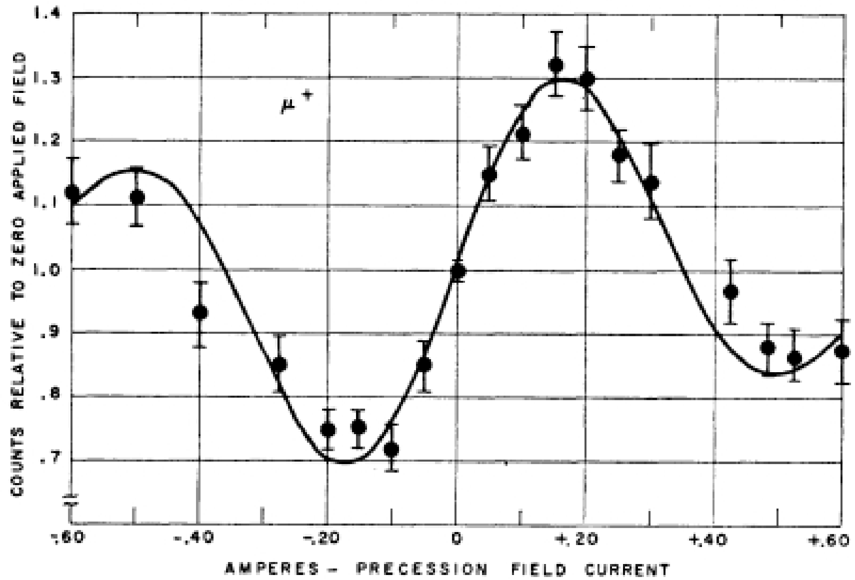
$$I(t) \propto \exp\left(-\frac{t}{\tau}\right)\left[1+\alpha P_\mu \cos(\theta - \omega_s t)\right]$$

$\tau \approx 2.2\ \mu s$: mean muon decay time

θ : angle between detected electron and incident beam direction

Results with π^+ beam

Rate of detected electrons with $0.75 < t < 2.0\ \mu s$ versus precession field



Full curve is computed under the assumptions $g_\mu = 2$; $\alpha P_\mu = -⅓$

- Clear evidence for parity violation in both $\pi \rightarrow \mu \nu$ and $\mu \rightarrow e \nu \bar{\nu}$ decay:
  $\alpha P_\mu = -1/3$ (estimated error 10%)
- First measurement of the muon magnetic moment : $g_\mu = 2.00 \pm 0.10$
- Data with negatively charged beam show reduced asymmetry: $(\alpha P)_{\mu^-} \approx 0.15\ (\alpha P)_{\mu^+}$

Measurement of the muon anomalous magnetic moment

Muon magnetic moment $g_\mu \left(\frac{e}{2mc} \right) \frac{\hbar}{2}$

For a spin ½ particle obeying the Dirac equation ***g*** **= 2**
Quantum fluctuations of the electromagnetic field around the muon modify this value:

$$g_\mu = 2(1 + a_\mu) \qquad\qquad a_\mu = \frac{g_\mu - 2}{2}$$

Anomalous magnetic moment $a_\mu \approx 1 / 850$

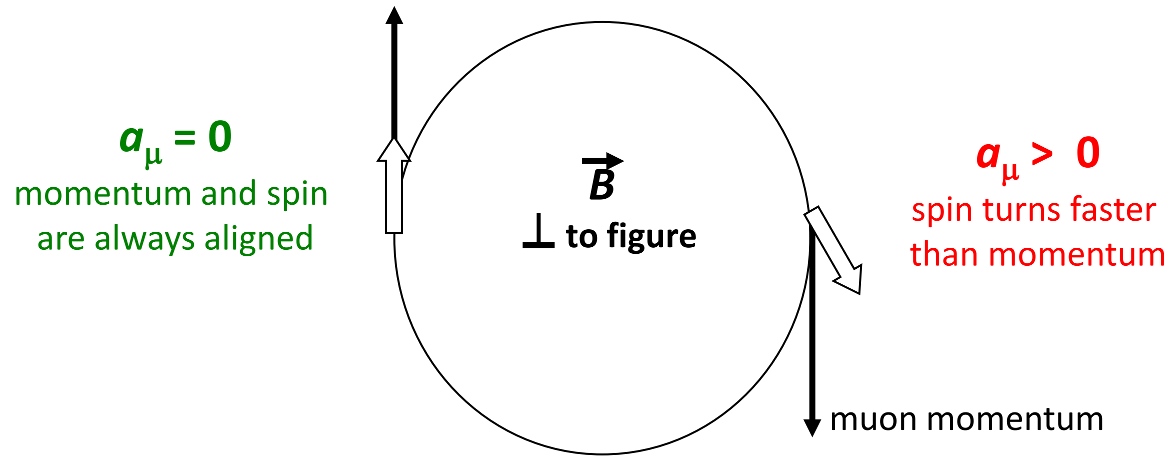
Inject longitudinally polarized muons with momentum $\vec{p}$
into a uniform magnetic field $\vec{B}$

$$\vec{\omega}_c = -\left(\frac{e}{mc} \right) \frac{\vec{B}}{\gamma}$$ muon angular velocity ($\omega_c / 2\pi$ "cyclotron frequency")

$$\vec{\omega}_s = -\left(\frac{e}{mc} \right) \left(\frac{1}{\gamma} + a_\mu \right) \vec{B}$$ muon spin precession

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{e}{mc} \right) a_\mu \vec{B}$$ spin precession relative to the momentum vector

An independent, precise measurement of the muon spin precession at rest provides the value of $g_\mu (e / mc)$ – B is measured precisely using proton magnetic resonance



One full momentum turn → angle between spin and momentum $2\pi a_\mu \gamma \approx \gamma/135$
→ need many turns to measure a_μ precisely

Original motivation to measure a_μ : to understand the difference between muon and electron (mass difference associated with different interaction?)

Four measurements of a_μ with increasing precision have been performed so far

1958 – 62: First CERN experiment with slow muons

Special dipole magnet, measure muon polarization after 440 turns

$$a_\mu = (1.162 \pm 0.005) \times 10^{-3}$$

1962 – 68: 1st muon storage ring at CERN (orbit diameter 5 m)

p = 1.28 GeV/c, γ = 12, measure muon polarization over 2500 turns

$$a_\mu = (1.16616 \pm 0.00031) \times 10^{-3}$$

Storage rings require focusing to keep circulating beam inside vacuum chamber.
This is usually achieved using magnetic field gradients (quadrupole components).

In the 1st muon storage ring at CERN $\Delta B/B \approx 0.2\%$ over the full radial aperture of 8 cm

→ **the knowledge of the radial distribution of the circulating muons introduces a systematic uncertainty on the measurement of a_μ**

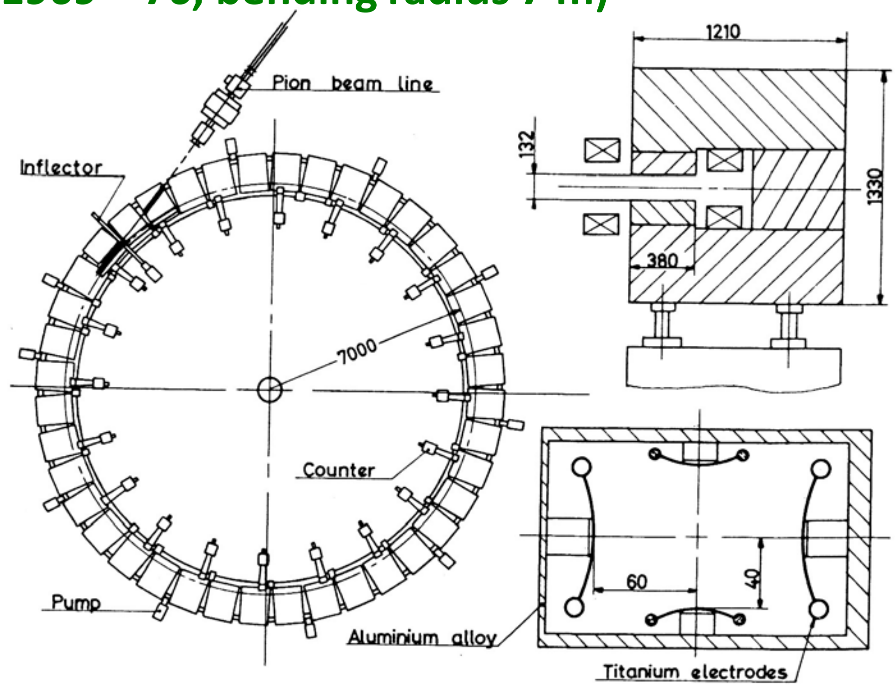
New idea: use uniform magnetic field and electrostatic focusing

In the presence of an electrostatic field $\vec{E}$ (β = muon v/c)

$$\vec{\omega}_a = -\left(\frac{e}{mc}\right)\left[a_\mu \vec{B} + \left(\frac{1}{\gamma^2 - 1} - a_\mu\right)\vec{\beta}\times\vec{E}\right]$$

factor = 0
for γ = 29.304
p = 3.094 GeV/c
"magic" momentum

Idea first implemented in the 2nd muon storage ring at CERN (1969 – 76, bending radius 7 m)

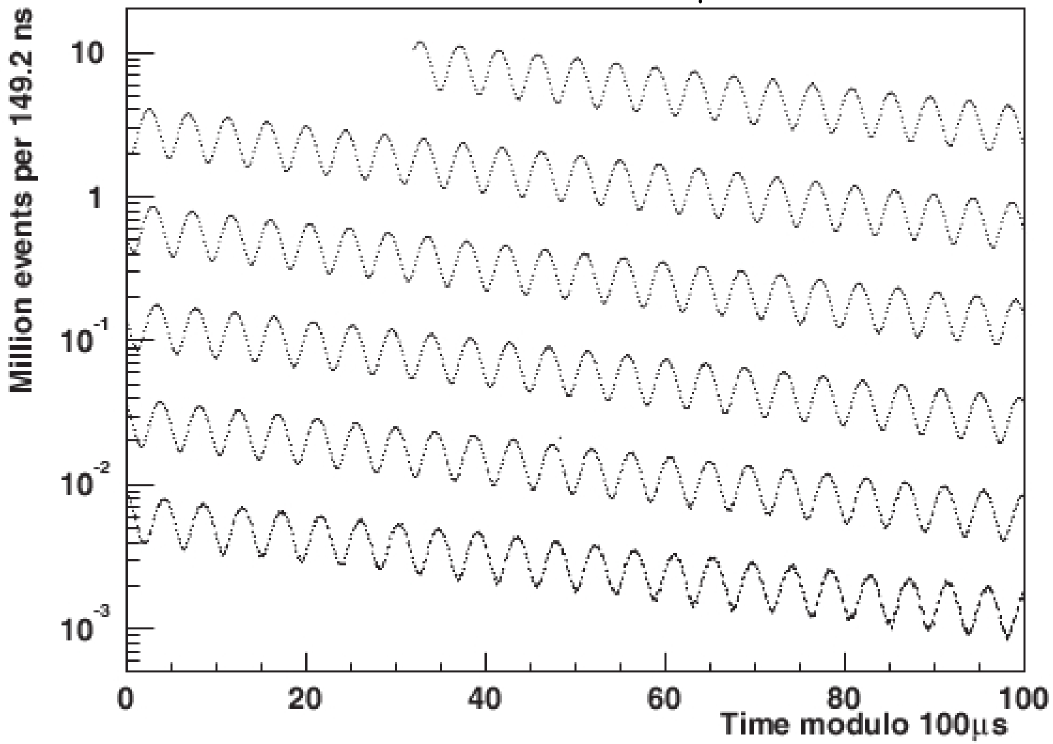


Final result:

$$a_\mu = (1.165924 \pm 0.000009) \times 10^{-3}$$

1997 – 2006: 3rd muon storage ring at Brookhaven National Laboratories (BNL)
Continuous superconducting magnet, bending radius 7 m,
"magic" momentum muons

Time modulation from $a_\mu \neq 0$



Final BNL result: $a_\mu = (1.1659209 \pm 0.0000006) \times 10^{-3}$

This result differs by ~2.5 standard deviations from the SM prediction which requires the calculation of 1st and 2nd order hadronic loops, themselves affected by theoretical uncertainties, to reach a precision comparable to the measurement.

Measurement of the neutrino helicity

M. Goldhaber, L. Grodzins, A.W. Sunyar, Phys. Rev. **109** (1958) 1015

$$_{63}Eu^{152m} + e^- \rightarrow (_{62}Sm^{152})^* + \nu \rightarrow {}_{62}Sm^{152} + \gamma$$

$J^P =$ 0^- 1^- 0^+

(orbital electron capture, $\tau_{1/2} = 9.3$ hr)

Consider the decay topologies in which neutrino and photon are emitted back – to -back with the neutrino momentum along +z :

$p_\gamma = 0.960$ MeV/c (also 0.840 MeV/c) $p_\nu = 0.840$ MeV/c

Angular momentum component along +z (J_z)
(ν momentum along +z , γ momentum along –z)

Initial state		Intermediate state		ν helicity	Final state			γ helicity
Eu^{152m}	e^-	$(Sm^{152})^*$	ν		Sm^{152}	ν	γ	
0	+1/2	+1	-1/2	-1	0	-1/2	+1	-1
0	-1/2	-1	+1/2	+1	0	+1/2	-1	+1

Final state photon and neutrino emitted in the opposite direction have the same helicity

Method: measure photon helicity for photons emitted opposite to neutrinos

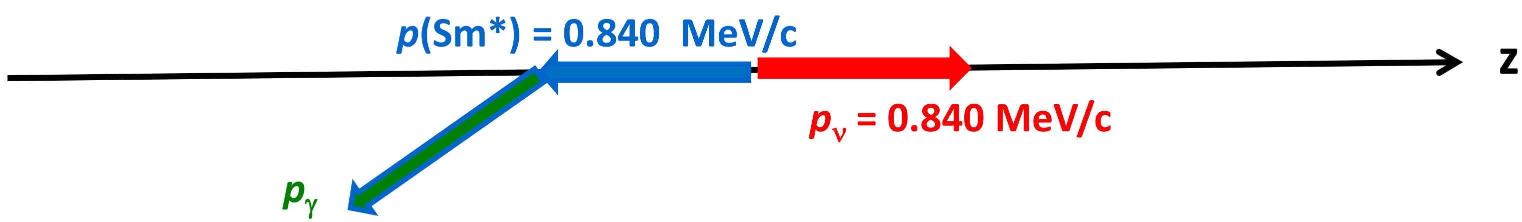
- **The photon helicity measurement is based on the different photon transmission in magnetized iron depending on the relative alignment of the photon and electron polarizations $\vec{s}_\gamma$, $\vec{s}_e$**

Compton scattering cross – section: $\sigma_C = \sigma_0 - \sigma_1 \vec{s}_\gamma \cdot \vec{s}_e$ $(\sigma_1 > 0)$

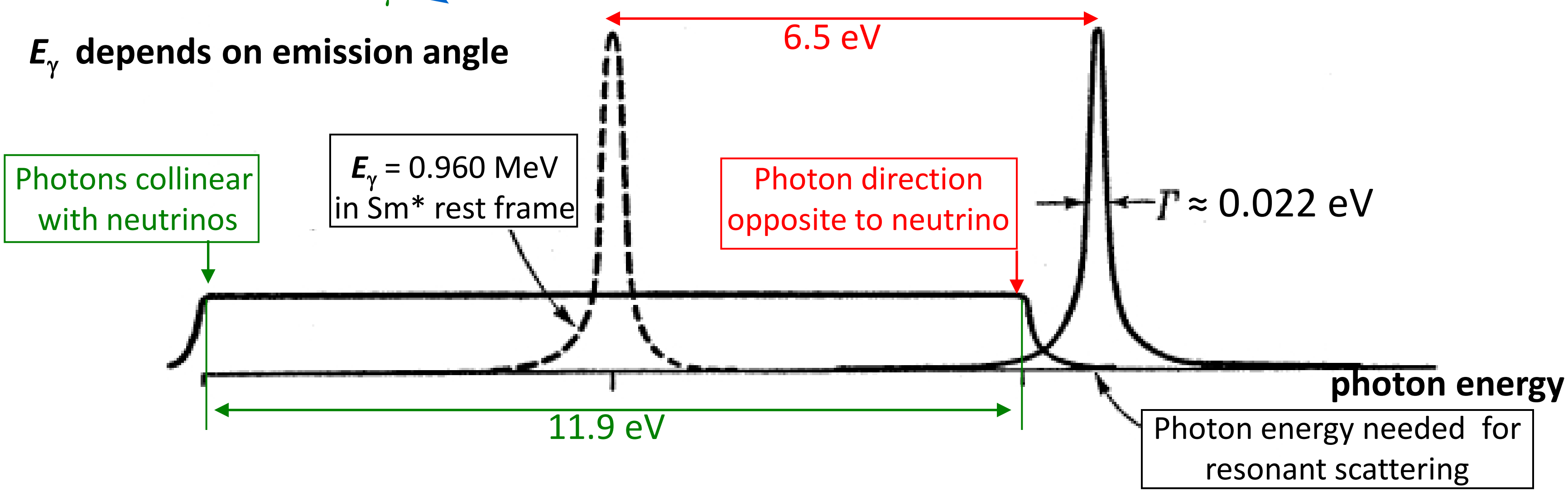
Smaller cross – section → higher transmission for parallel spins

In magnetized Iron only the two outermost electrons are polarized, with spins antiparallel to the magnetic field direction

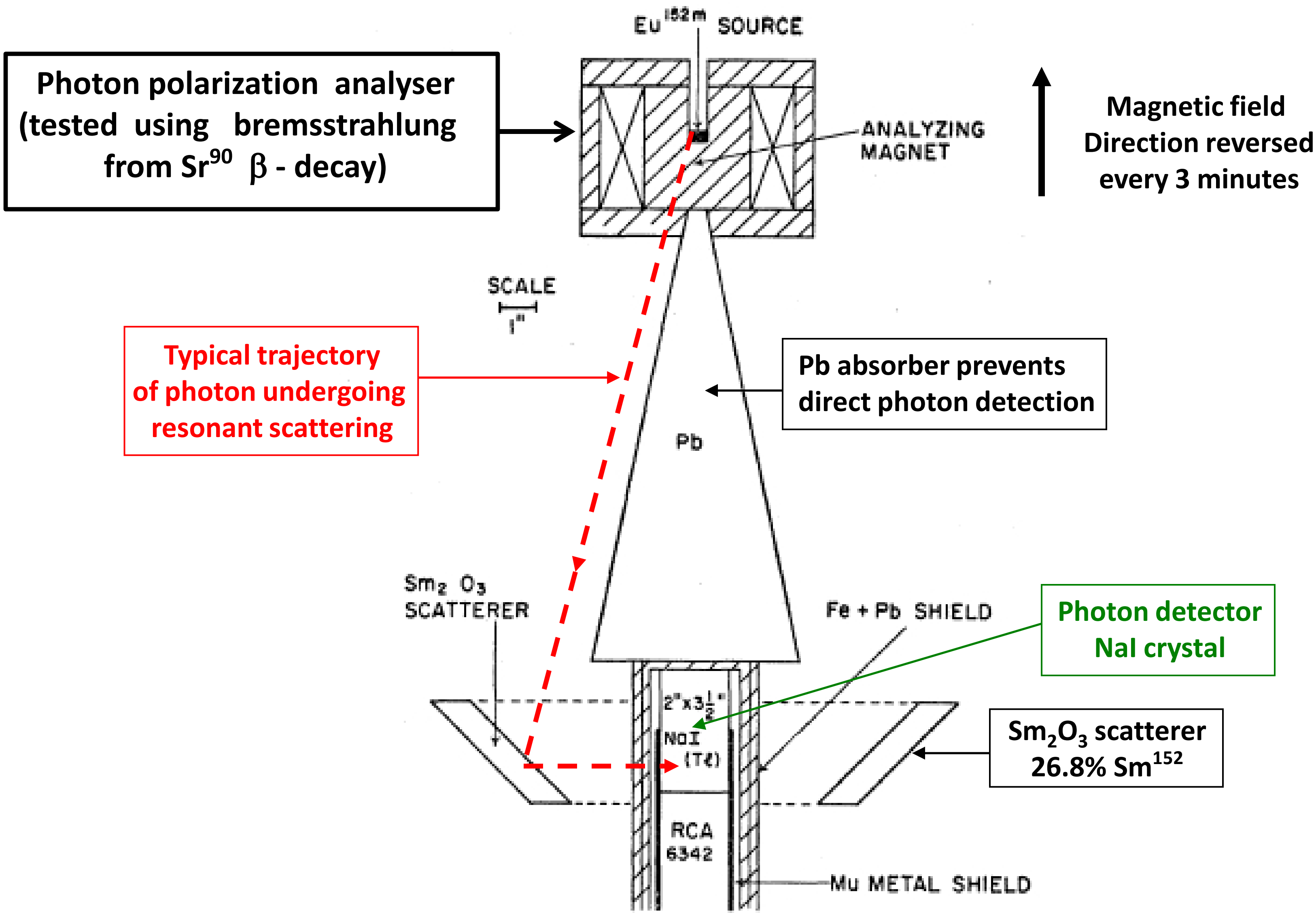
- **Photons emitted in direction opposite to neutrinos are selected by resonant scattering on Sm_2O_3 : $\gamma + Sm^{152} \rightarrow (Sm^{152})^* \rightarrow Sm^{152} + \gamma$**



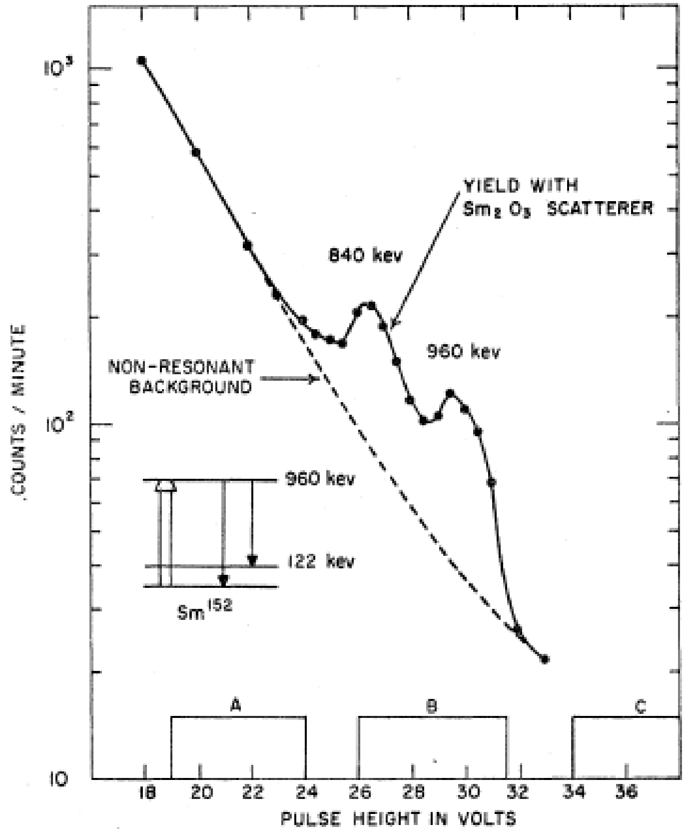
E_γ depends on emission angle



Detector


Photon polarization analyser
(tested using bremsstrahlung
from Sr^{90} β - decay)
Eu^{152m} SOURCE
ANALYZING
MAGNET
Magnetic field
Direction reversed
every 3 minutes
SCALE
1"
Typical trajectory
of photon undergoing
resonant scattering
Pb absorber prevents
direct photon detection
Pb
Sm_2O_3
SCATTERER
Fe + Pb SHIELD
Photon detector
NaI crystal
2"x3½"
NaI
(Tl)
Sm_2O_3 scatterer
26.8% Sm^{152}
RCA
6342
Mu METAL SHIELD

Results



(proportional to photon energy)

~3 x 10^6 counts recorded in channel B

Measured asymmetry with respect to magnetic field reversal:

$$\Delta = \frac{N_- - N_+}{0.5(N_- + N_+)} = +0.017 \pm 0.003$$

N_+ (N_-) : counts with field up (down)

Higher photon transmission with field down → electron spin up → photon spin up

Measured value of Δ consistent with photon polarization (68 ± 14)% and negative helicity

Expect ~75% reduction of photon polarization from detected angular region

→ Result consistent with 100% negative helicity of neutrinos

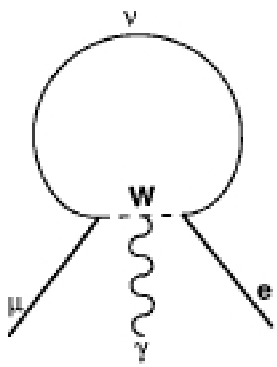
Discovery of the 2nd neutrino (ν_μ)

Historical introduction

1950s: negative searches for the rare muon decay $\mu \to e + \gamma$ at synchrocyclotrons
(Berkeley, Chicago, Nevis, CERN)

$$B(\mu \to e+\gamma) = \frac{\Gamma(\mu \to e+\gamma)}{\Gamma(\mu \to e+\nu+\bar{\nu})} < 10^{-8}$$

- **No selection rule forbidding this decay was known**
- **Expect $\mu \to e + \gamma$ decay as a higher-order weak transition, but the decay amplitude could not be calculated because of divergent integrals in Fermi's theory**
- **Assumption: the weak interaction is mediated by the exchange of a charged vector boson $W^\pm$ → the cross-section for neutrino interactions does not increase indefinitely with energy . Also, $B(\mu \to e + \gamma)$ can be calculated under reasonable assumptions on the W mass**



Prediction: $B(\mu \to e + \gamma) \approx 10^{-4}$
(Feinberg 1958)

An important remark (Cabibbo & Gatto, Feinberg & Weinberg 1960) :

the $\mu \to e + \gamma$ transition amplitude may be very small (or even zero) for real photons, while being large for virtual photons

→ search for neutrinoless μ^- capture $\underbrace{\mu^- + (A,Z)}$ $\to$ $e^- + (A,Z)$

muonic atom
formed by stopping
μ^- in matter

Result of a 1961 CERN experiment:
(Conversi et al, 1961)

$$\frac{\Gamma(\mu^- + Cu \to e^- + Cu)}{\Gamma(\mu^- + Cu \to \nu + Ni^*)} < 2.4 \times 10^{-7}$$

Invent a new quantum number ("muonic flavor") which distinguishes muons from electrons and forbids $\mu \to e + \gamma$ decay and neutrinoless μ^- capture

However, the ordinary decay $\mu \to e + \nu + \bar{\nu}$ is allowed

→ two different neutrinos are required in order to conserve muonic flavor

$$\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e \qquad\qquad \mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

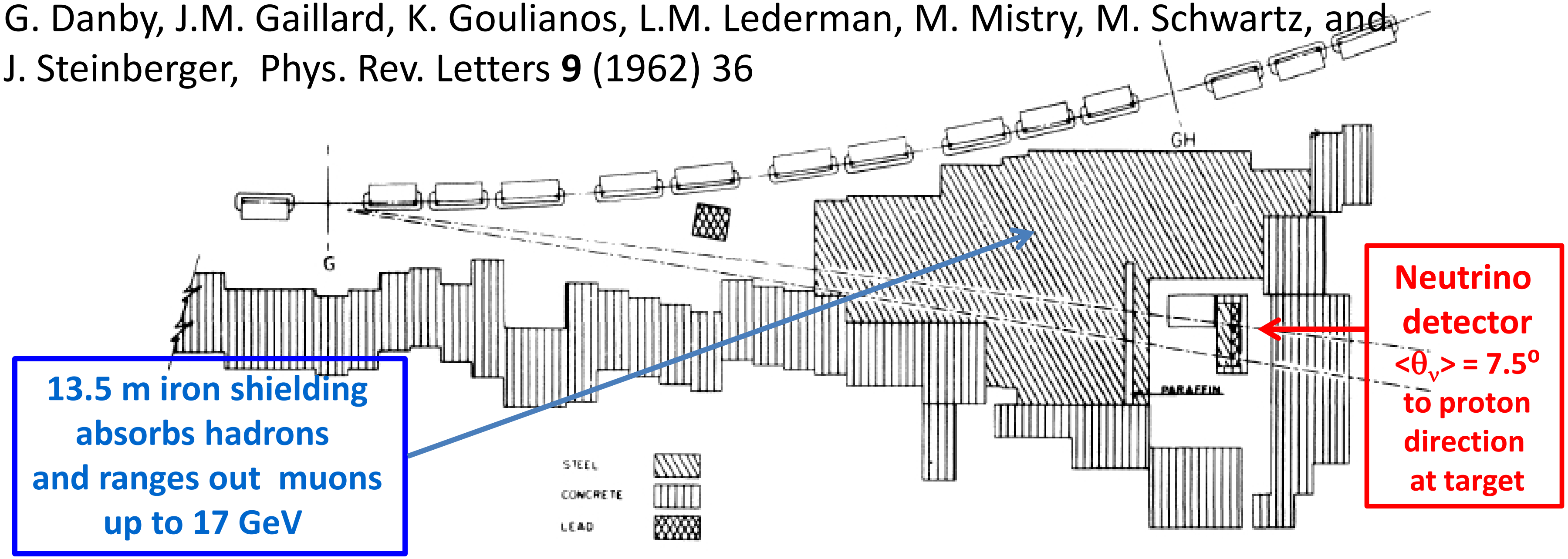
➡ Expect neutrinos from $\pi^+ \to \mu^+ + \nu_\mu$ decay to interact producing only μ^- in reaction ν_μ + nucleon $\to \mu^-$ + anything else

Two experimental proposals:

- B. Pontecorvo (1959): send medium-energy (few x 100 MeV) proton beam into heavy "beam dump" → $\pi^+ \rightarrow \mu^+ + \nu \rightarrow e^+ + \bar{\nu} + \nu$ (most π^- are absorbed before decaying). Detect $\bar{\nu}$ interactions using the Reines – Cowan method. Observe no event if $\bar{\nu} = \bar{\nu}_\mu \neq \bar{\nu}_e$ ($E_\nu \approx \frac{1}{2} m_\mu c^2$).
- M. Schwartz (1960): use neutrinos from $\pi^+ \rightarrow \mu^+ + \nu$ decay in flight at a high – energy accelerator (a method to study neutrino interactions at high energy, no mention of $\nu_\mu \neq \nu_e$ in Schwartz's original article)

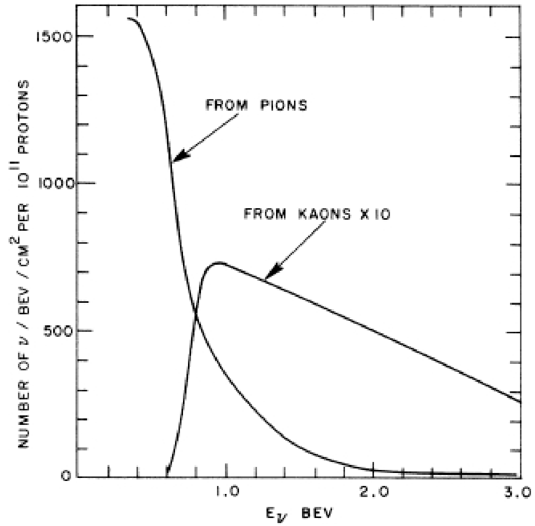
Based on the proposal by Schwartz, an experiment was performed at BNL using the 30 GeV AGS high-energy proton synchrotron (working at 15 GeV for this experiment)

G. Danby, J.M. Gaillard, K. Goulianos, L.M. Lederman, M. Mistry, M. Schwartz, and J. Steinberger, Phys. Rev. Letters **9** (1962) 36



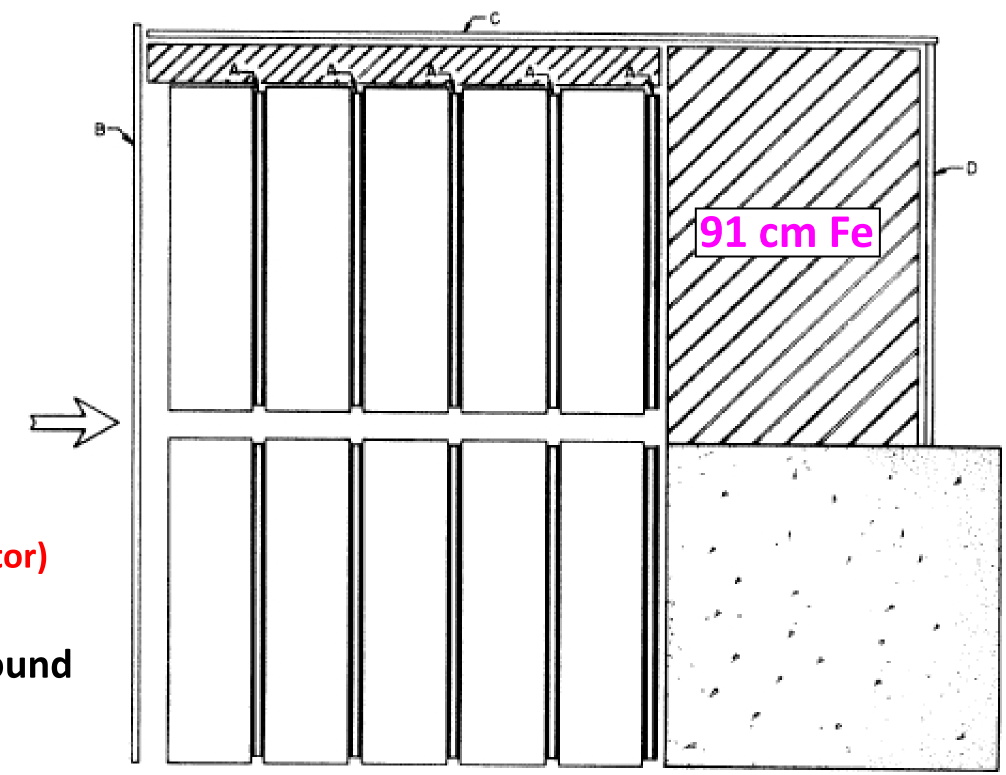
Calculated neutrino energy spectrum at detector from $\pi^\pm \rightarrow \mu^\pm$ and $K^\pm \rightarrow \mu^\pm$ decay in flight

Estimated uncertainty 30% for E_ν > 300 MeV

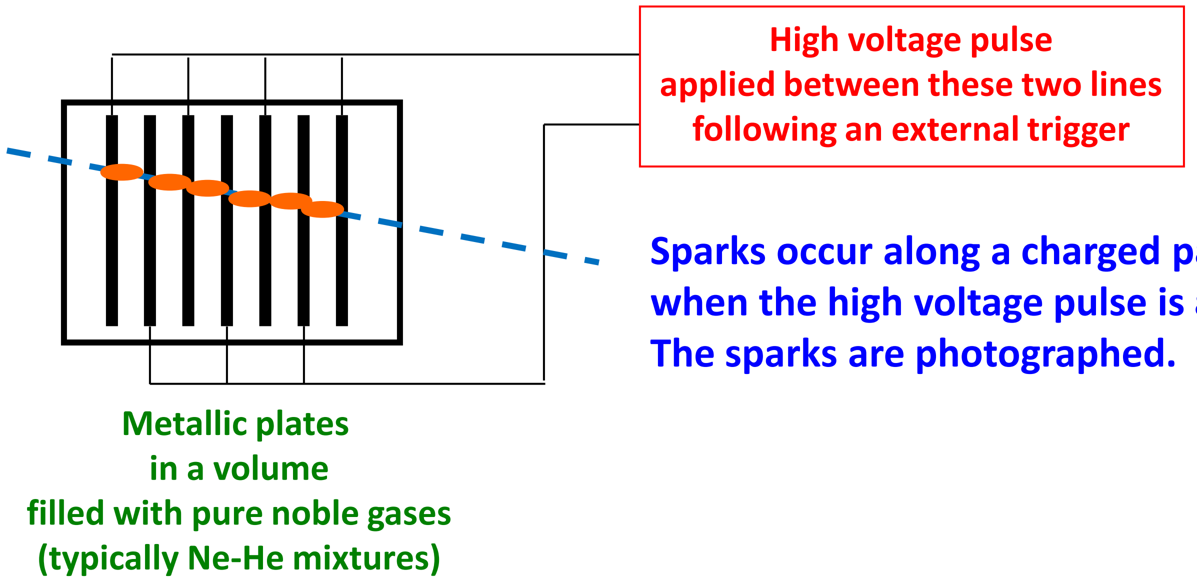


10 – ton neutrino detector

- **10 spark chamber modules**
- **1 module: 9 Al plates, each 112 x 112 x 2.5 cm**
- **A: scintillation counters used in two-fold coincidence for trigger**
- **B, C, D: anticoincidence counters (to remove background from charged particles entering the detector)**
- **Events are recorded only during the AGS beam spills, reducing cosmic ray background by ~10^6**



Spark chambers: track detectors popular in the 1960s (before the invention of MultiWire Proportional Chambers and Drift Chambers)



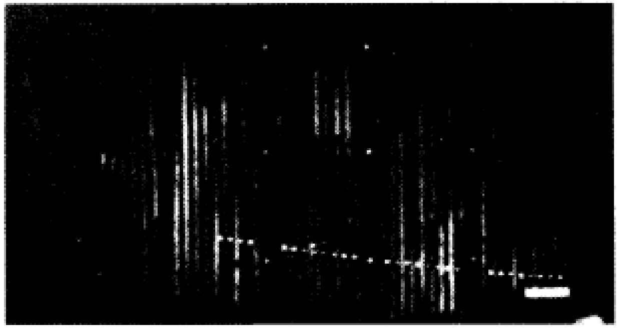
Sparks occur along a charged particle track when the high voltage pulse is applied.
The sparks are photographed.

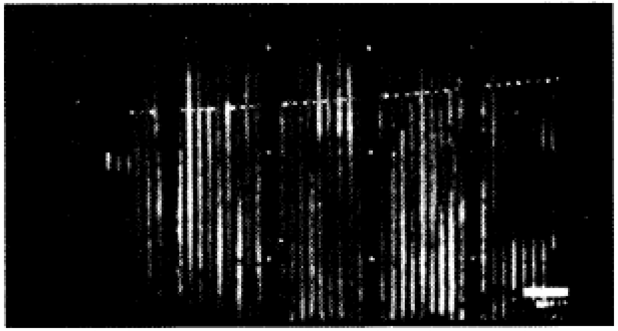
Results for 3.48 x 10^{17} protons on target (~400 data-taking hours)

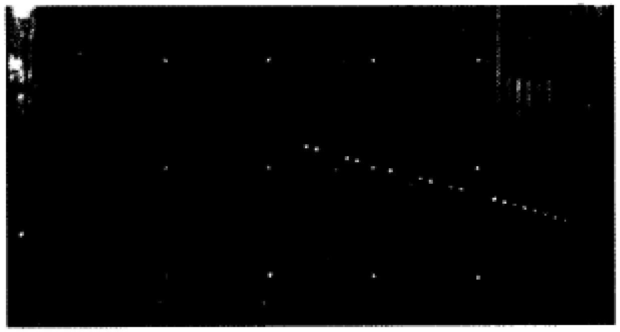
113 events originating inside the detector:

- 49 single tracks with p_μ < 300 MeV/c (momentum estimated assuming that the track is a muon)
- 34 single tracks with p_μ > 300 MeV/c
- 22 "vertex" events (more than one track at the origin)
- 8 "shower" events

Estimated cosmic ray background 5 ± 1 events



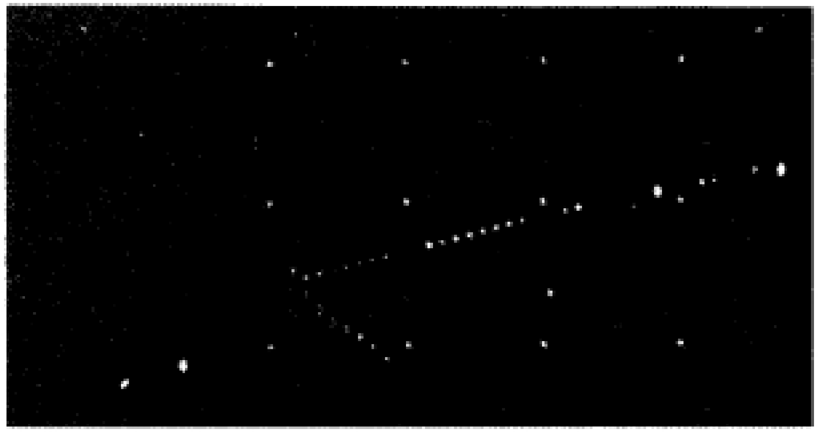




Three typical single track events
with $p_\mu > 300$ MeV/c

Total track length 820 cm Aluminium
→ no interaction observed
The mean free path in Al is < 100 cm for π^+
and ~9 cm for electrons
→ tracks are muons

In a special run, 1.2 m of iron are removed from the shielding and replaced by an equivalent thickness of Pb placed as close as possible to the proton target to absorb $\pi^\pm$ and $K^\pm$ before decaying
→ The event rate drops by a factor ~5
as expected for neutrinos from
$\pi^\pm$ and $K^\pm$ decay



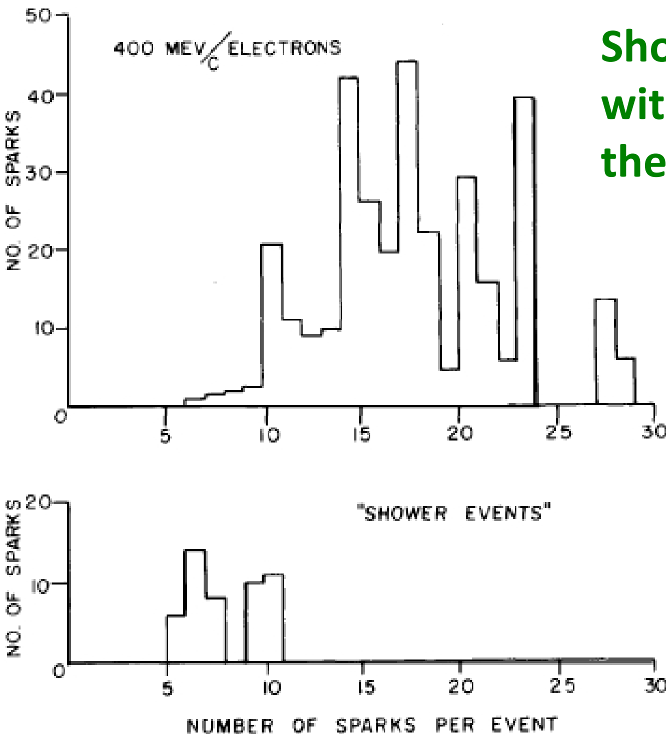
A typical "vertex" event

15 "vertex" events have visible energy < 1 GeV

7 have visible energy > 1 GeV

The 8 "shower events" are single tracks, too irregular to be muons – are they electrons?

Compare number of sparks in these events with number of sparks measured for 400 MeV/c electrons



Shower events not consistent with 400 MeV/c electrons – the authors suggest that these events might be neutron background

Conclusions:

- The 34 single tracks with p > 300 MeV/c are consistent with muons
- No event consistent with a single electron is seen
- Interactions of neutrinos from $\pi^{\pm}$ or $K^{\pm}$ decay produce muons and not electrons

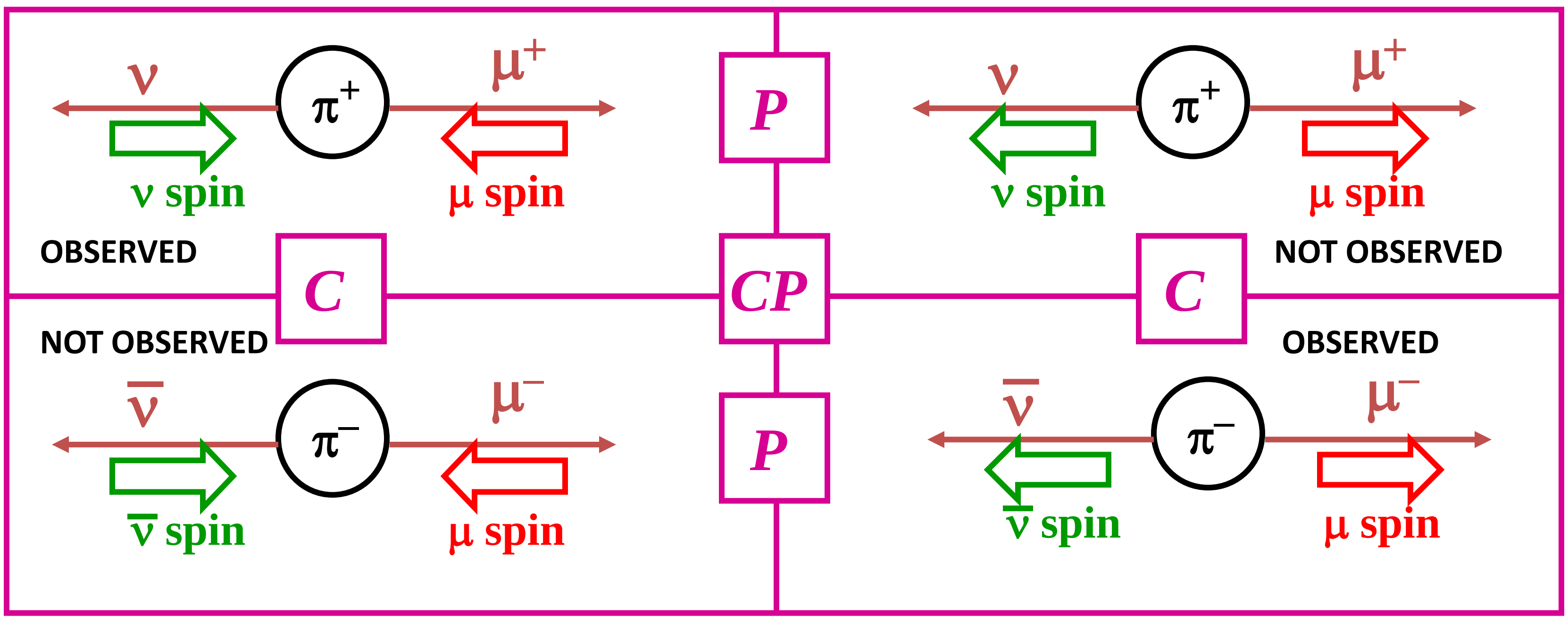
$\Rightarrow \nu_\mu \neq \nu_e$

DISCOVERY OF THE VIOLATION OF CP SYMMETRY

Studies of weak decays in the late 1950s had shown that Parity (P) and Charge Conjugation (C) symmetries are maximally violated in the weak interaction, leading to the V – A theory with two-component neutrinos.

However, the weak interactions appeared to be invariant under combined C and P transformations → CP symmetry

An example of CP symmetry with maximal violation of C and P: $\pi^\pm \rightarrow \mu^\pm$ decay



K^0 and $\overline{K}^0$ mesons have common decay modes resulting in $K^0 - \overline{K}^0$ mixing:

Example: $$K^0 \Leftrightarrow \pi^+\pi^- \Leftrightarrow \overline{K}^0$$

Because of strangeness conservation in the strong interaction, hadronic collisions produce pure K^0 or $\overline{K}^0$ states.

However, because of mixing, the state at a certain distance from the production point is a superposition of K^0 and $\overline{K}^0$ states. Two eigenstates of CP were defined:

$$K_1^0 = \frac{K^0 + \overline{K}^0}{\sqrt{2}}$$ **(CP = +1) ; and** $$K_2^0 = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$$ **(CP = -1)**

(Gell-Mann and Pais, 1955)

$\pi^+\pi^-$ and $\pi^0\pi^0$ states with J = 0 have CP = +1: they were allowed by CP conservation for K_1^0 , forbidden for K_2^0 decay, with the consequence that K_1^0 and K_2^0 have different lifetimes: $\tau(K_2^0) > \tau(K_1^0)$

A long lifetime K^0 meson was discovered in 1958 at the BNL 3 GeV Cosmotron using a cloud chamber in a magnetic field (Bardon, Lane, Lederman, Chinowsky)

[Today's lifetime values are $\tau(K_S^0)$ = 8.95 x 10^{-11} s, $\tau(K_L^0)$ = 5.12 x 10^{-8} s]

K_1^0 regeneration (Pais, Piccioni 1956)

Because of strangeness conservation in the strong interaction, K^0 and $\overline{K}^0$ interact differently with matter.
As a consequence, in a pure K_2^0 state traversing some material the K^0 and $\overline{K}^0$ amplitudes change → K_1^0 will appear
K_1^0 regeneration was first observed in 1957

Coherent K_1^0 regeneration from macroscopic volumes of material also occurs as an effect of the different K^0 and $\overline{K}^0$ scattering amplitudes at 0^o.
The momentum transfer is very small

$$|Q| = \frac{[m(K_2^0)]^2 - [m(K_1^0)]^2}{2E} \qquad \textbf{with} \qquad m(K_2^0) - m(K_1^0) \approx 3.5\times 10^{-6}\ \text{eV}$$

→ the regenerated K_1^0 follows the direction of the incident K_2^0
(M.L. Good 1957)

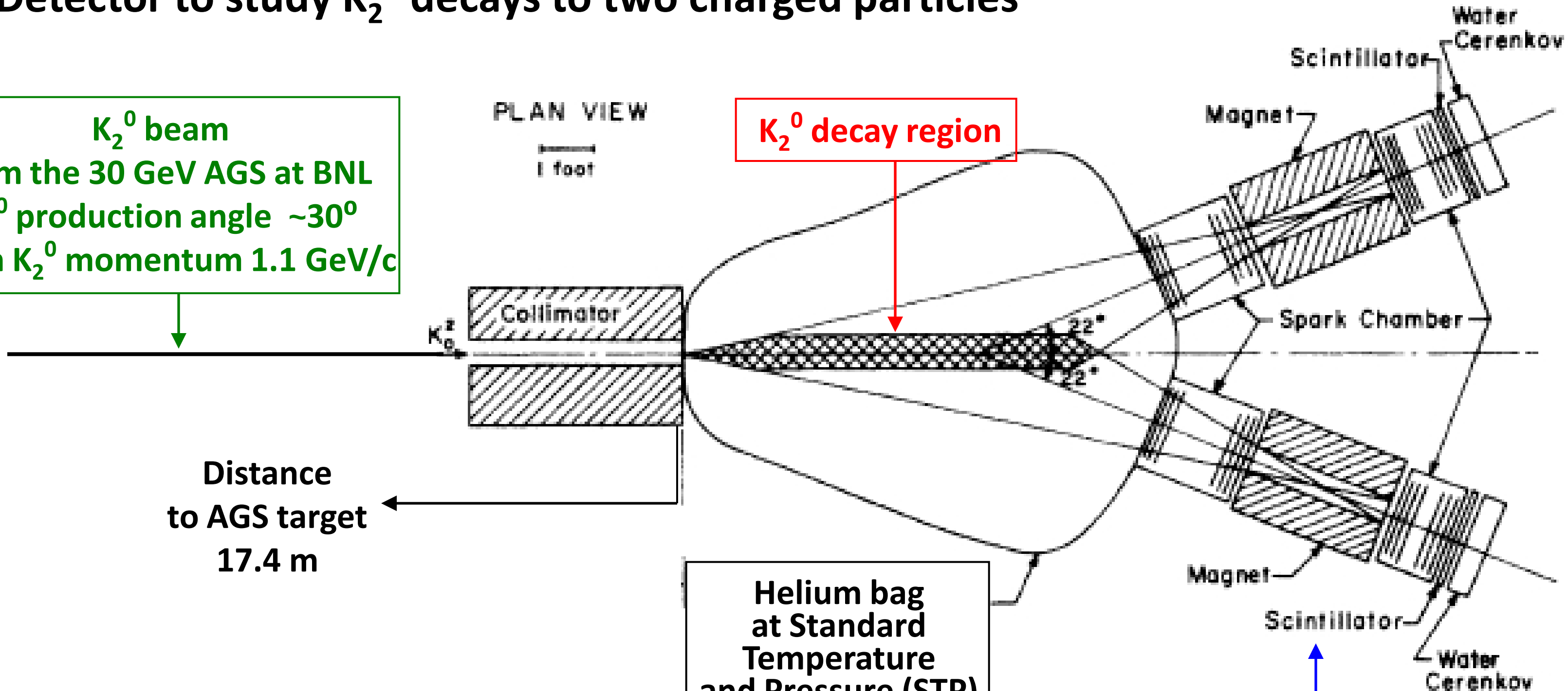
Anomalously large coherent K_1^0 regeneration in liquid hydrogen was observed in 1963 :
19 $K_1^0 \to \pi^+\pi^-$ events collinear with the incident K_2^0 beam ($0.999 < \cos\theta < 1.$)
to be compared with an expectation of 5 events.
(Adair et al., 1963)

Evidence for the 2π decay of the K_2^0 meson

J.H. Christenson, J.W. Cronin, V.L. Fitch, and R. Turlay, Phys. Rev Lett. **13** (1964) 138

Detector to study K_2^0 decays to two charged particles

K_2^0 beam
from the 30 GeV AGS at BNL
K_2^0 production angle ~30°
Mean K_2^0 momentum 1.1 GeV/c



K_2^0 decay region

Distance to AGS target 17.4 m

Helium bag at Standard Temperature and Pressure (STP)

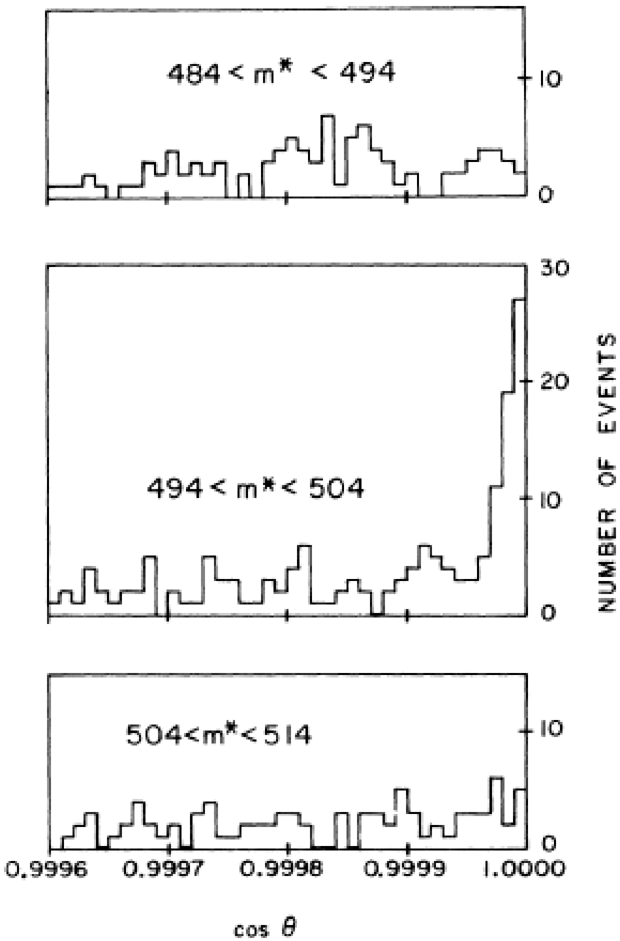
Two identical magnetic spectrometers for charged particle track reconstruction.
Each spectrometer consists of :

- thin plate spark chambers;
- a magnet with bending power 0.452 T x m
- counters for spark-chamber trigger

Final event sample: 5211 K_2^0 decays to two particles of opposite charge sign

Study event distribution in two variables:

- **m* : the invariant mass distribution assuming that both particles are pions;**
- **θ : the angle between the pair total momentum and the K_2^0 beam direction (expect cos θ distribution to peak at 1.0 for two-body decays)**



m* interval below the K^0 mass (497.6 MeV)
Three-body K_2^0 decays with undetected neutral $(\pi^{\pm} e^{\mp}\nu, \pi^{\pm} \mu^{\mp}\nu)$
No peak at cos θ = 1.0

m* interval centered at the K^0 mass
A clear peak at cos θ = 1.0 is observed
The peak contains 45 ± 9 events
(after background subtraction)
consistent with $K_2^0 \to \pi^+\pi^-$ decay

m* interval above the K^0 mass
No peak at cos θ = 1.0

The detector response to $K^0 \to \pi^+\pi^-$ decay is measured using $\pi^+\pi^-$ decays from K_1^0 coherently regenerated by 43 g/cm^2 Tungsten placed at different positions along the decay region

To explain the observed effect need a K_1^0 regeneration rate in Helium gas at STP higher than expected by a factor $\sim 10^6$

The only plausible explanation is the decay $K_2^0 \rightarrow \pi^+\pi^-$ implying violation of CP symmetry .

Branching ratio for $K_2^0 \rightarrow \pi^+\pi^-$ decay calculated from the observed number of events and the total number of K_2^0 decay, after correction for detection efficiencies:

$$R = \frac{K_2^0 \rightarrow \pi^+\pi^-}{K_2^0 \rightarrow \text{all charged modes}} = (2.0 \pm 0.4) \times 10^{-3}$$

The two states propagating in space with definite lifetime are no longer CP eigenstates:

$$K_S^0 = \frac{K_1^0 + \varepsilon K_2^0}{\sqrt{2}} = \frac{(1+\varepsilon)K^0 + (1-\varepsilon)\overline{K}^0}{\sqrt{2}\sqrt{1+|\varepsilon|^2}} \qquad \text{(short lifetime)}$$

$$K_L^0 = \frac{K_2^0 + \varepsilon K_1^0}{\sqrt{2}} = \frac{(1+\varepsilon)K^0 - (1-\varepsilon)\overline{K}^0}{\sqrt{2}\sqrt{1+|\varepsilon|^2}} \qquad \text{(long lifetime)}$$

The complex parameter ε is the amplitude of the small "CP impurity"

Two experimental verifications

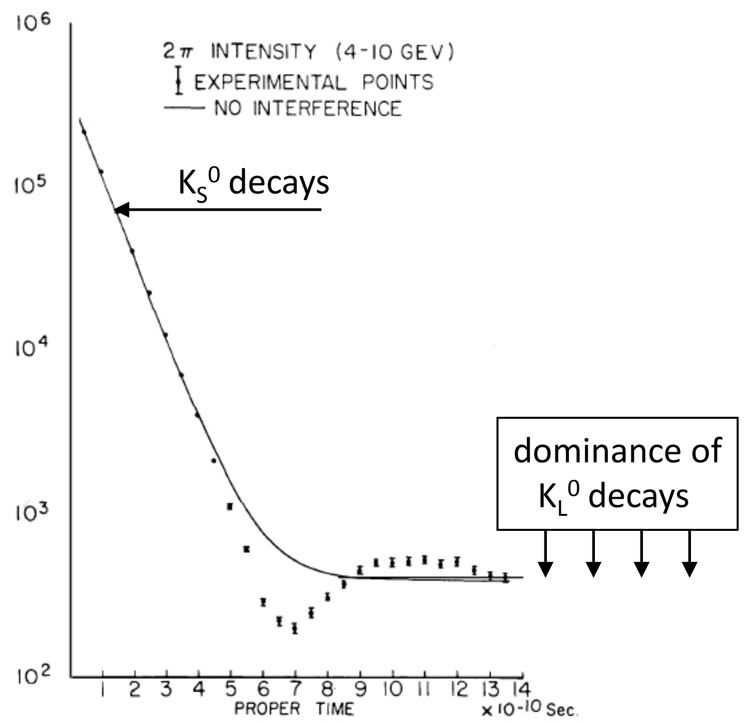
Charge asymmetry in K_L^0 semi-leptonic decays $K_L^0 \rightarrow \pi^{\pm}\ell^{\mp}\nu(\bar{\nu})$

K^0, $\overline{K^0}$ semi-leptonic decays:
$$K^0 \equiv (d\,\bar{s}) \rightarrow (d\,\bar{u}\,\ell^+\,\nu) \equiv \pi^-\,\ell^+\,\nu$$
$$\overline{K}^0 \equiv (\bar{d}\,s) \rightarrow (\bar{d}\,u\,\ell^-\,\bar{\nu}) \equiv \pi^+\,\ell^-\,\bar{\nu}$$
$(\ell = e, \mu)$

$$A = \frac{N(\ell^+) - N(\ell^-)}{N(\ell^+) + N(\ell^-)} = \frac{\left|\langle K^0 | K_L^0 \rangle\right|^2 - \left|\langle \overline{K}^0 | K_L^0 \rangle\right|^2}{\left|\langle K^0 | K_L^0 \rangle\right|^2 + \left|\langle \overline{K}^0 | K_L^0 \rangle\right|^2} = \frac{|1+\varepsilon|^2 - |1-\varepsilon|^2}{|1+\varepsilon|^2 + |1-\varepsilon|^2} = \frac{2\,\mathrm{Re}(\varepsilon)}{1+|\varepsilon|^2}$$

Present values (measured) : $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $A = (3.32 \pm 0.06) \times 10^{-3}$

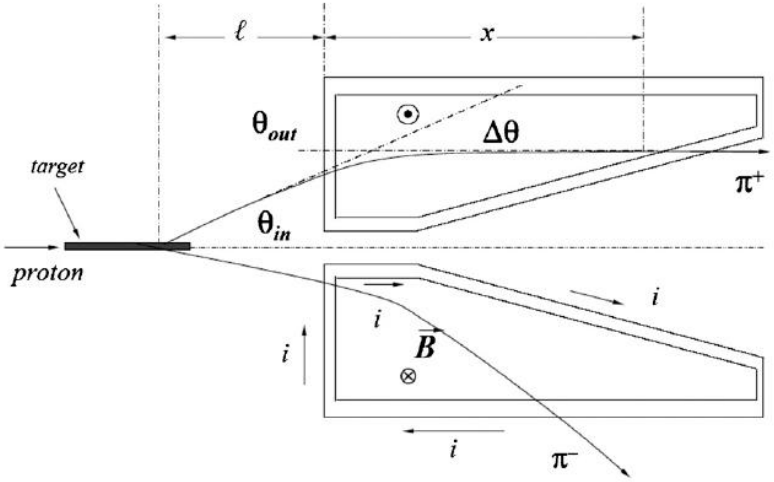
Interference of the $K_L^0 \rightarrow \pi^+\pi^-$ and $K_S^0 \rightarrow \pi^+\pi^-$ decay amplitudes observed by placing a Carbon regenerator, 81 cm long, in a 4 – 10 GeV K_L^0 beam from the AGS: number of observed $\pi^+\pi^-$ decays as a function of the K^0 flight time from regenerator to K^0 decay point in the K^0 rest frame
[W. Carithers, et al., Phys. Rev. Lett. 34 (1975) 1244]



1973: First Observation of Neutrino Neutral – Current Interactions

Improvements in neutrino beams after the discovery of the second neutrino

- **Extraction of the proton beam from the accelerator and transport to an external target**
- **Focusing of positively or negatively charged hadrons to produce an almost parallel beam with wide momentum distribution using "magnetic horns" (invented at CERN in 1963 by S. Van der Meer)**



- **Axially symmetric conductors**
- **Pulsed current**
- **Cylindrically symmetric magnetic field perpendicular to the hadrons produced in the target**
- **Changing the current pulse direction selects opposite charge hadron beams :**
  $\pi^+, K^+ (\rightarrow \nu_\mu) \longrightarrow \pi^-, K^- (\rightarrow \bar{\nu}_\mu)$

1961 – 71 : Development of a renormalizable Unified Electro-weak Theory with Spontaneous Symmetry Breaking (Glashow, Weinberg, Salam, 't Hooft)

This theory predicted new types of neutrino interactions by exchange of the Z boson:

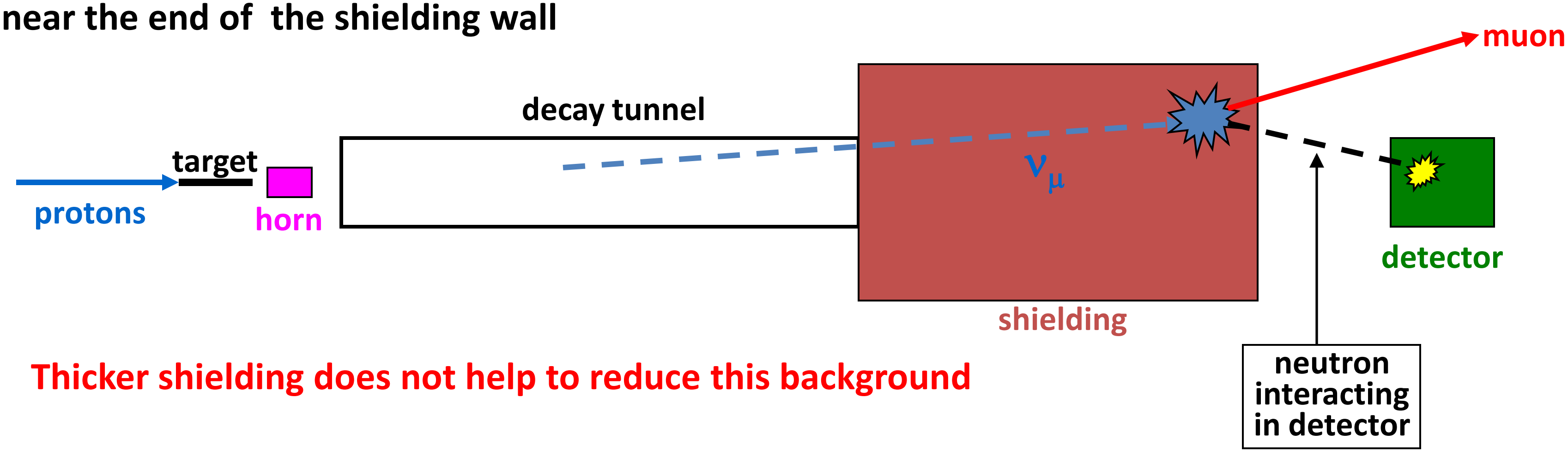
$$\nu\ (\bar{\nu}) + \text{nucleon} \rightarrow \nu\ (\bar{\nu}) + \text{hadrons}$$

$$\nu_\mu\ (\bar{\nu}_\mu) + \text{electron} \rightarrow \nu_\mu\ (\bar{\nu}_\mu) + \text{electron}$$

Why did it take ~10 years to discover neutrino Neutral – Current interactions ?

ν + nucleon $\rightarrow$ ν + hadrons [cross–section typically $\approx 2 \times 10^{-39}\, E_\nu\, cm^2$ (E_ν in GeV)]:

Incident neutrino energies 1 – 2 GeV → little visible energy in the detector → difficult to separate the interaction from interactions of neutrons produced by neutrino interactions near the end of the shielding wall

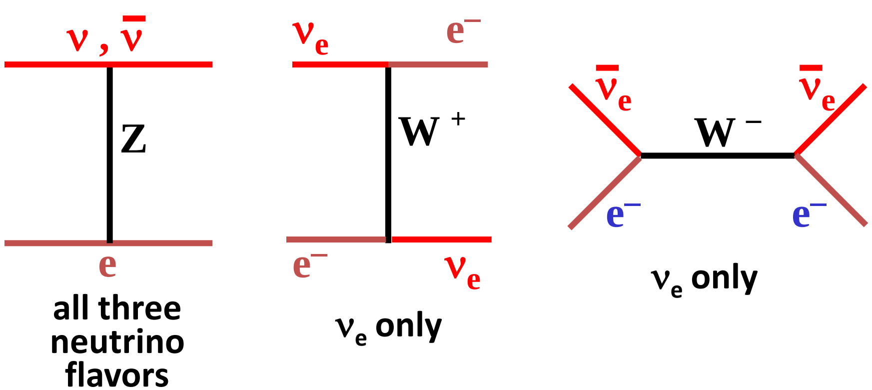


Thicker shielding does not help to reduce this background

ν_μ ($\bar{\nu}_\mu$) + electron $\rightarrow$ ν_μ ($\bar{\nu}_\mu$) + electron

Very small cross–section, typically = A x $10^{-42}\, E_\nu$ cm^2 (E_ν in GeV) ;

Background from ν_e – electron scattering (Charged – Current interaction)



The factor A depends on $\sin^2\theta_W$ (unknown until 1973)

Present values:

$$\nu_e \;:\; A \approx 9.5\,;\;\; \bar{\nu}_e \;:\; A \approx 3.4$$

$$\nu_\mu \;:\; A \approx 1.6\,;\;\; \bar{\nu}_\mu \;:\; A \approx 1.3$$

The general opinion in the early 1970s: if neutrino Neutral–Current interactions exist at all, one needs neutrino beams from a higher energy proton accelerators to discover them:

- Higher cross-section, higher visible energy ;
- Longer muon tracks from ν_μ Charged – Current interactions → easier separation between the two interaction types

However, quite unexpectedly, neutrino Neutral – Current interactions were discovered using neutrino beams from the CERN 26 GeV proton accelerator ($\langle E_\nu \rangle \approx 1.5$ GeV)

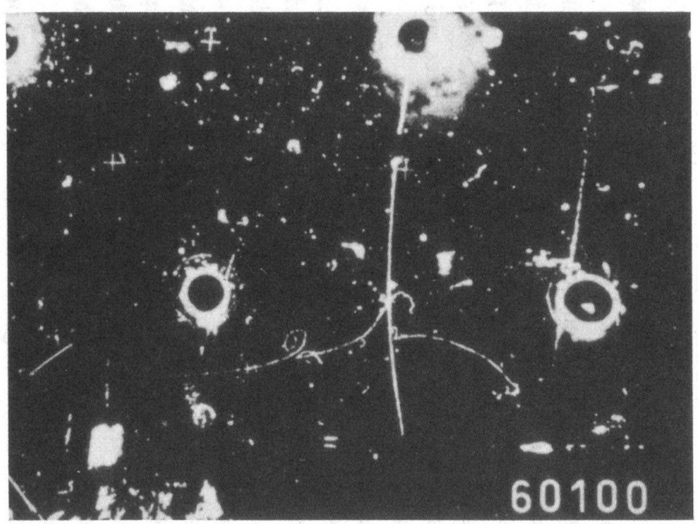
The first hint: an event consisting only of an electron collinear with the beam (mostly $\bar{\nu}_\mu$) in the heavy liquid bubble chamber Gargamelle designed and built by a group led by André Lagarrigue at Ecole Polytechnique (France)

Electron energy 385 ± 100 MeV ; electron angle to beam direction $1.4^o \pm 1.4^o$

F.J. Hasert, et al., Phys. Lett. **46B** (1973) 121

$$\frac{\text{Flux } \nu_e}{\text{Flux } \bar{\nu}_\mu} < 1\%$$

Antineutrino beam direction



4.8 m long bubble chamber filled with CF_3Br

Useful volume 6.5 m^3

Density 1.5 g/cm^3

Radiation length 11 cm

Expected number of $\nu_e + e^- \rightarrow \nu_e + e^-$ events with $E_e > 300$ MeV, $\theta_e < 5^o$: 0.03 ± 0.02

Observation of neutrino-like interactions without muon or electron in Gargamelle

F.J. Hasert, et al., Phys. Lett. **46B** (1973) 138

Events with neutrino beam: 102 Neutral-Current (NC), 428 Charged-Current (CC) events

Events with antineutrino beam: 64 NC, 148 CC events

Study also Associated Stars (AS): neutron stars associated with a CC event giving a muon visible in the chamber. Observe 15 AS with ν , 12 with $\bar{\nu}$.

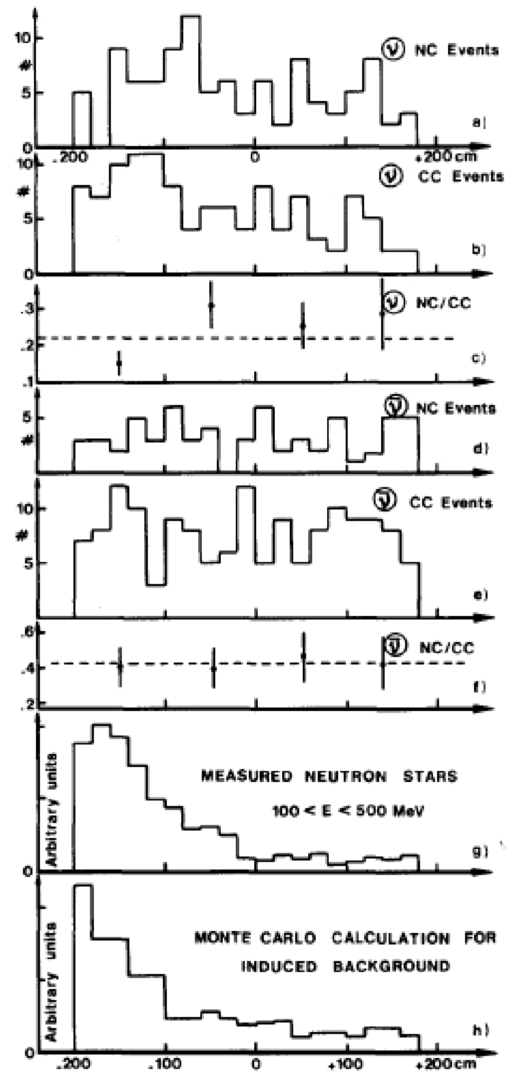
Require total visible energy > 1 GeV in NC events,
total hadronic energy > 1 GeV in CC events.

Distributions of event origin along the beam axis: NC and CC distributions are similar, consistent with uniform distributions as expected for neutrino interactions .

$$(\mathrm{NC/CC})_{\nu} = 0.21 \pm 0.03$$

$$(\mathrm{NC/CC})_{\bar{\nu}} = 0.45 \pm 0.09$$

Associated Stars show decreasing distributions, as expected from the known neutron interaction length.



1973 Discovery of neutral – current neutrino interactions:
the first experimental evidence in favor of the unified electro-weak theory

first measurement of the weak mixing angle θ_w

➡ first quantitative prediction of the $W^{\pm}$ and Z mass values:

$$m_W = 60 - 80 \text{ GeV}$$

$$m_Z = 75 - 95 \text{ GeV}$$

too large to be produced by any existing accelerators

The ideal machine to produce and study the W and Z bosons in the most convenient experimental conditions: a high-energy e^+e^- collider

$$e^+e^- \to Z \qquad\qquad e^+e^- \to W^+W^-$$

still far in the future in the 1970's (first operation of LEP in 1989)

1976: the shortcut to W and Z production

(presented at the Neutrino 76 conference in Aachen)

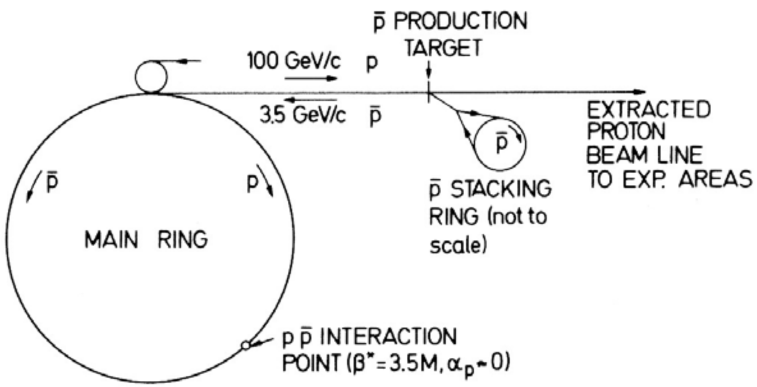
PRODUCING MASSIVE NEUTRAL INTERMEDIATE VECTOR BOSONS WITH EXISTING ACCELERATORS*)

C. Rubbia and P. McIntyre
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
and

D. Cline
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

Presented by C. Rubbia

Abstract: We outline a scheme of searching for the massive weak boson (M = 50 – 200 GeV/c^2). An antiproton source is added either to the Fermilab or the CERN SPS machines to transform a conventional 400 GeV accelerator into a $p\bar{p}$ colliding beam facility with 800 GeV in the center of mass (E_{eq} = 320,000 GeV). Reliable estimates of production cross sections along with a high luminosity make the scheme feasible.



Dominant W and Z production processes at a proton – antiproton collider:

$u + \bar{d} \to W^+$ $\quad\quad$ $\bar{u} + d \to W^-$

$u + \bar{u} \to Z$ $\quad\quad$ $d + \bar{d} \to Z$

Cross-sections calculable from electroweak theory + knowledge of proton structure functions

- **Energy requirements:**

  proton (antiproton) momentum at high energies is carried by gluons (~ 50%) and valence quarks (antiquarks) (~ 50%)

On average: $\quad \text{quark momentum} \approx \frac{1}{6}(\text{proton momentum})$

➡ **collider energy ≈ 6 x boson mass ≈ 500 – 600 GeV**

- **Luminosity requirements:**

  Inclusive cross-section for $p + \bar{p} \to Z$ + anything at ~ 600 GeV: $\sigma \approx 1.6$ nb

  Branching ratio for $Z \to e^+ e^-$ decay ≈ 3%

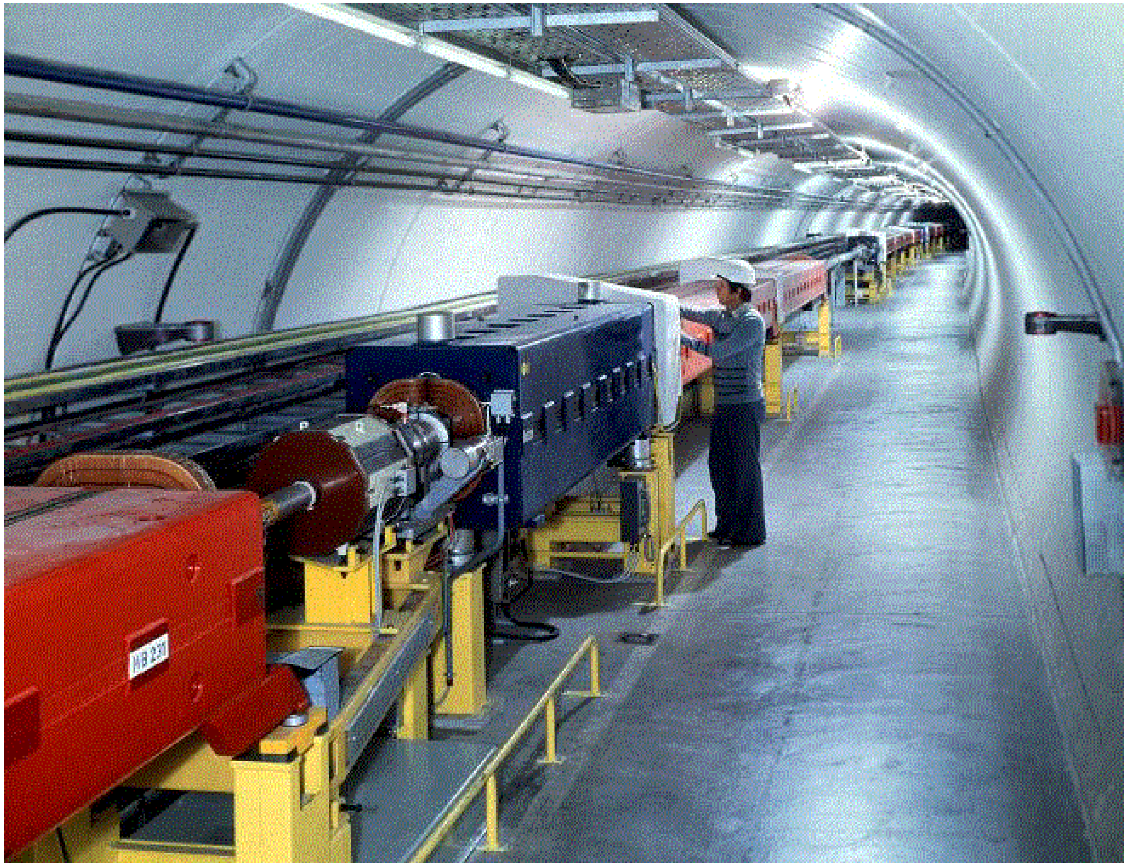
$$\sigma(\bar{p}p \to Z \to e^+e^-) \approx 50\ \text{pb} = 5 \times 10^{-35}\ \text{cm}^2$$

Event rate = L σ [s^{-1}] $\quad$ (L ≡ luminosity)

➡ **1 event / day ⇒ L ≈ 2.5 x 10^{29} cm^2 s^{-1}**

CERN accelerators in 1976

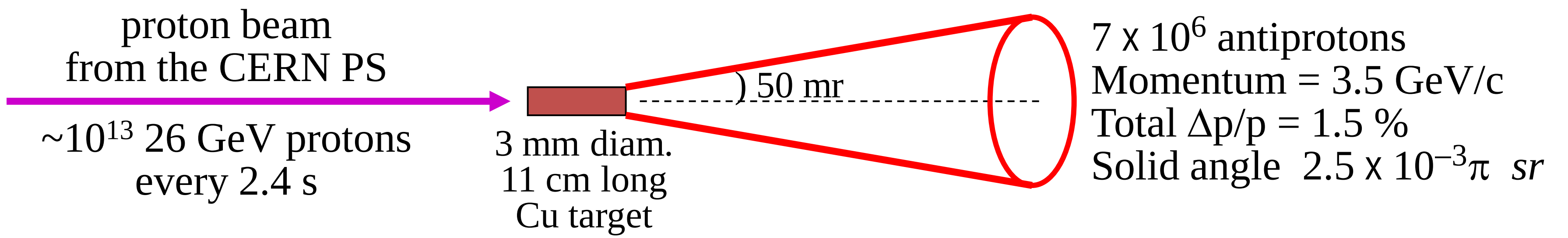
- 26 GeV proton synchrotron (PS) in operation since 1959
- Intersecting Storage Rings (ISR): a proton – proton collider, 31 GeV/beam
- 450 GeV proton synchrotron (SPS) just starting operation



A view of the CERN SPS

To achieve luminosities $\geq 10^{29}$ cm^{-2} s^{-1} need an antiproton source capable of delivering once per day 3×10^{10} $\bar{p}$ distributed into few (3 – 6) tightly collimated bunches within the angular and momentum acceptance of the SPS

Antiproton production:



Number of antiprotons / PS cycle OK

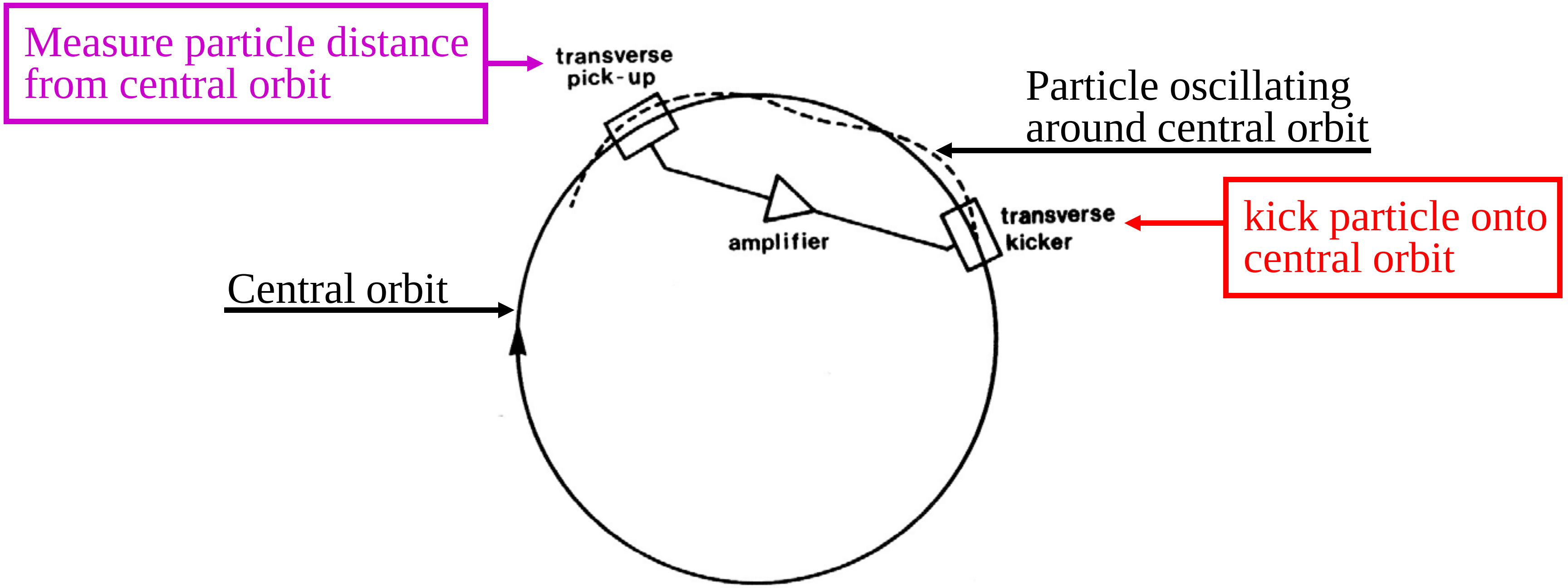
but phase space volume too large by a factor $\geq 10^8$ to fit into SPS acceptance even after acceleration to the injection energy of 26 GeV

must increase the antiproton phase space density by $\geq 10^8$ before sending them to the SPS ("cooling")

"Stochastic" cooling

(invented at CERN by Simon van der Meer in 1972)

Example: cooling of the horizontal motion



In practice, the pick-up system measures the average distance from central orbit of a group of particles (depending on frequency response)

Independent pick-up – kicker systems to cool:

- **horizontal motion**
- **vertical motion**
- **longitudinal motion (decrease of $\Delta p/p$)**
  (signal from pick-up system proportional to Δp)

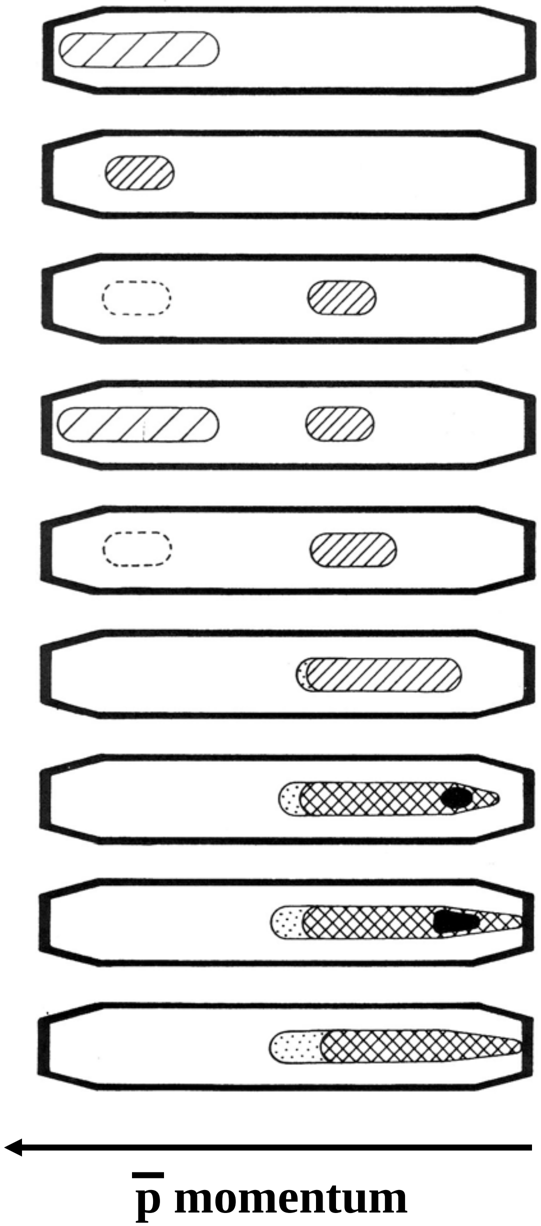
The CERN Antiproton Accumulator (AA)

3.5 Gev/c large-aperture ring for antiproton storage and cooling

(during construction)

AA operation

Section of the AA vacuum chamber



The first pulse of 7 x 10^6 $\bar{p}$ has been injected

Precooling reduces momentum spread

First pulse is moved to the stack region where cooling continues

Injection of 2nd $\bar{p}$ pulse 2.4 s later

After precooling 2nd pulse is also stacked

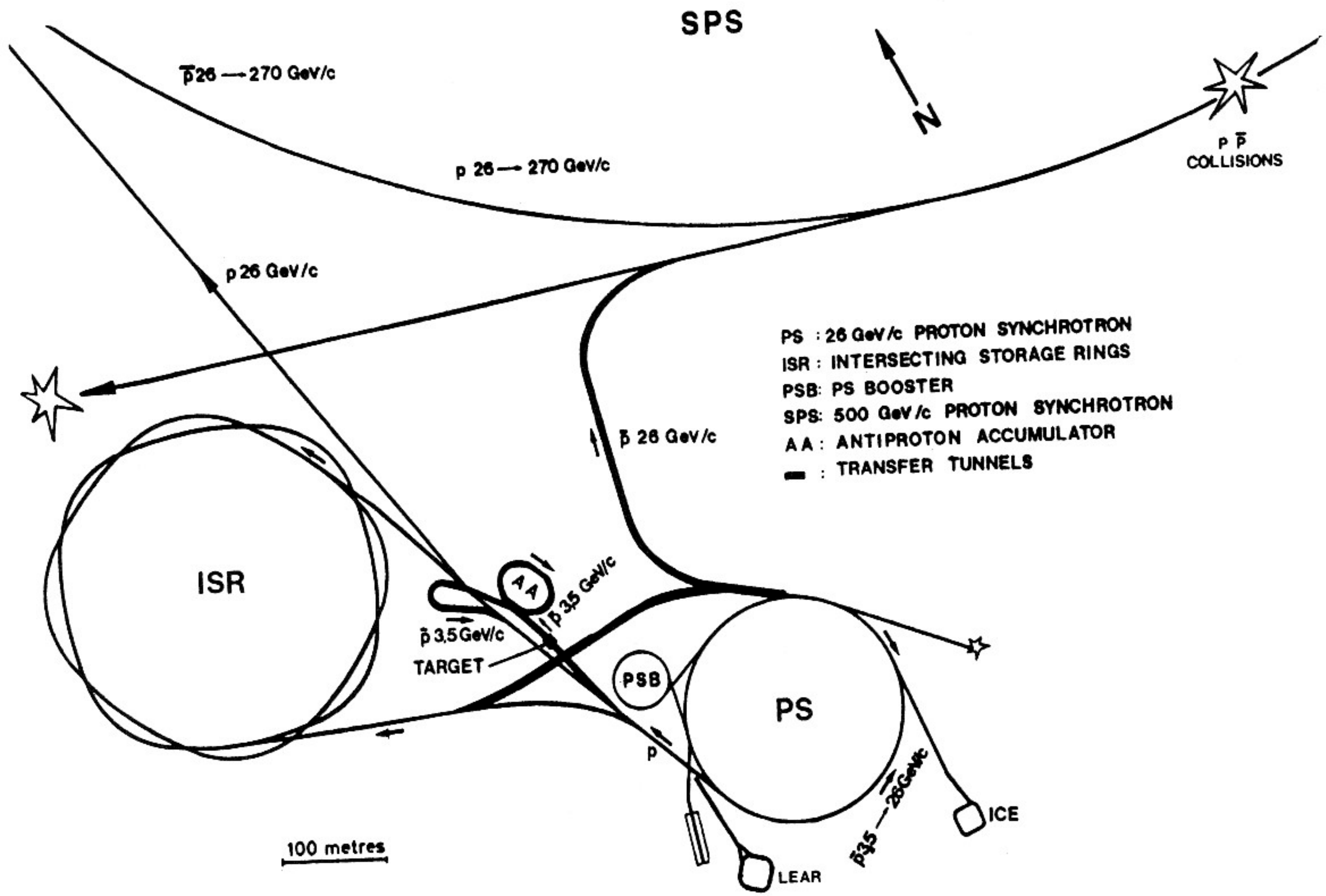
After 15 pulses the stack contains 10^8 $\bar{p}$

After cooling for one hour a dense core is formed inside the stack

After one day the core contains enough antiprotons for transfer to the SPS

The remaining $\bar{p}$ are used for next day accumulation

Sketch of the CERN accelerators in the early 1980's



1986 – 90: add another ring ("Antiproton Collector" AC) around the AA – larger acceptance for single $\bar{p}$ pulses (7×10^7 $\bar{p}$ / pulse $\Rightarrow$ ~ tenfold increase of stacking rate)

Proton – antiproton collider operation, 1981 - 90

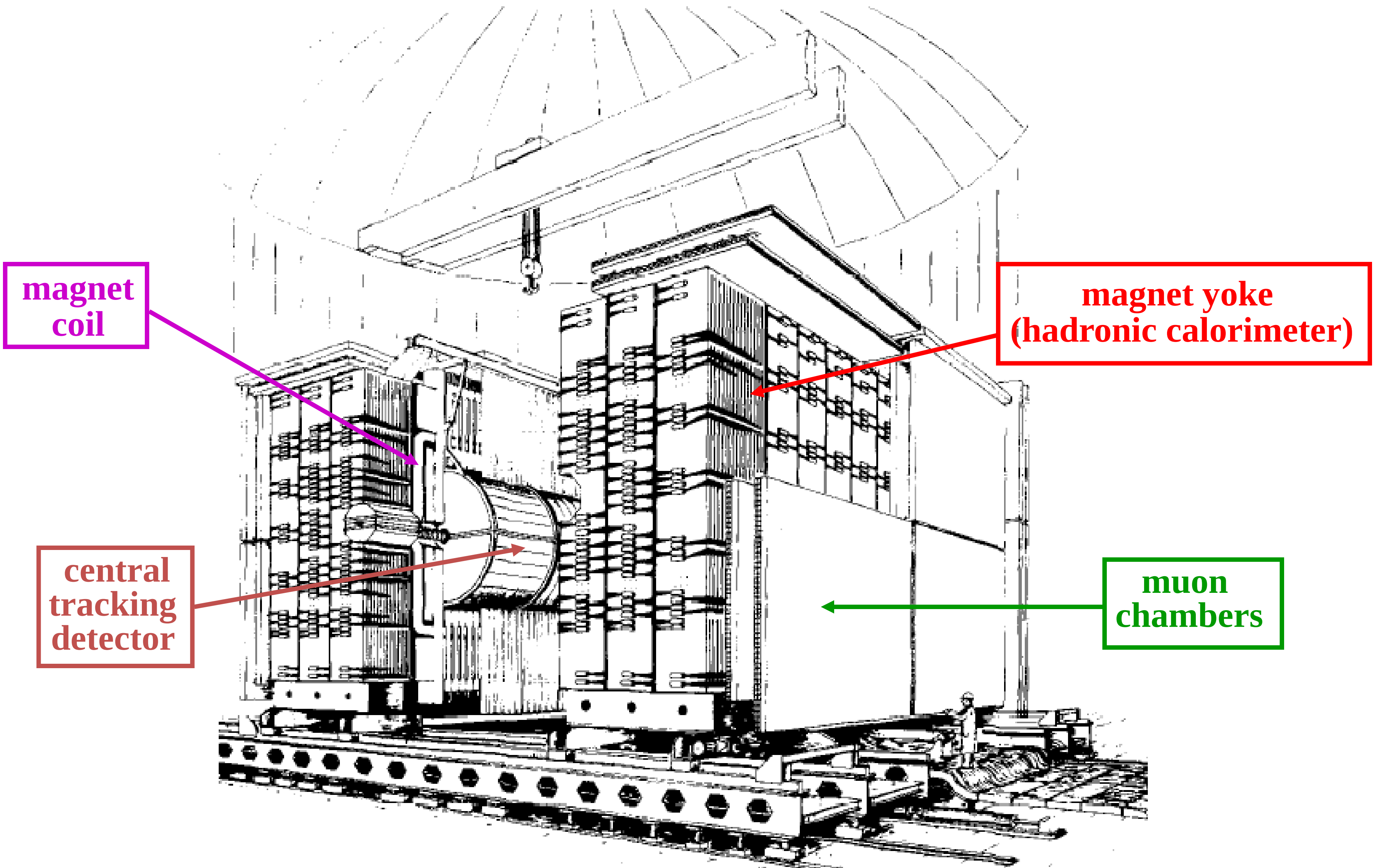
Year	Collision Energy (GeV)	Peak luminosity ($cm^{-2} s^{-1}$)	Integrated luminosity (cm^{-2})
1981	546	$\sim 10^{27}$	2.0×10^{32}
1982	546	5×10^{28}	2.8×10^{34}
1983	546	1.7×10^{29}	1.5×10^{35}
1984-85	630	3.9×10^{29}	1.0×10^{36}
1987-90	630	$\sim 2 \times 10^{30}$	1.6×10^{37}

← W discovery (1982)

← Z discovery (1983)

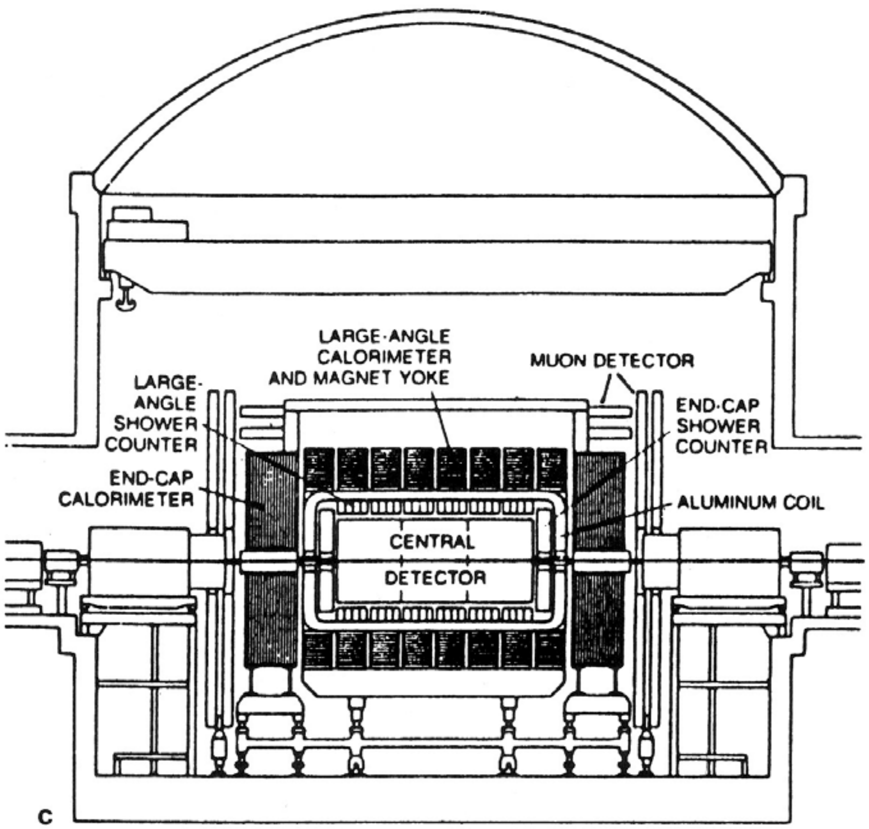
1991: end of collider operation

UA1 detector



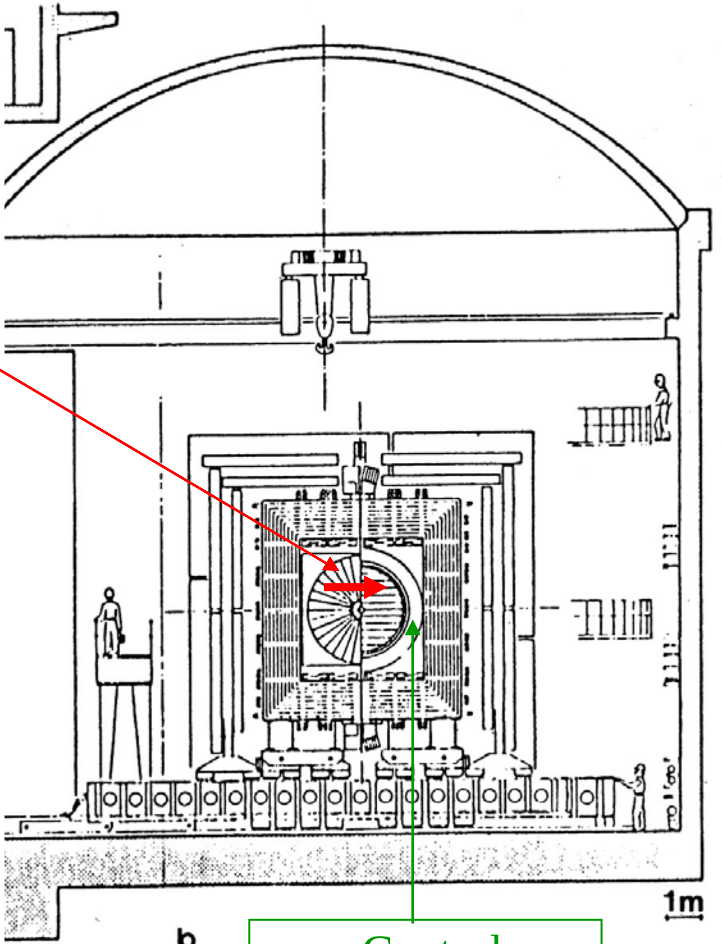
(shown with the two halves of the dipole magnet opened up)

Vertical section along beam axis



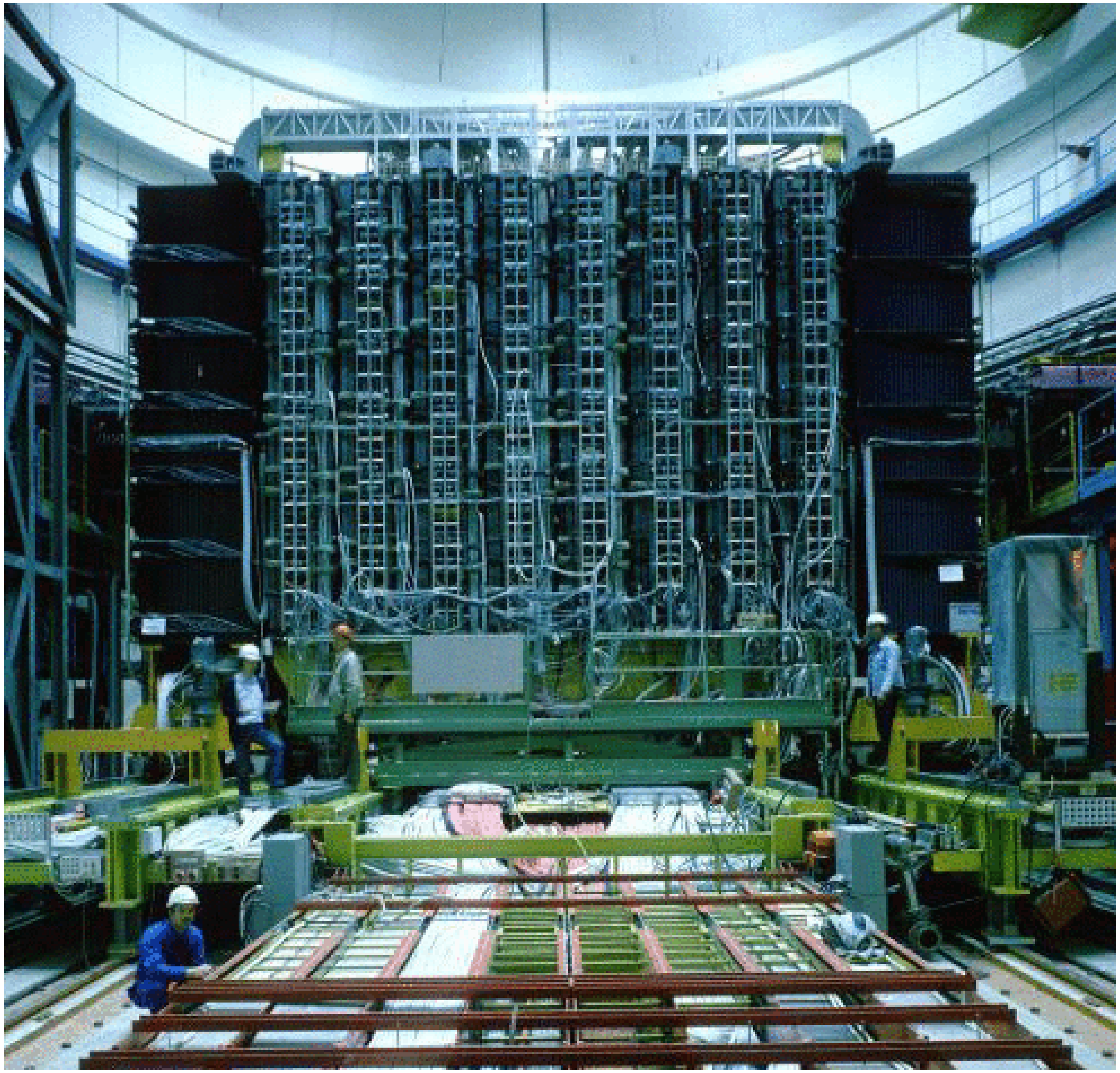
View normal to beam axis

Magnetic field direction

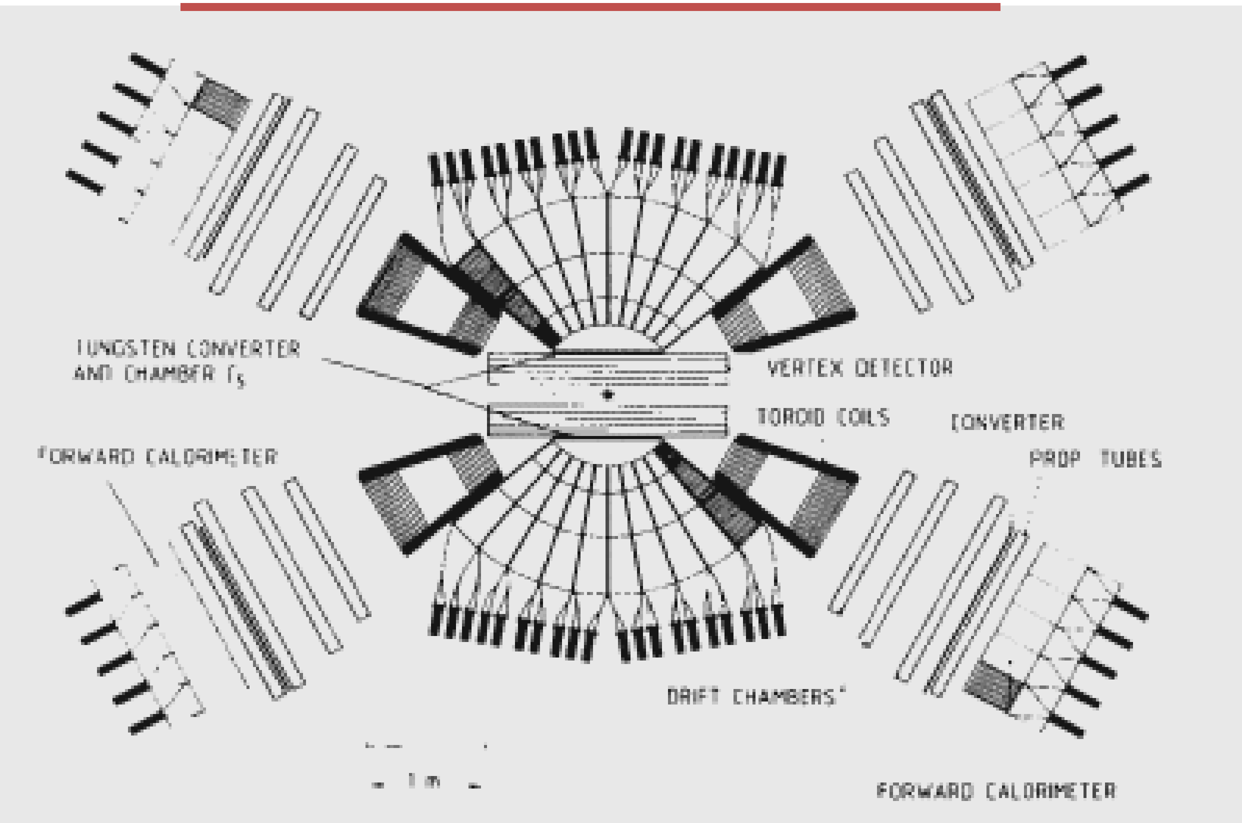


Central electromagnetic calorimeter

UA1 detector during assembly



UA2 Detector 1981 - 85

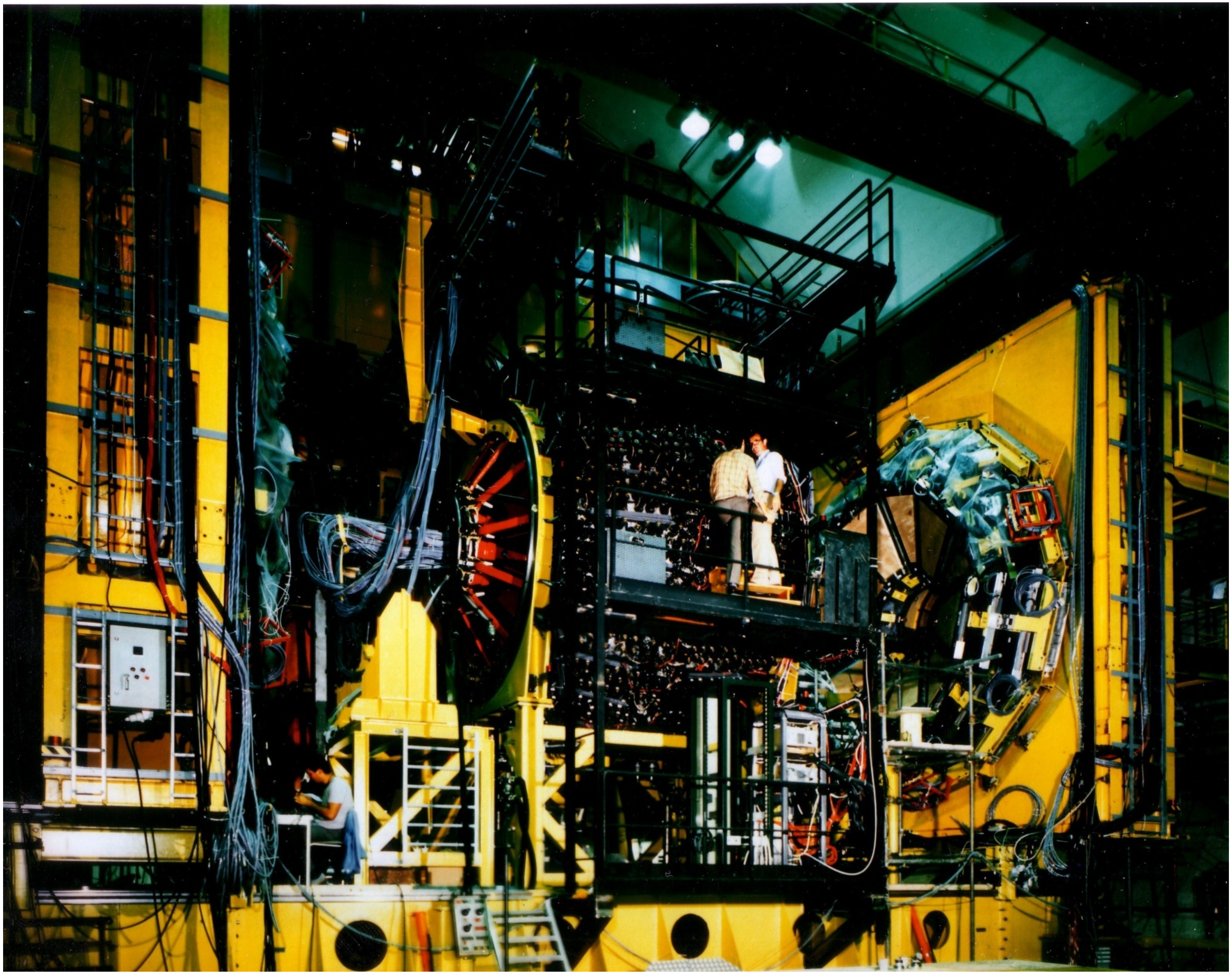


Central region: tracking detector ("vertex detector");
"pre-shower" detector (converter + proportional chamber)
electromagnetic and hadronic calorimeters;
no magnetic field

20° – 40° regions : toroidal magnetic field;
tracking detectors;
"pre-shower" detector + electromagnetic calorimeter.

No muon detector

UA2 detector during assembly



W discovery

Dominant decay mode (~70%) $W \rightarrow q\,\overline{q}' \rightarrow$ two hadronic jets ovewhelmed by two-jet background from QCD processes

$\Rightarrow$ search for leptonic decays:

$W^+ \rightarrow e^+ + \nu_e$ (UA1, UA2)

$W^+ \rightarrow \mu^+ + \nu_\mu$ (UA1 only)

(and charge-conjugate decays)

Expected signal from $W \rightarrow e\,\nu$ decay:

- large transverse momentum (p_T) isolated electron
- p_T distribution peaks at $m_W / 2$ ("Jacobian peak")
- large missing transverse momentum from the undetected neutrino

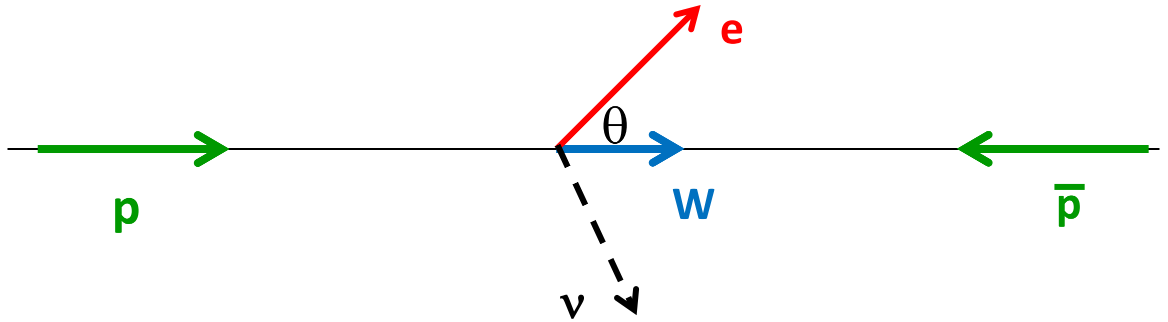
(W produced by quark-antiquark annihilation, e.g. $u + \overline{d} \rightarrow W^+$, is almost collinear with beam axis; decay electron and neutrino emitted at large angles to beam axis have large p_T)

NOTE

Missing longitudinal momentum cannot be measured at hadron colliders because of large number of high-energy secondary particles emitted at very small angles inside the machine vacuum pipe

Jacobian peak in W → e ν decay
A kinematical property of two-body decays

At the CERN proton – antiproton collider W's (and alsoZ's) are produced with Little transverse momentum with respect to the beam axis:



The electron transverse momentum with respect to the beam axis is Lorentz – invariant :

$$p_T = p_e \sin\theta = (M_W/2)\sin\theta^*$$

Electron p_T distribution : $$\frac{\mathrm{dN}}{\mathrm{d}p_T} = \frac{\mathrm{dN}}{\mathrm{dcos}\theta^*}\left|\frac{\mathrm{dcos}\theta^*}{\mathrm{d}p_T}\right|$$ **Jacobian**

$$\cos\theta^* = \sqrt{1-\sin^2\theta^*} = \sqrt{1-(2p_T/M_W)^2} \Rightarrow \left|\frac{\mathrm{d}\cos\theta^*}{\mathrm{d}p_T}\right| = \frac{4p_T/M_W{}^2}{\sqrt{1-(2p_T/M_W)^2}}$$

Jacobian singularity (→ peak) at $p_T = M_W/2$

Neutrinos from μ ν decay of charged pions collinear with the decay tunnel axis:

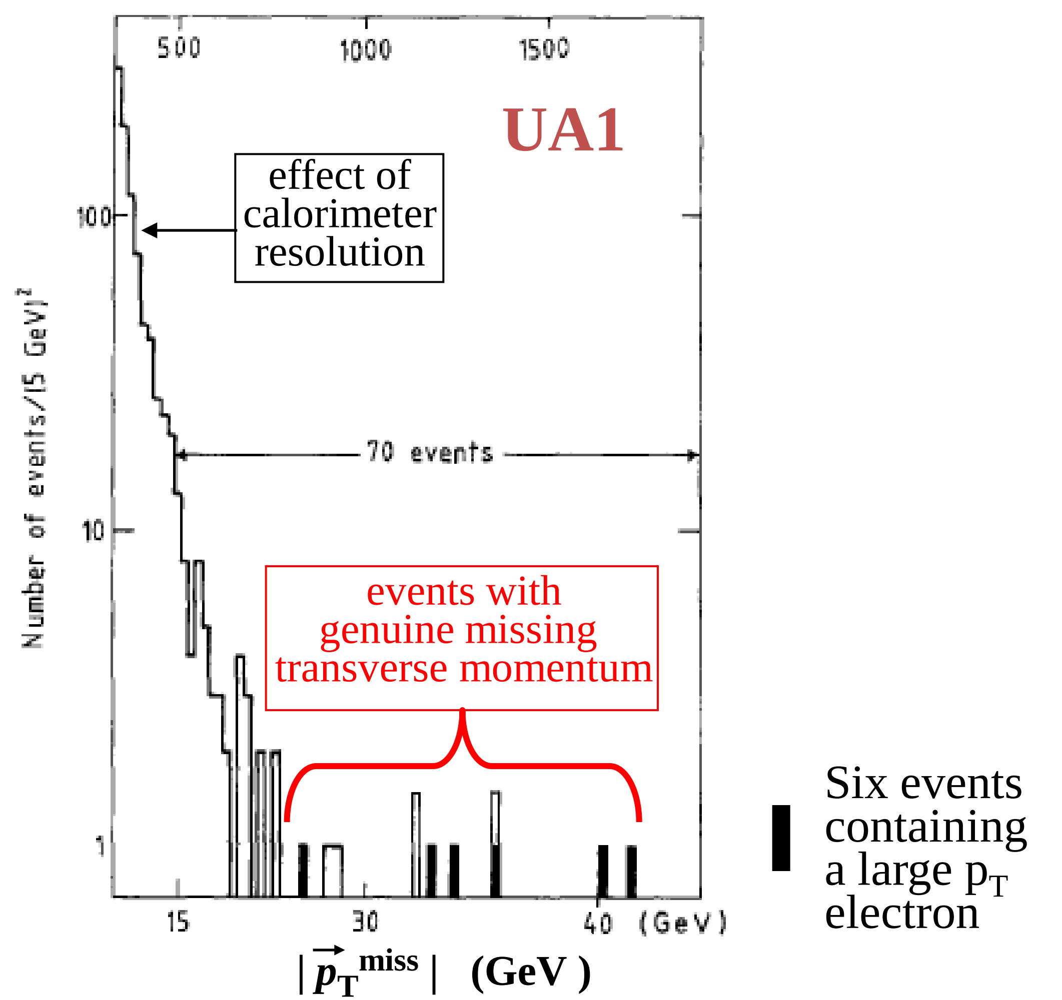
- **The neutrino transverse momentum has a Jacobian peak at $p_T = p^* = 0.030$ GeV/c ;**
- **Off-axis neutrino beam at angle θ has a peak at momentum $p = 0.030/\sin\theta$ GeV/c**

Missing transverse momentum ($\vec{p}_T^{\,miss}$)

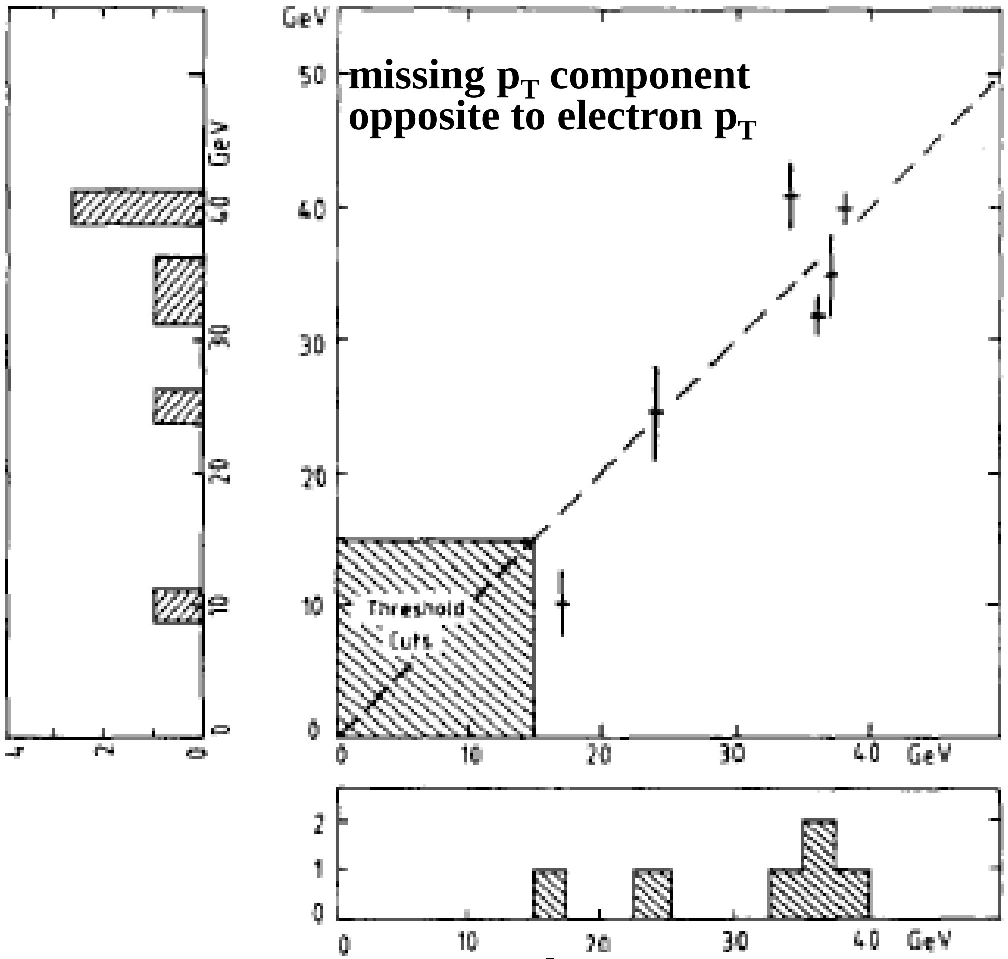
- Associate momentum vector $\vec{p}$ to each calorimeter cell with energy deposition > 0
- Direction of $\vec{p}$ from event vertex to cell centre
- $|\vec{p}|$ = energy deposited in cell
- Definition:

$$\vec{p}_T^{\,miss} + \sum_{cells} \vec{p}_T = 0$$

(momentum conservation in plane perpendicular to beam axis)



UA1: correlation between electron p_T and missing p_T

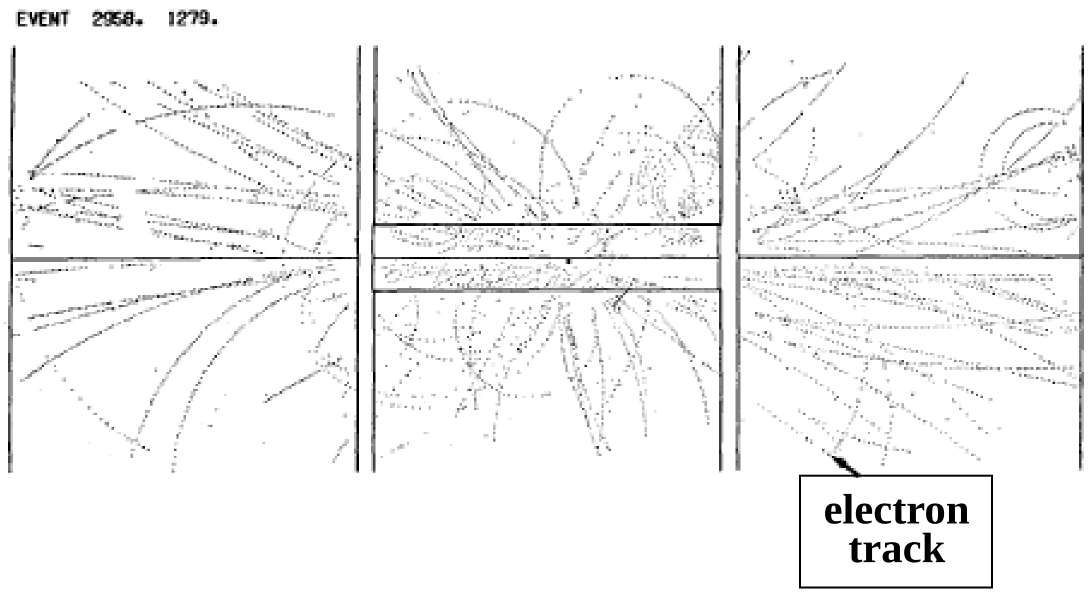


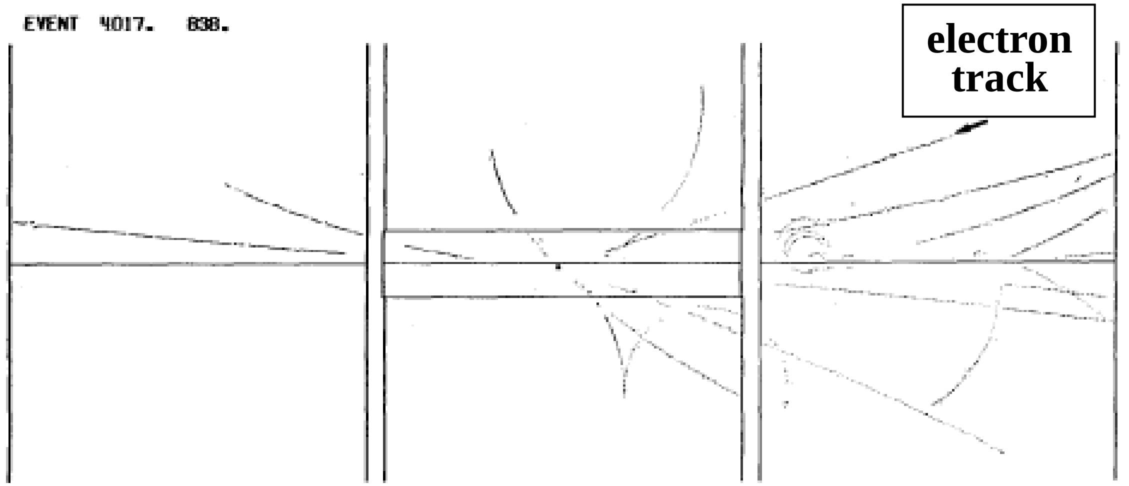
electron p_T

Six events with large p_T electron and large missing p_T opposite to electron p_T consistent with $W \rightarrow e\,\nu$ decay

(result announced at a CERN seminar on January 20, 1983)

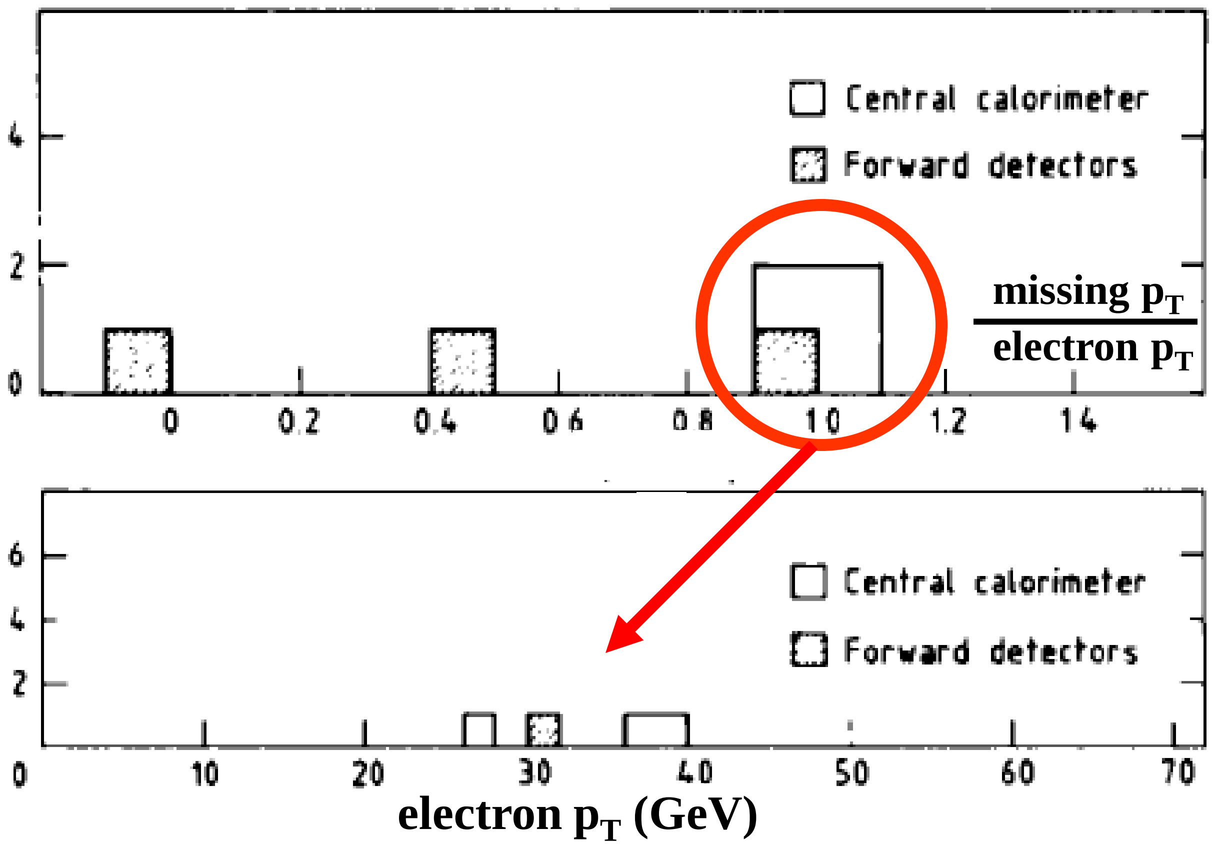
Two UA1 W → e ν events





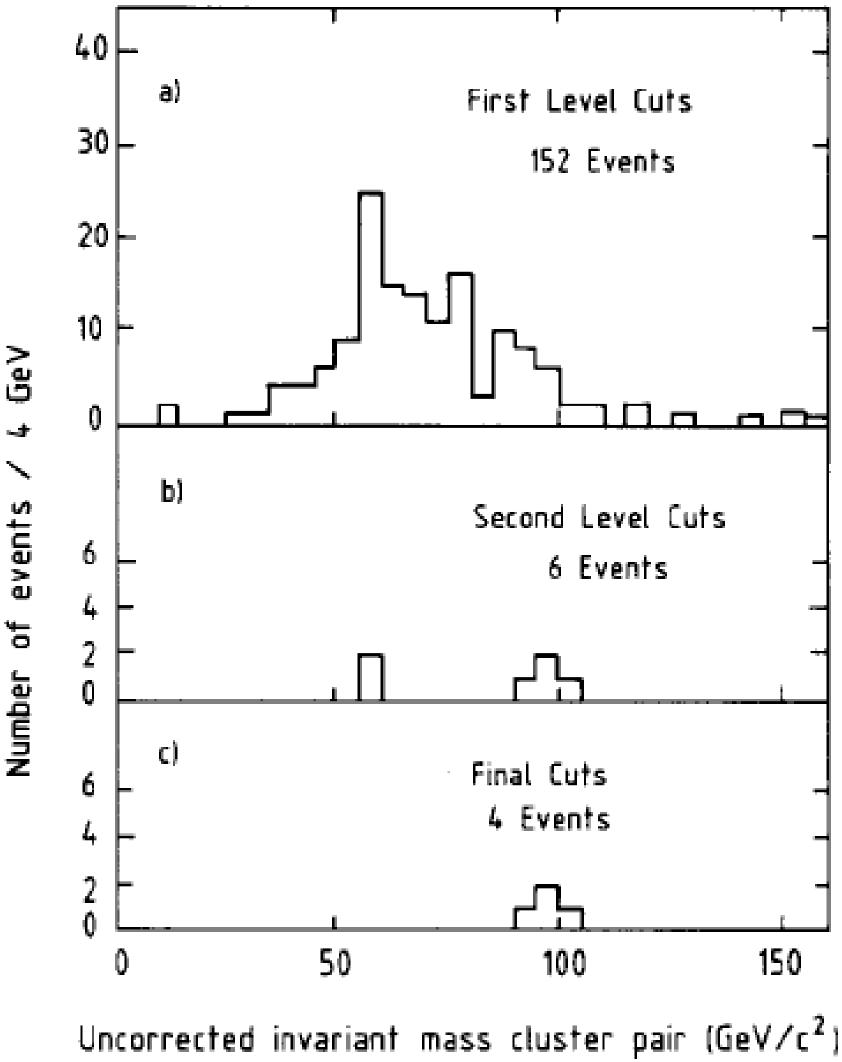
UA2: results presented at a CERN seminar on January 21, 1983

Six events containing an electron with $p_T > 15$ GeV



UA1: observation of $Z \rightarrow e^+ e^-$

(May 1983)

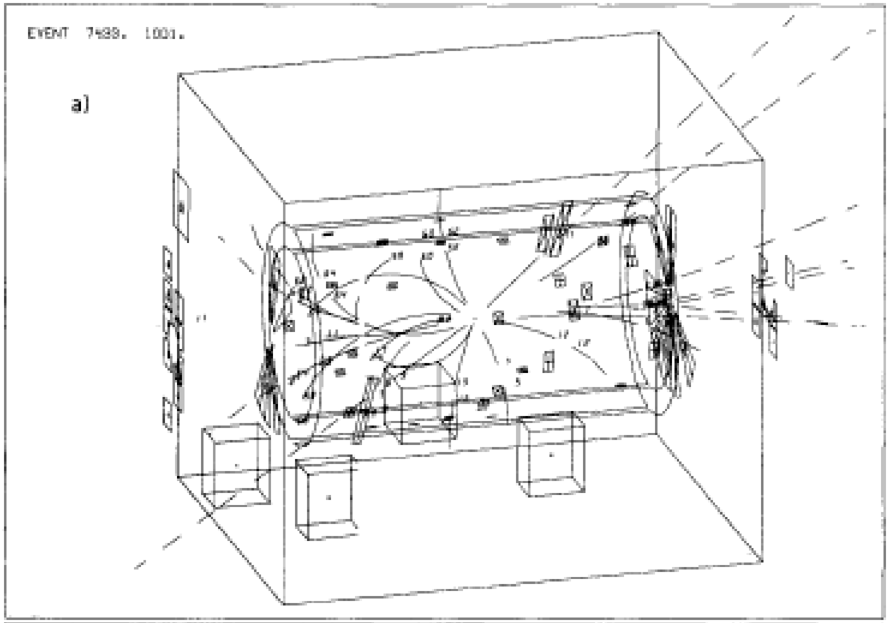


Two energy clusters ($p_T > 25$ GeV) in electromagnetic calorimeters; energy leakage in hadronic calorimeters consistent with electrons

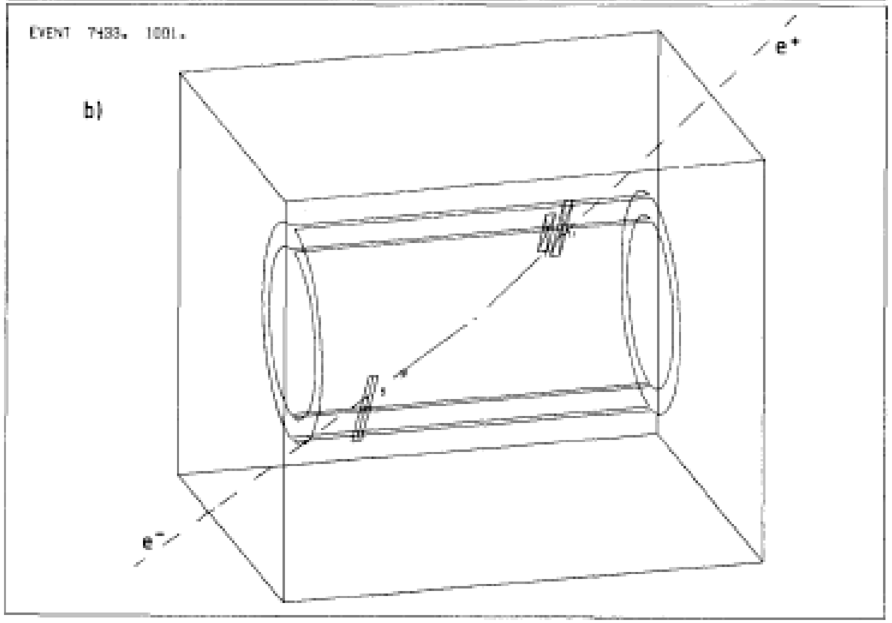
Isolated track with $p_T > 7$ GeV pointing to at least one cluster

Isolated track with $p_T > 7$ GeV pointing to <u>both</u> clusters

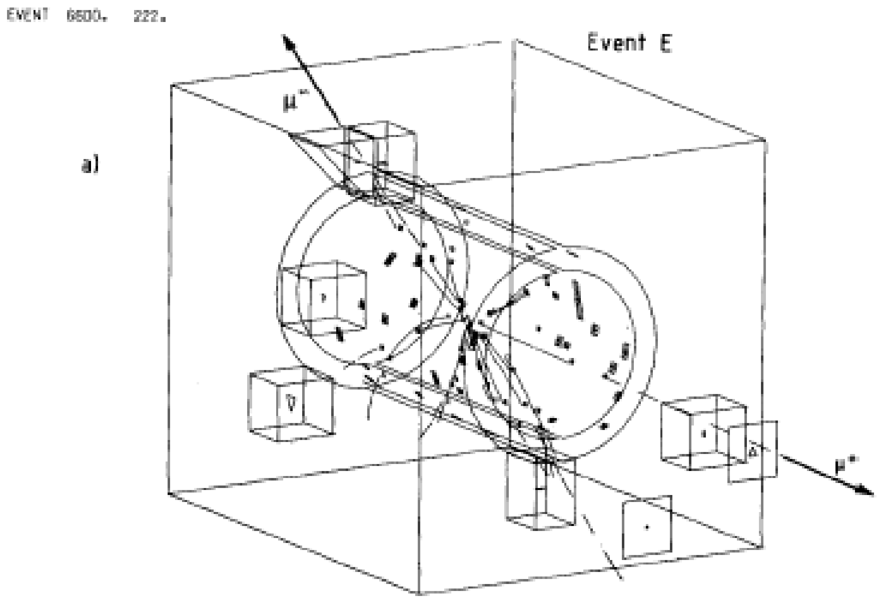
UA1 Z → $e^+ e^-$ event



Display of all reconstructed tracks and calorimeter hits



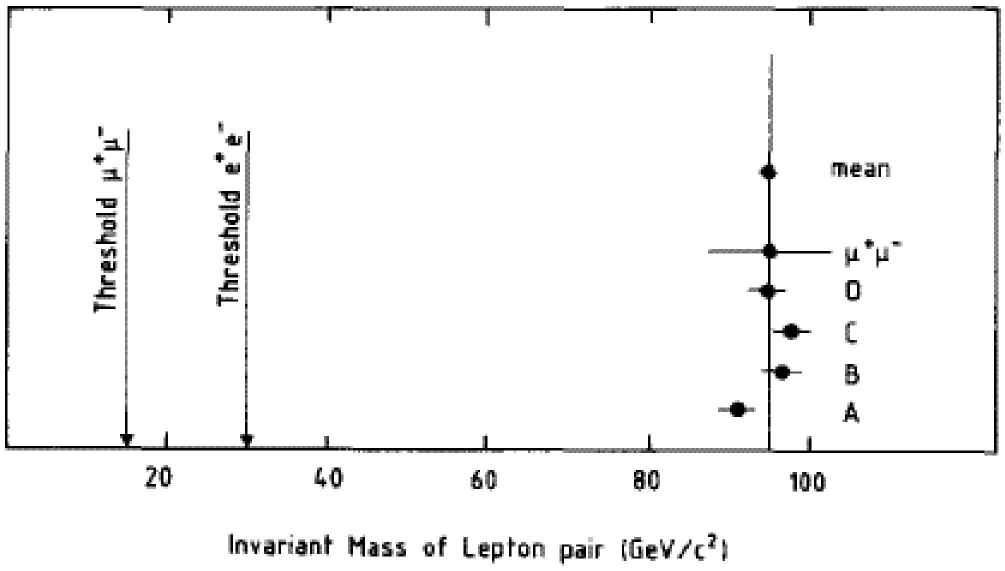
Display of tracks and calorimeter hits with $p_T > 2$ GeV



UA1 $Z \rightarrow \mu^+ \mu^-$ event

(May 1983)

The only $\mu^+ \mu^-$ pair observed during the 1983 collider run



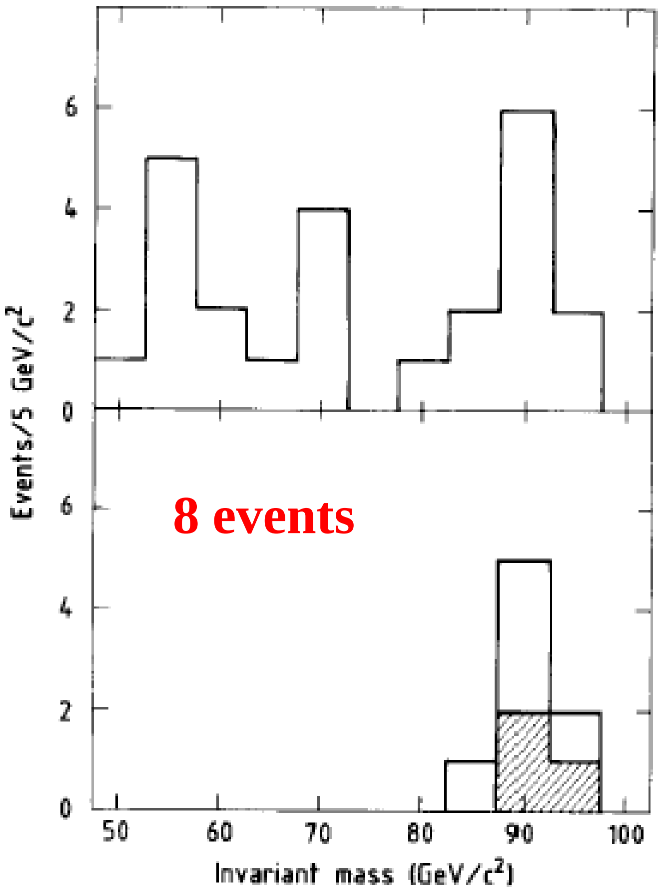
UA1:
all lepton pairs from the 1983 run

$$m_Z = 95.2 \pm 2.5 \pm 3.0 \text{ GeV}$$

(stat) (syst)

UA2: observation of $Z \to e^+ e^-$

(June 1983)



Two energy clusters with $p_T > 25$ GeV in electromagnetic calorimeters; energy leakage in hadronic calorimeters consistent with electrons

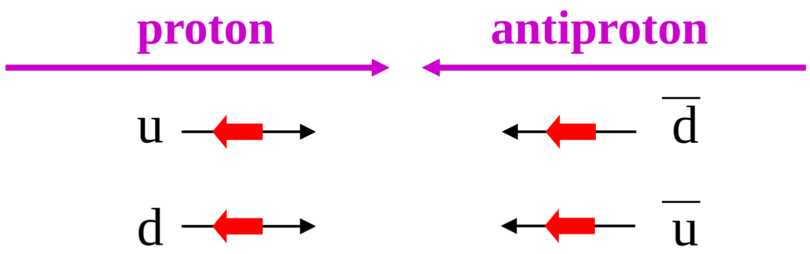
A track identified as an isolated electron pointing to at least one of the two clusters

Track identified as an isolated electron pointing to both energy clusters

$$m_Z = 91.9 \pm 1.3 \pm 1.4 \text{ GeV}$$

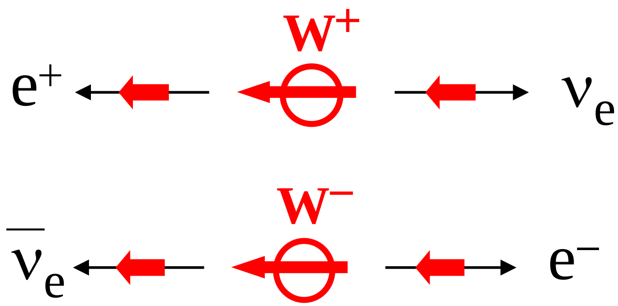
(stat) (syst)

Charge asymmetry in W $\rightarrow$ e ν decay



$W^{\pm}$ polarization along antiproton direction
(consequence of V – A coupling)

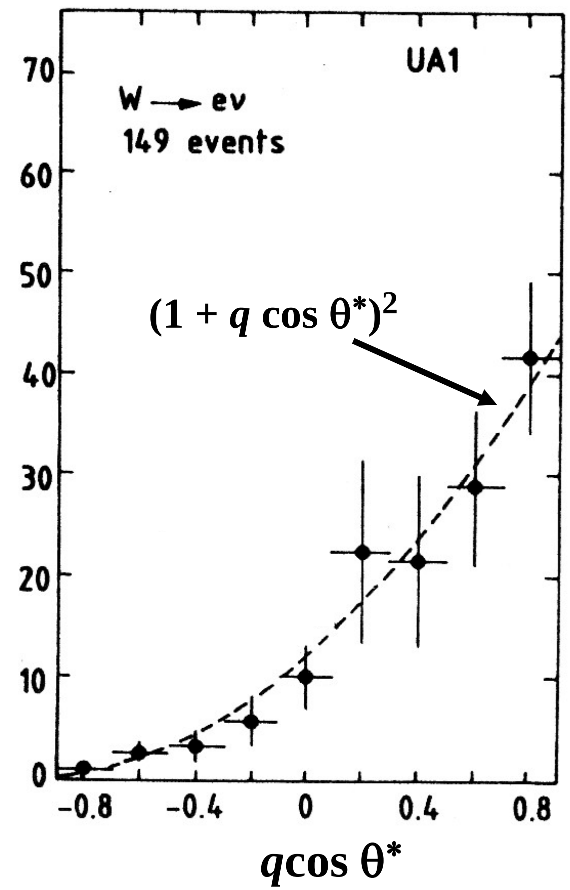
In the W rest frame:



Electron (positron) angular distribution:

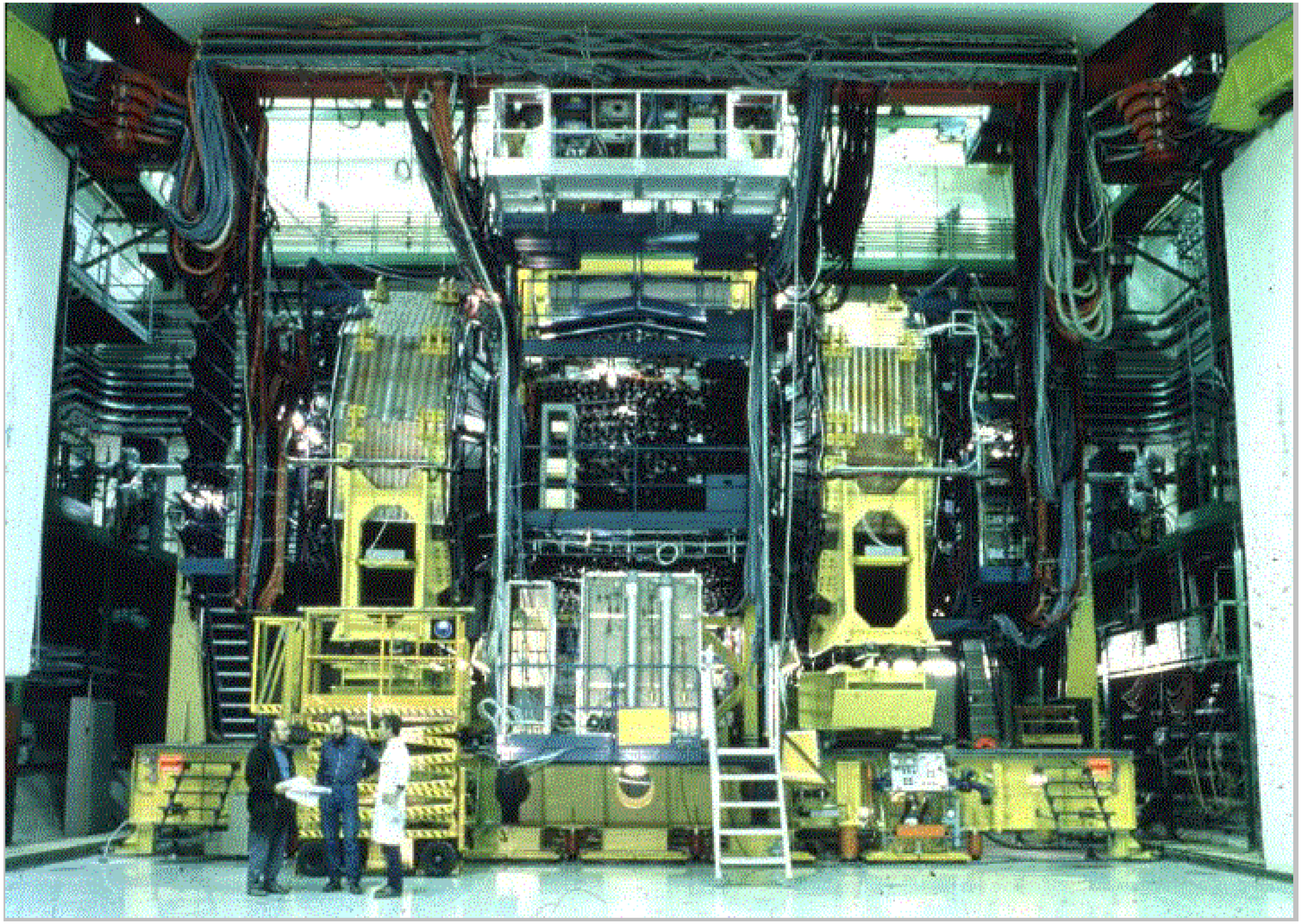
$$\frac{dn}{d\cos\theta^*} \propto \left(1 + q\cos\theta^*\right)^2$$

***q* = +1 for positrons; *q* = –1 for electrons**
θ* = 0 along antiproton direction



UA2 detector 1987 – 90

- Tenfold increase of collider luminosity
- Full calorimetry down to ~5° ⇒ improved measurement of missing p_T
- No magnetic field, no muon detectors

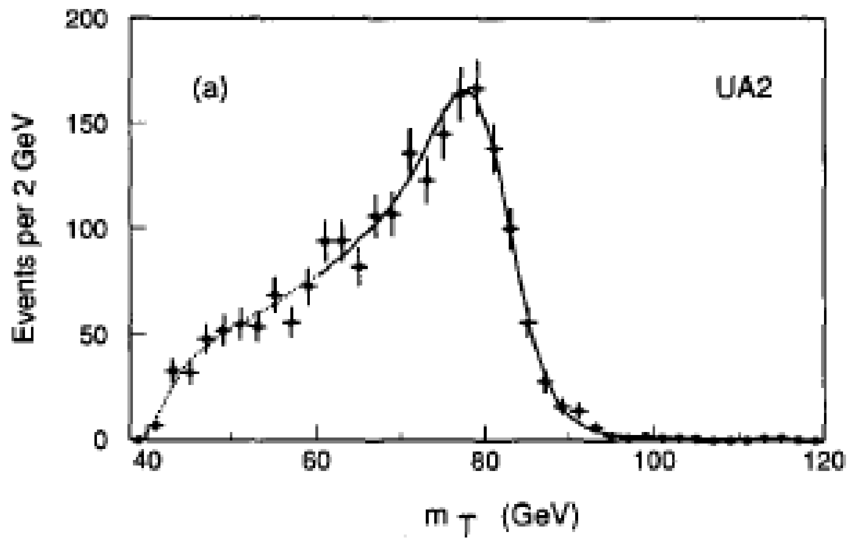


UA2: precise measurement of $\frac{m_W}{m_Z}$

(mass ratio has no uncertainty from calorimeter calibration)

2065 $W \rightarrow e\,\nu$ events with the electron in the central calorimeter ($\theta = 90° \pm 50°$)

Distribution of "transverse mass" m_T
(**m_T :** invariant mass using only the e and ν momentum components normal to beam axis – the longitudinal component of the ν momentum cannot be measured at hadron colliders)



Fit of the distribution with m_W as fitting parameter:

$$m_W = 80.84 \pm 0.22\,\mathrm{GeV}$$

Two samples of $Z \to e^+ e^-$ events :

- both electrons in central calorimeter (95 events)

$$m_Z = 91.65 \pm 0.34\,\text{GeV}$$

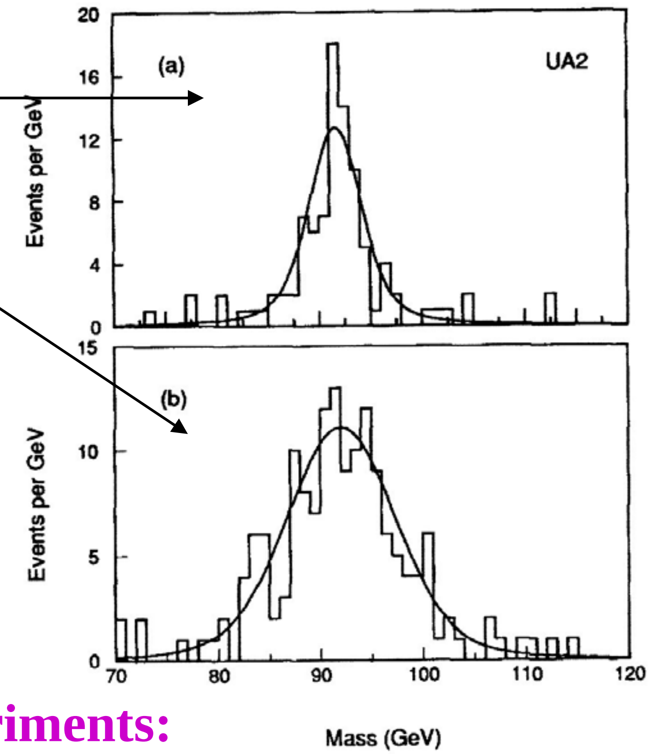
- only one electron in central calorimeter (156 events)

$$m_Z = 92.10 \pm 0.48\,\text{GeV}$$

- combined samples:

$$m_Z = 91.74 \pm 0.28\,\text{GeV}$$

$$\frac{m_W}{m_Z} = 0.8813 \pm 0.0036 \pm 0.0019$$



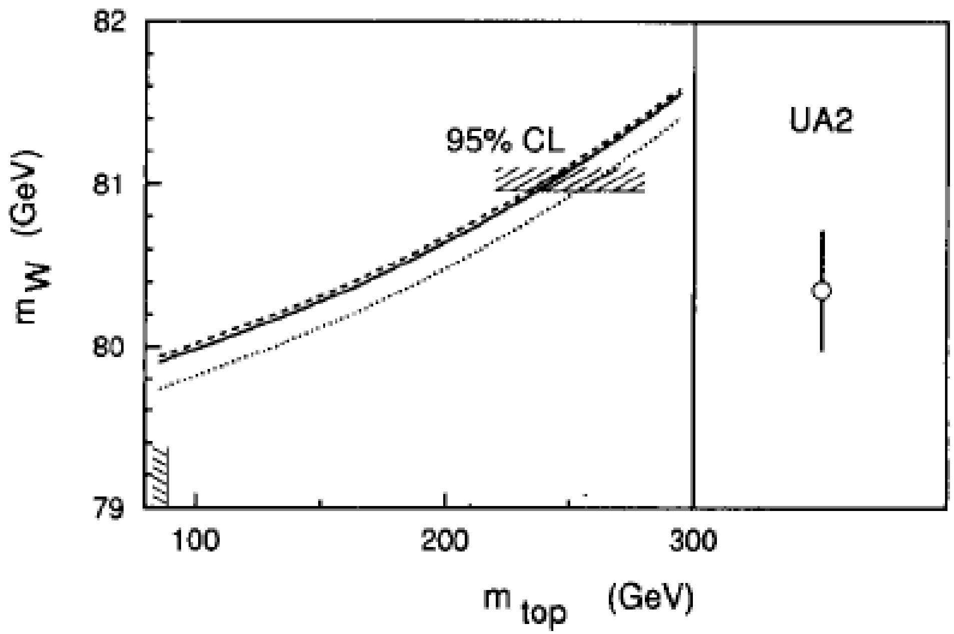
Using precise measurement of m_Z from LEP experiments:

$$m_W = 80.35 \pm 0.33 \pm 0.17\,\text{GeV}$$

bounds on the mass of the top quark in the frame of the Standard Model:

$$m_{top} = 160^{+50}_{-60}\ \text{GeV}$$

(five years before the top quark discovery at Fermilab)



Final comment

There is a long list of glorious experiments as important as those discussed here. Among these:

- **Discovery of the muon and studies of its properties and interactions;**
- **Discovery of the positron and (later) of the antiproton;**
- **Discovery of the charged and neutral π – meson;**
- **Discovery of strange particles;**
- **Discovery of the quark structure of the nucleons;**
- **Discovery of hadrons containing *c* and *b* quarks;**
- **Discovery of the 3rd lepton (τ);**
- **Discovery that there are only 3 light, active neutrinos.**

To this list, one should add all the precision experiments which have contributed to the development of the Standard Model in its present form .