EXPERIMENTS AT CERN
IN THE DECADE 1964 – 1974

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- **The CERN physics "environment" in the years 1964 – 74**
  Size of experiments, detectors, data acquisition, analysis
- **A personal selection of experiments at the PS and ISR**

For a more complete description of physics results from those years see:
L. Van Hove and M. Jacob, Highlights of 25 years of physics at CERN, Physics Reports 62 (1980) 1

The CERN physics environment in the years 1964 – 74

- Many experiments (typically, ~ 10 / year) with relatively short data – taking time (typically, one month)
- Small groups (< 10 physicists)
- Little theoretical guidance (no Standard Model yet !)
- Two classes of experiments (managed by two CERN Divisions):
  - Bubble chamber experiments
  - Electronic experiments

Bubble chambers

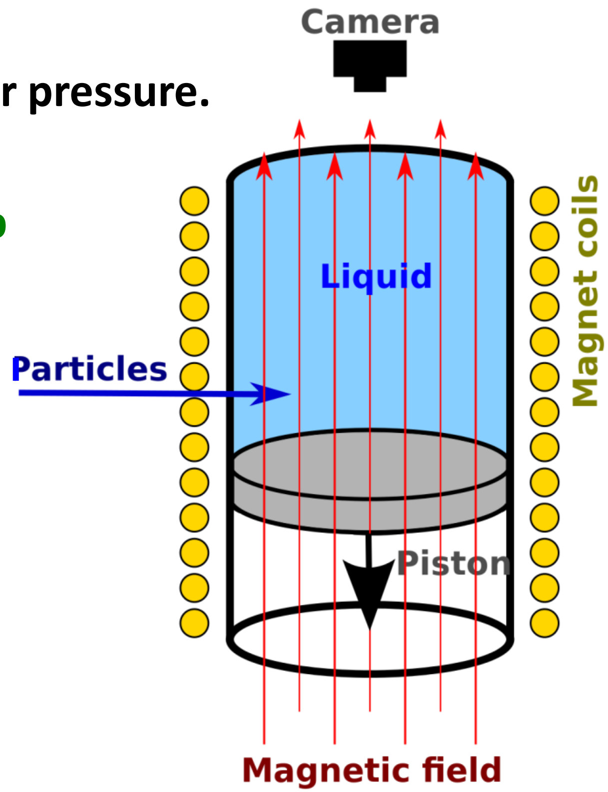
(invented by D.A. Glaser in 1952)

Volumes filled with liquid close to the boiling point, kept under pressure.

Few milliseconds before the arrival of the beam particles (fast ejection) expansion by a piston produces a pressure drop

→ superheated liquid → bubbles form first on the ionization providing photographic images of charged particle tracks

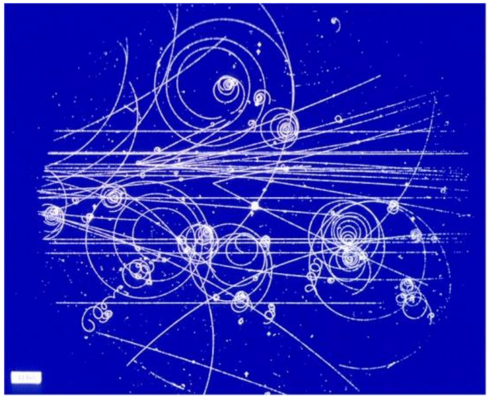
Used liquids: H_2, D_2, He_4, Ne, C_3H_8 (propane), freon, Xe



No trigger on selected events ;

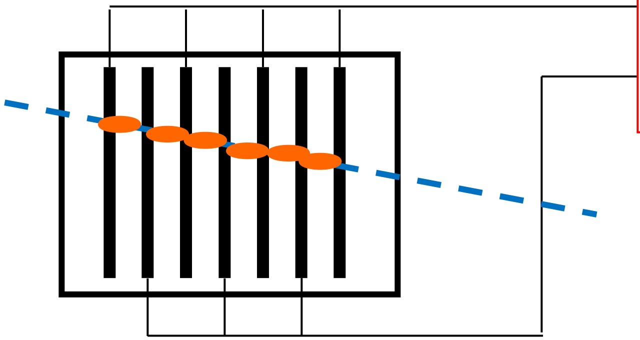
Rate limitation from number of tracks / picture .

Example of crowded picture



Event photographs (stereo views) are scanned by physicists and track points are digitized (manually, then automatically) and stored onto magnetic tapes

Charged particle tracking in electronic detectors is achieved by spark chambers (invented by Fukui and Miyamoto in 1959)



High voltage pulse
applied between these two lines
following an external trigger

Sparks occur along a charged particle track
when the high voltage pulse is applied (not later than
0.5 μs after the track time)
Max. trigger rate ~ few per second

Metallic plates in a volume
filled with pure noble gases
(typically Ne-He mixtures)

Initially, spark chambers are "read out" by photographic cameras providing stereo views of events.

Event photographs are then scanned and digitized as for bubble chambers .

Data acquisition in electronic experiments

On – line computers appear around 1964 and are used more and more for data acquisition and detector monitoring .

They allow the development of more "automatic" spart chamber read –out techniques:

- Sonic chambers (with microphones in the corners of each plane to detect the spark noise and measure its position from signal timing)
- Magnetic core read-out: the ground planes are made of wires traversing ferrite cores which are magnetized by the spark current and read out as a computer memory (made also of ferrite cores in those times)
- Magnetostrictive read-out: detection of the magnetic perturbation induced by the sparks on a nickel ribbon perpendicular to the ground wires, and propagating along the ribbon with the speed of sound.

Between the late 1960s and the early 1970s, spark chambers are gradually replaced by Multi–Wire Proportional Chambers and Drift Chambers (invented by G. Charpak in 1968)

Data analysis

Magnetic tapes containing the digitized information from tracking detectors (bubble chambers, spark chambers, MWPCs) are analysed in the CERN Computer Center or in external Institutes using reconstruction and analysis programs generally written in Fortran

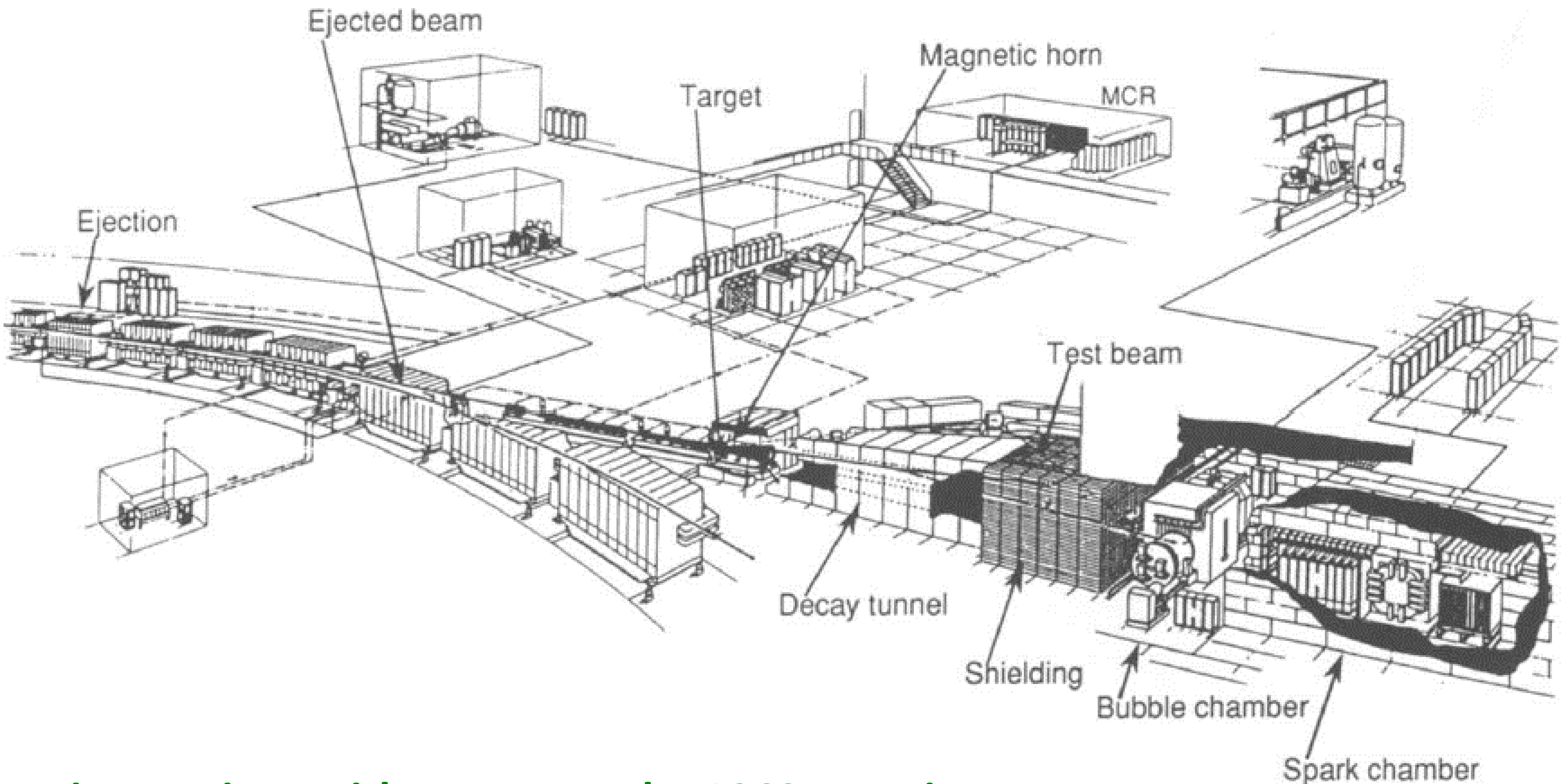
During data – taking a few tapes are taken to the CERN Computer Center by one of the physicists on shift for fast analysis of a subsample of events to monitor the detector performance ("Bicycle on – line")

A personal selection of experiments at the PS and ISR

- Neutrino experiments
- Experiments on CP violation
- Hadron spectroscopy
- Exclusive reactions at high energy
- First results from ISR experiments
- Searches for fractionally charged particles
- The three muon "g – 2" experiments

Neutrino physics at CERN begins in the PS South Hall in 1963

Layout of the beam and experiments

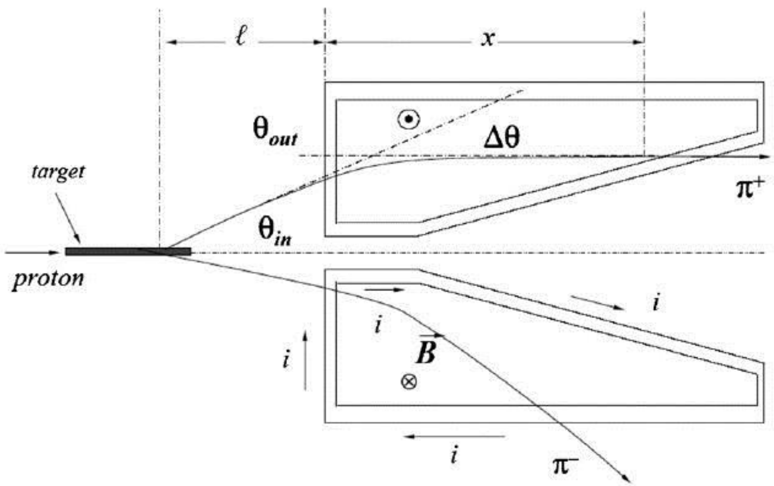


Two innovations with respect to the 1962 experiment at the Brookhaven AGS which discovered the 2nd neutrino (ν_μ) :

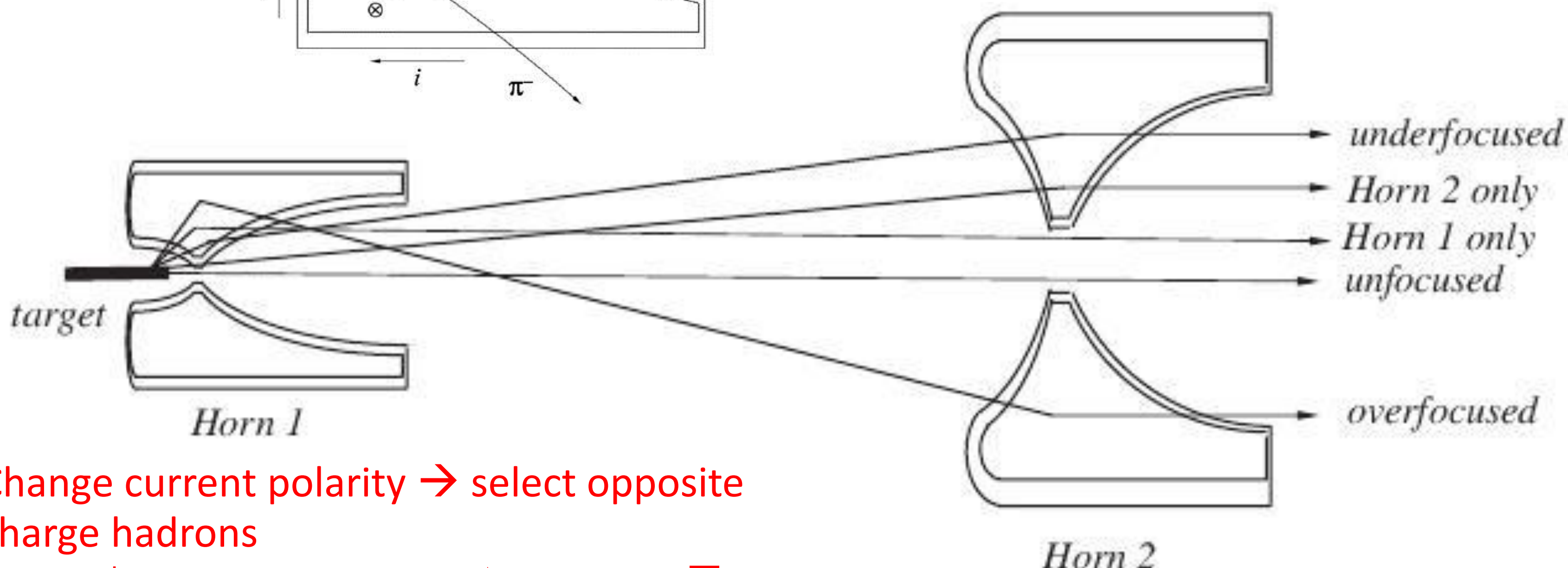
- **Fast extraction of the primary proton beam from the PS and use of an external target to produce pions and kaons decaying to neutrinos;**
- **The invention of the magnetic horn**

Wide band neutrino beams

Charged hadrons ($\pi^\pm$, $K^\pm$) produced at the target are focussed into an almost almost parallel beam with wide momentum distribution by magnetic "horns" (invented at CERN by Simon van der Meer)



- Axially symmetric conductors
- Pulsed current
- Magnetic field normal to hadron momentum



Change current polarity → select opposite charge hadrons

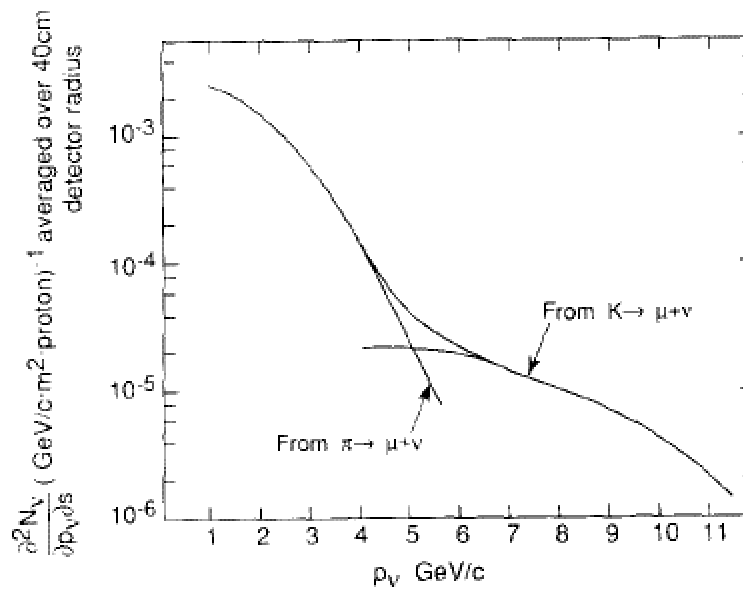
$\pi^+ \ (\to \nu_\mu)$ ➡ $\pi^- \ (\to \bar{\nu}_\mu)$

Simon van der Meer
explaining the horn working principles

Horn
inner conductor

Horn
outer conductor

Horn installed
on the beam line
(1964)



Typical neutrino energy spectrum
(wide-band, horn-focused beam from the CERN PS)

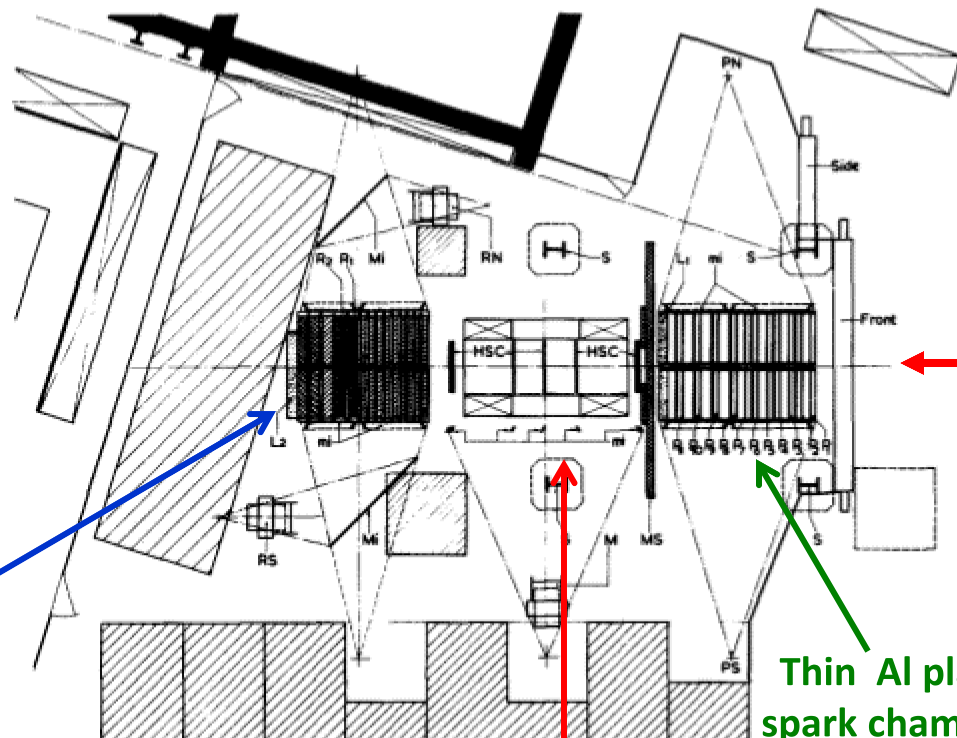
Neutrino detectors

1. **A Heavy Liquid Bubble Chamber (HLBC) filled with CF_3Br (*freon*) in a 2.7 T magnetic field**

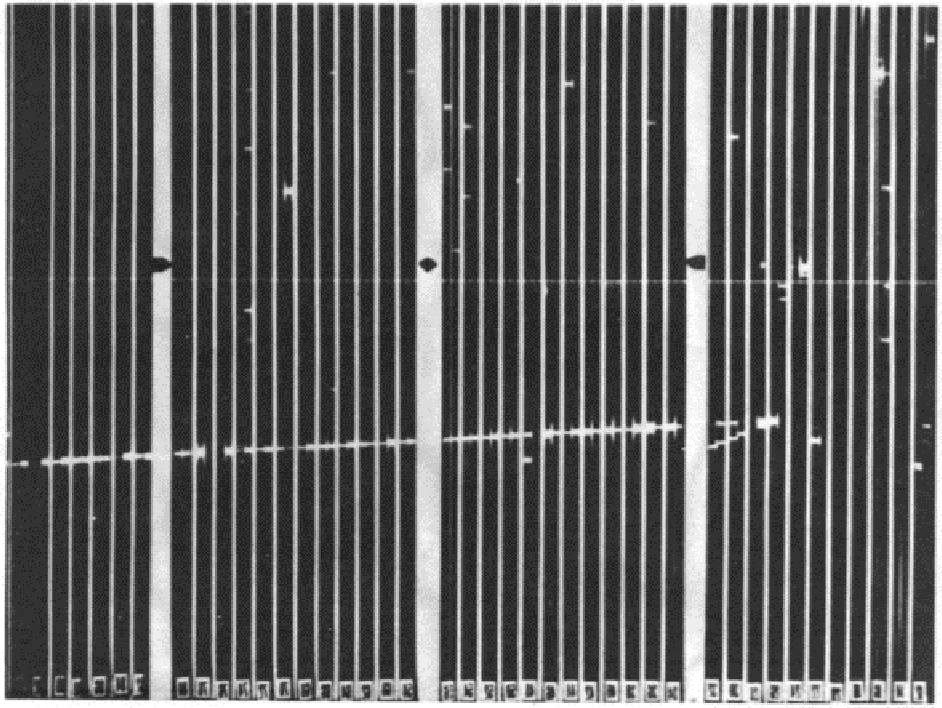
   Diameter 1.2 m, volume 500 liters (0.75 tons of freon)

   Nuclear interaction mean free path in freon ~ 0.6 m , radiation length 11 cm

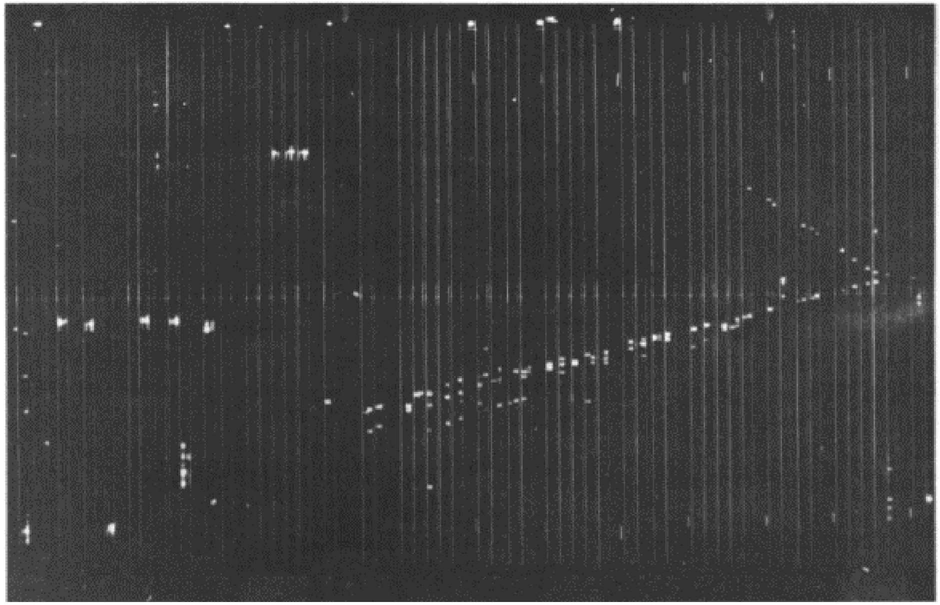
2. **A spark chamber detector with a fiducial mass of ~15 tons**



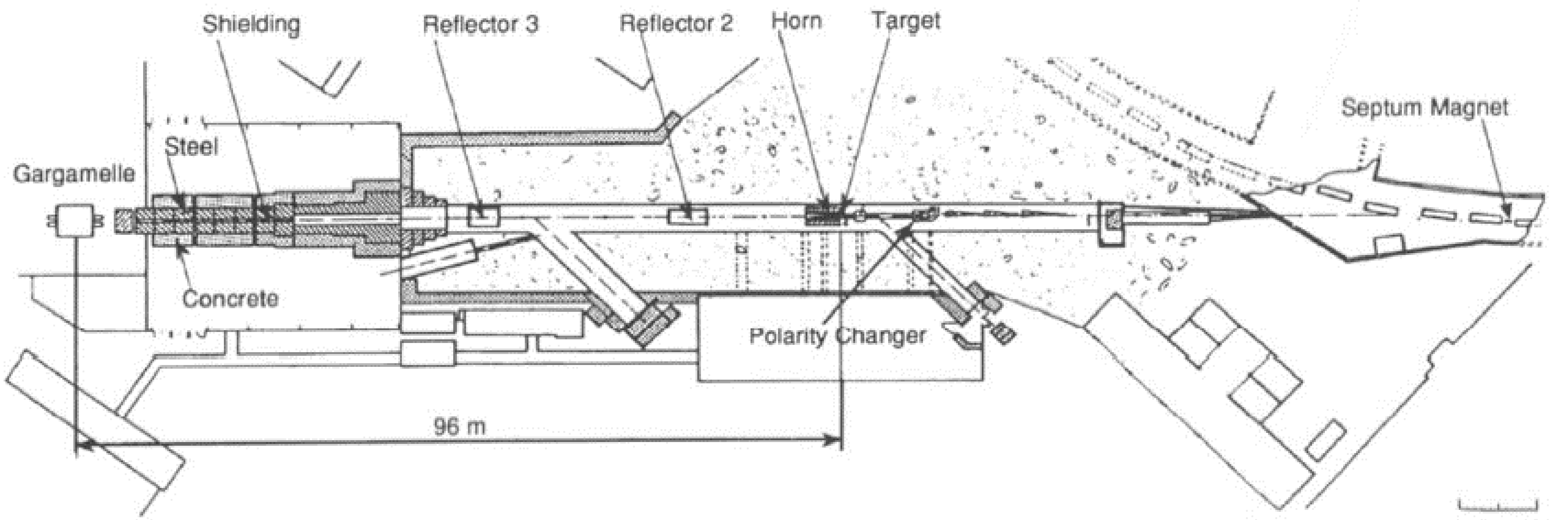
Spark chamber picture of a
$\nu_\mu + n \rightarrow \mu^- + p$
"quasi-elastic" event
418 events in the 1963-64 runs



Spark chamber picture of a
$\nu_e + n \rightarrow e^- + p$
"quasi-elastic" event
39 events in the 1963-64 runs
(consistent with expected ν_e flux)



1966 – 74 : a new neutrino beam in the PS South – East Area



DETECTORS

1966 – 70 : The 1.2 m diam. Heavy Liquid Bubble Chamber filled with C_3H_8 (propane) followed by a spark chamber detectors;

1971 – 74: The giant Heavy Liquid Bubble Chamber Gargamelle filled with freon

Among the results from the early neutrino experiments:

- **Measurement of the cross-section versus energy of the quasi-elastic process** $\nu_\mu + n \rightarrow \mu^- + p$
- **Measurement of the nucleon weak axial form factor from the Q^2 distribution of quasi-elastic events**
- **Measurement of the cross-section versus energy of resonance production:**
  $\nu_\mu + p \rightarrow \mu^- + \Delta^{++} \rightarrow \mu^- + p + \pi^+$
  $\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + n + \pi^+$
  $\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + p + \pi^\circ$
- **Study of multi-pion production by neutrinos**
- **Search for $\mu^- e^+$ and $\mu^- \mu^+$ pairs as a possible signature for the production of a light (mass < 2 GeV) weak boson W:**
  ν_μ + nucleus $\rightarrow \mu^-$ + nucleus + W^+, followed by $W^+ \rightarrow e^+ + \nu$ or $W^+ \rightarrow \mu^+ + \nu$

Measurement of the neutrino – nucleon total cross-section in the 1.2 m diameter heavy liquid bubble chamber

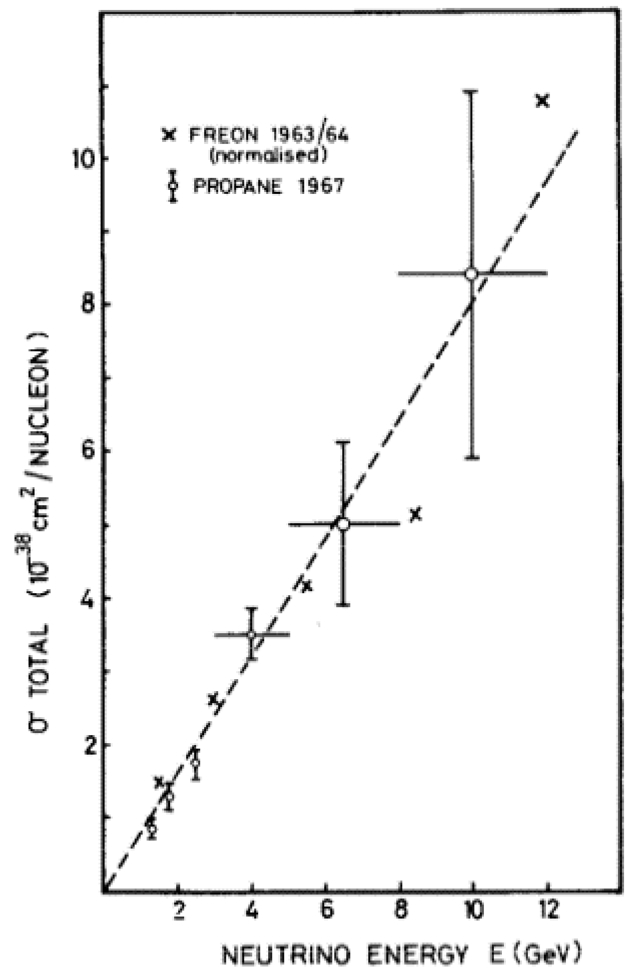
I. Budagov et al., Phys. Lett. 30B (1969) 364

$\sigma_{TOT}(\nu_\mu - \text{nucleon}) = (0.8 \pm 0.2)\ E\ (\text{GeV}) \times 10^{-38}\ \text{cm}^2$

The linear rise with energy is a consequence of the quark structure of the nucleon, which had just been discovered at SLAC by measuring "deep-inelastic" electron – nucleon scattering

→ Demonstration that neutrinos interact with light, point-like nucleon constituents

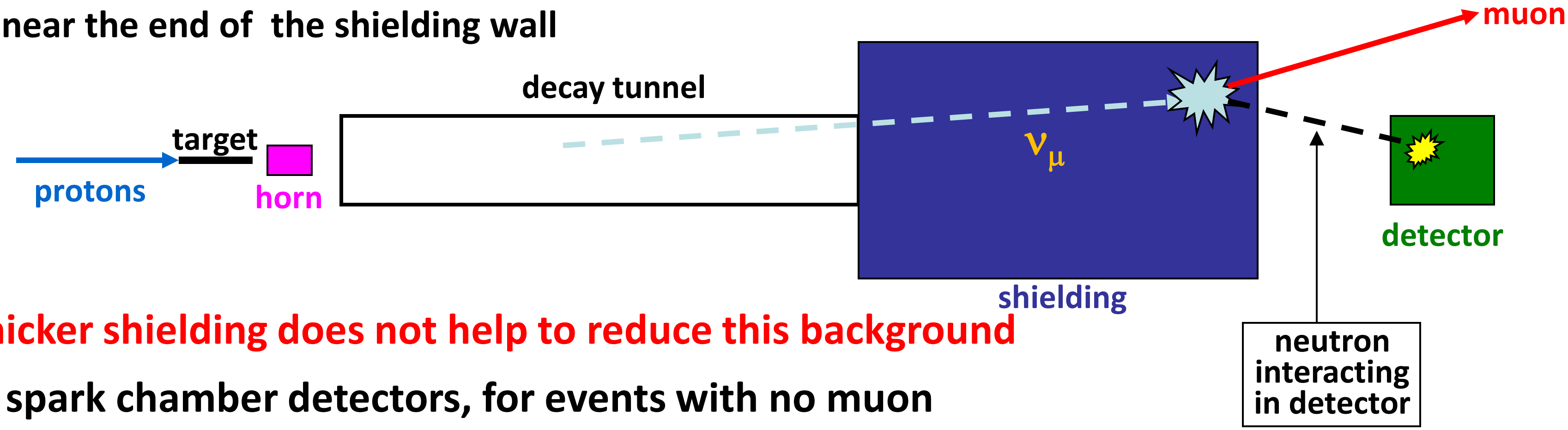
See the recent paper by D.H. Perkins "An early neutrino experiment: how we missed quark substructure in 1963", The European Physics Journal H 38 (2013) 713



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

In spark chamber detectors, for events with no muon the trigger is inefficient to low energy hadronic showers

Attempt to detect the elastic reaction $\nu + p \rightarrow \nu + p$ in the 1.2 m diam. HLBC filled with propane (D.C. Cundy et al, Phys. Lett. 31B (1970) 478)

Observe 4 events with proton kinetic energy 150 – 500 MeV corresponding to

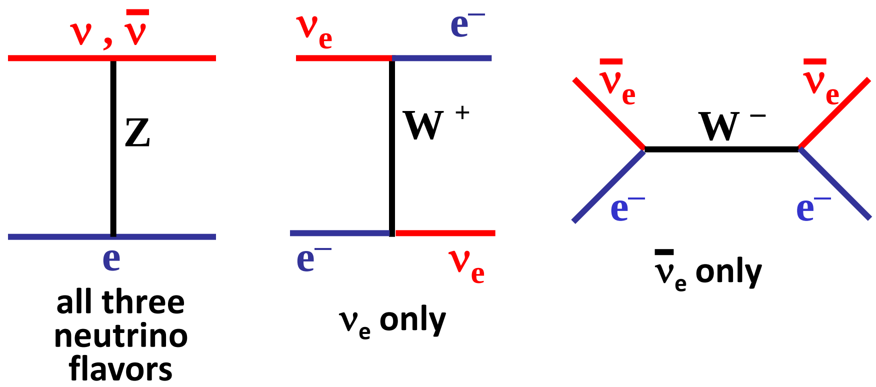
$$\frac{\sigma(\nu_\mu + p \rightarrow \nu_\mu + p)}{\sigma(\nu_\mu + n \rightarrow \mu^- + p)} = 0.12 \pm 0.06$$ **(the authors consider this result as an upper limit).**

In 1979 this ratio is measured to be 0.11 ± 0.02 by the BNL-Harvard-Pennsylvania coll.
30 ton liquid scintillator contained in 216 independent cells → 217 events (background 38%)

See A. Entenberg et al. Phys. Rev. Lett. 42 (1979) 1198

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

Very small cross–section, typically = A x 10^{-42} E_ν 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:

ν_e : A ≈ 9.5; $\bar{\nu}_e$: A ≈ 3.4

ν_μ : A ≈ 1.6; $\bar{\nu}_\mu$: A ≈ 1.3

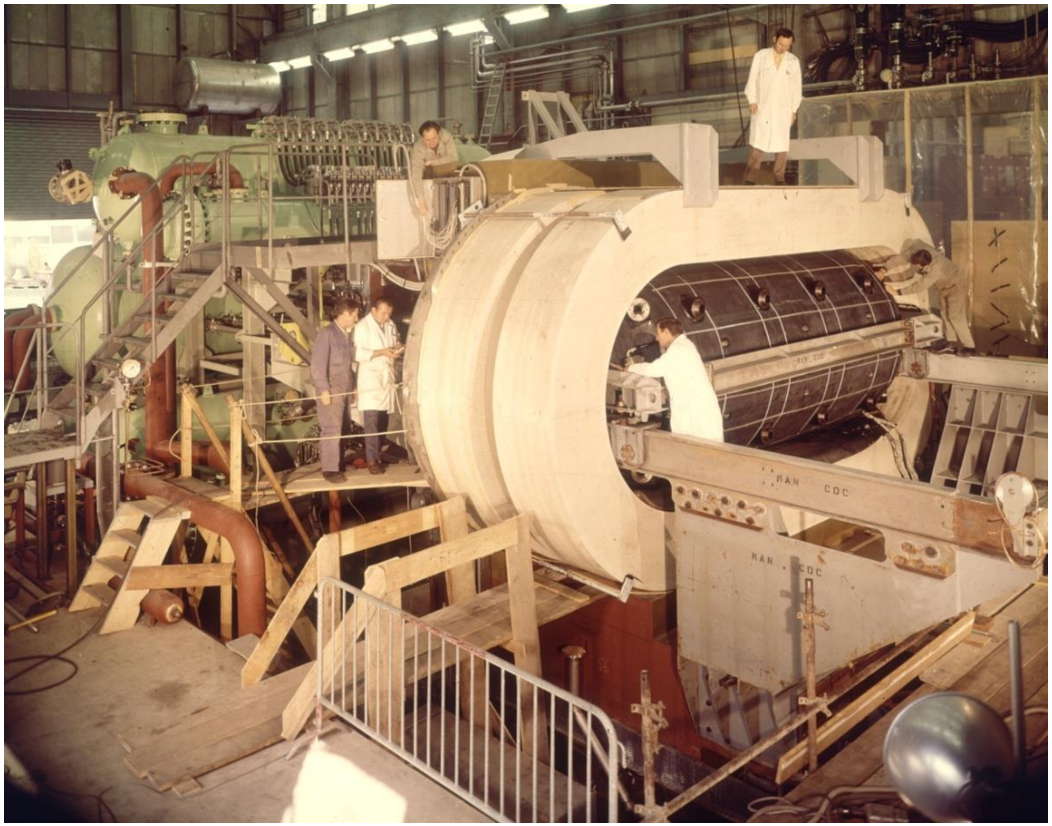
The general opinion in the early 1970s: if neutrino Neutral – Current interactions exist at all, one needs neutrino beams from a higher energy proton accelerators to discover them:

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

Gargamelle

- Designed and built in France by André Lagarrigue and collaborators
- Cylindrical body 4.8 m long, 1.85 m diameter, volume 12 m^3
- Magnetic field 1.8 T

André Lagarrigue



Gargamelle during assembly

Inside the chamber body

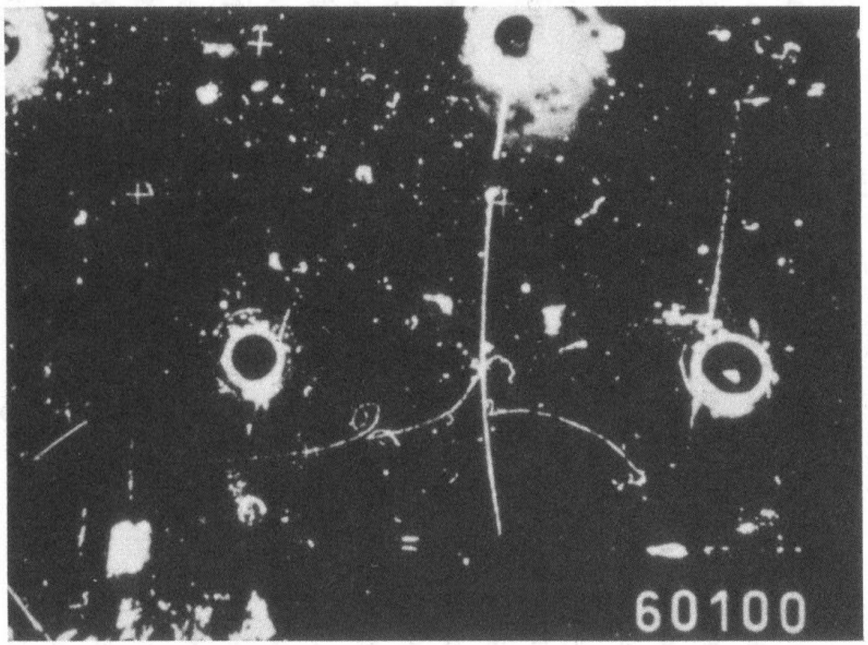
1973: observation of an event consisting only of an electron collinear with the beam in the heavy liquid bubble chamber Gargamelle from an exposure to the antineutrino beam (mostly $\bar{\nu}_\mu$)

Electron energy 385 ± 100 MeV ; electron angle to beam direction 1.4° ± 1.4°

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

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

Antineutrino beam direction



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

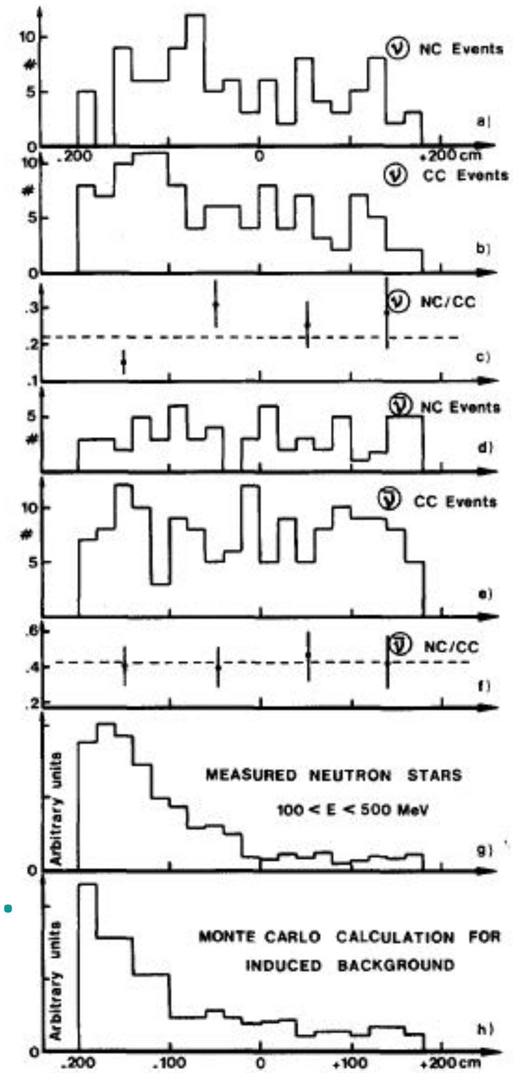
F.J. Hasert, et al., Phys. Lett. **46B** (1973) 138

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.

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



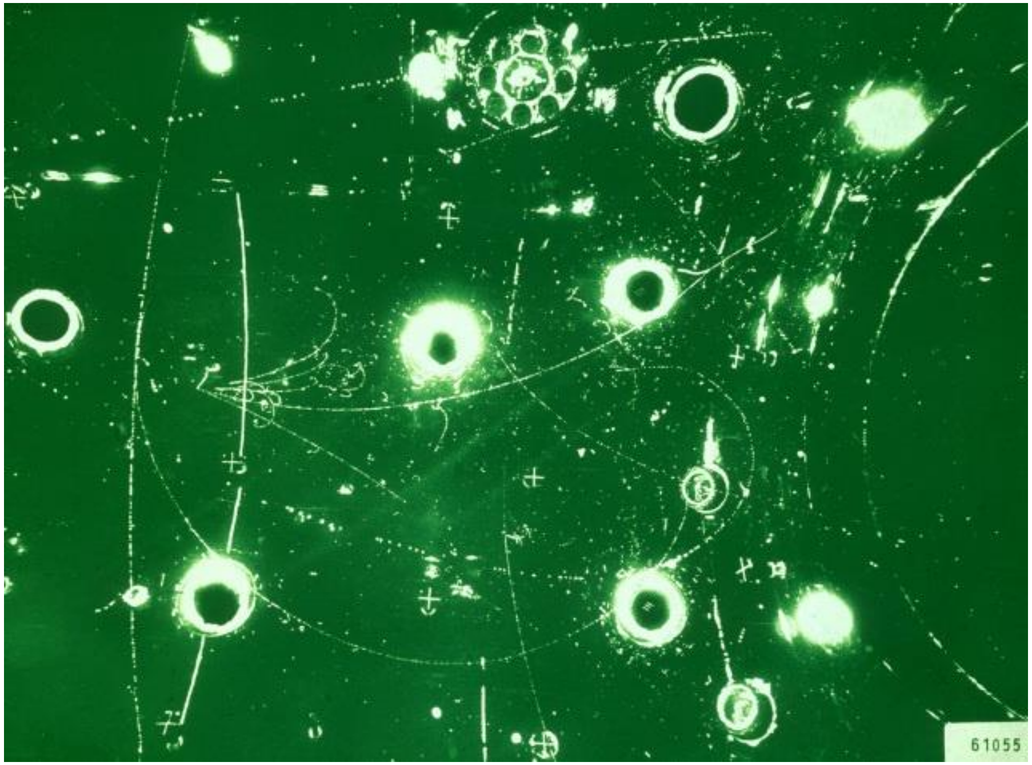
Distributions of event origin along the beam axis: NC and CC distributions are similar, consistent with uniform distributions as expected for neutrino interactions .

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

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

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

Example of a neutrino interaction producing a hadronic shower and no muon



Neutrino beam direction

Demonstration that quarks have fractional electric charge

Compare deep-inelastic electron scattering with $\nu + \bar{\nu}$ Charged Current scattering from a target containing equal numbers of protons and neutrons (= equal numbers of up- and down- quarks and antiquarks).

Form of the structure function $F_2(x,y)$ in the quark model ($x = Q^2/2M_pE_{had}$, $y = E_{had}/E$) :

- **for electron scattering**

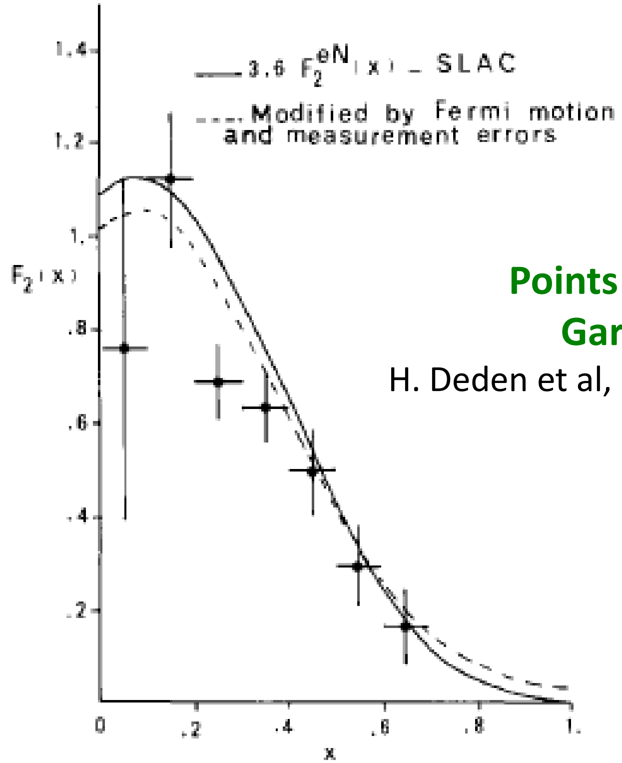
$$F_2^{em}(x,y) = [1+(1-y)^2]x[<e_q^{\ 2}>q(x) + <e_{\bar{q}}^{\ 2}>\bar{q}(x)] = \frac{5}{18}[1+(1-y)^2]x[q(x)+\bar{q}(x)]$$

$$<e_q^{\ 2}> = <e_{\bar{q}}^{\ 2}> = \frac{1}{2}\left(\frac{4}{9}+\frac{1}{9}\right)$$

- **for $\nu + \bar{\nu}$ scattering**

$$F_2^{\nu+\bar{\nu}}(x,y) = [1+(1-y)^2]x[q(x)+\bar{q}(x)]$$

$$F_2^{\nu+\bar{\nu}} = \frac{18}{5}F_2^{em} = 3.6F_2^{em}$$



Points with error bars: Gargamelle data

H. Deden et al, Nucl. Phys. B85 (1975) 269

CERN experiments on CP violation

The "July 1964 revolution": evidence for $\pi^+\pi^-$ decay of the long – lived K^0 meson in an experiment at the Brookhaven AGS – a decay violating CP symmetry
Decay rate ~ 2 x 10^{-3} with respect to all charged decay modes

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

The two mass eigenstates of the neutral K mesons before July 1964:

$$K_1^0 = \frac{K^0 + \overline{K}^0}{\sqrt{2}} \qquad K_2^0 = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$$

short–lived, CP = +1 **long–lived, CP = –1**

After July 1964:

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

short–lived **long–lived**

An early suggestion to explain the violation of CP symmetry in $K_L \rightarrow \pi^+\pi^-$ decay :

(Bell & Perring, Bernstein, Cabibbo and Lee)

the existence of a new long – range weak vector field producing a potential energy of equal magnitude but opposite sign for K^0 and $\overline{K}^0$.

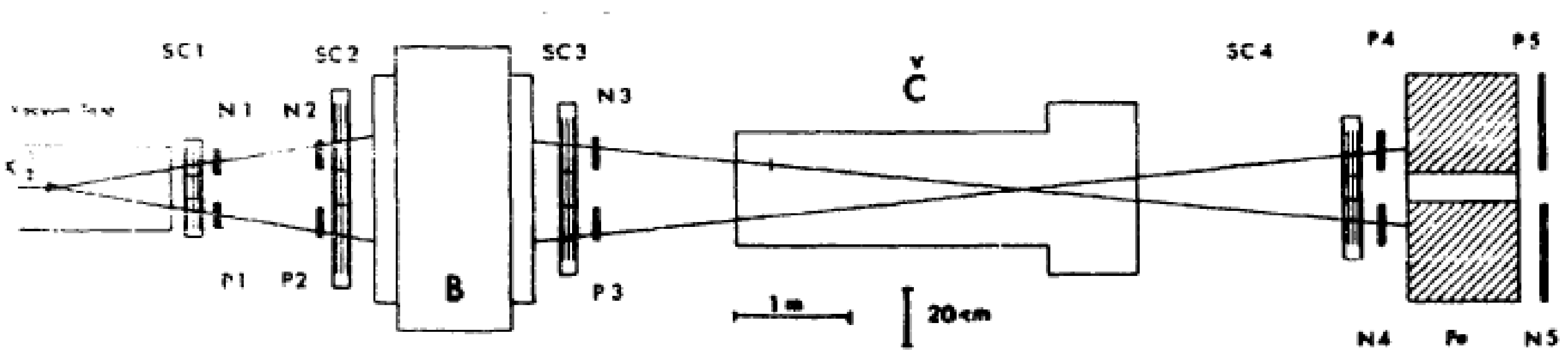
A $K^0 - \overline{K}^0$ mass splitting of $\sim 10^{-8}$ eV could produce $K_L \rightarrow \pi^+\pi^-$ decays at the rate measured in the AGS experiment but the rate would vary with the square of the K_L energy

→ Repeat the AGS experiment at a much higher beam momentum

(the average K_L momentum in the AGS experiment was 1.1 GeV/c)

Measurement of $K_L \rightarrow \pi^+\pi^-$ at a mean K_L momentum of 10.7 GeV

CERN – Orsay – MPI collaboration, Phys. Lett. **15** (1965) 58



- Neutral beam derived from an internal target at the PS
- Beam angle 8 mrad with respect to the circulating proton beam
- Charged pion / electron / muon separation by gas Čerenkov counter + Fe absorber
- Magnetic spectrometer: dipole magnet + optical spark chambers

Results:

- 44 ± 8 events consistent with $K_L \rightarrow \pi^+\pi^-$ decay
- Rate (3.5 ± 1.4) x 10^{-3} with respect to all charged modes, consistent with the AGS result

Another early suggestion to explain the apparent violation of CP symmetry in the decay $K_L \rightarrow \pi^+\pi^-$: violation of C symmetry in the electromagnetic interaction of hadrons, inducing violation of CP symmetry in weak hadronic decays through higher order corrections

(Lee & Wolfenstein, Okun', Prentki & Veltman)

1966: Experimental evidence for charge asymmetry in the decay $\eta \rightarrow \pi^+ \pi^- \pi^\circ$ (an electromagnetic process)

C. Baltay et al., Phys. Rev. Lett. **16** (1966) 1224

Bubble chamber experiment at the Brookhaven AGS studying the reaction $p + d \rightarrow \eta + p + p$ followed by $\eta \rightarrow \pi^+ \pi^- \pi^\circ$ (1441 events)

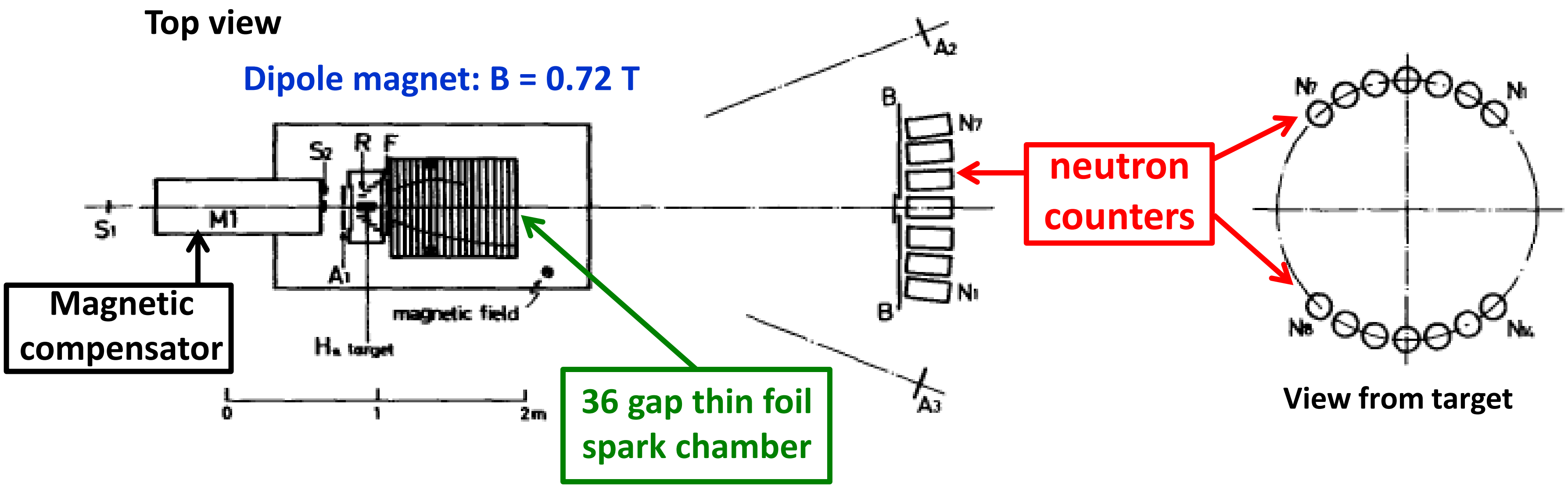
In the η rest frame define N_+ : number of events with $T(\pi^+) > T(\pi^-)$
N_- : number of events with $T(\pi^-) > T(\pi^+)$

Measured asymmetry $$A = \frac{N_+ - N_-}{N_+ + N_-} = 0.072 \pm 0.028$$

The CERN – ETH – Saclay experiment at the CERN PS

A.M. Cnops et al., Phys. Lett. **22** (1966) 546

$\pi^- + p \rightarrow \eta + n$; beam momentum 713 MeV/c ; 12 cm long liquid H_2 target



Identify $\pi^- + p \rightarrow \eta + n$ by neutron time-of-flight and angle (missing mass)

Frequent magnetic field reversals to reduce spurious charge asymmetries

Result based on 10665 $\eta \rightarrow \pi^+ \pi^- \pi^\circ$ decays :

Measured asymmetry $A = \dfrac{N_+ - N_-}{N_+ + N_-} = 0.003 \pm 0.011$

➡ no evidence for C violation in $\eta \rightarrow \pi^+ \pi^- \pi^\circ$ decay

Precise measurements of the $K_L \rightarrow \pi^+\pi^-$ decay parameters

$$\eta_{+-} = |\eta_{+-}| \exp(i\varphi_{+-}) = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$ (ratio of decay amplitudes); $\Delta m = m_L - m_S$

Two basic methods:

- **Measure the interference between $K_L \rightarrow \pi^+\pi^-$ and $K_s \rightarrow \pi^+\pi^-$ from coherent regeneration of K_s by one or more regenerators.**

  Interference term behind one regenerator :

$$2|\eta_{+-}\rho| e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t} \cos(\Delta m t + \varphi_\rho - \varphi_{+-})$$

$\rho = |\rho| e^{i\varphi_\rho}$: K_S coherent regeneration amplitude relative to K_L ;

t : time in the $K_{S,L}$ rest frame measured from regenerator exit

- **Measure the interference between $K_L \rightarrow \pi^+\pi^-$ and $K_s \rightarrow \pi^+\pi^-$ from initial K^0 or $\overline{K}^0$ states ("vacuum regeneration").**

  Interference term :

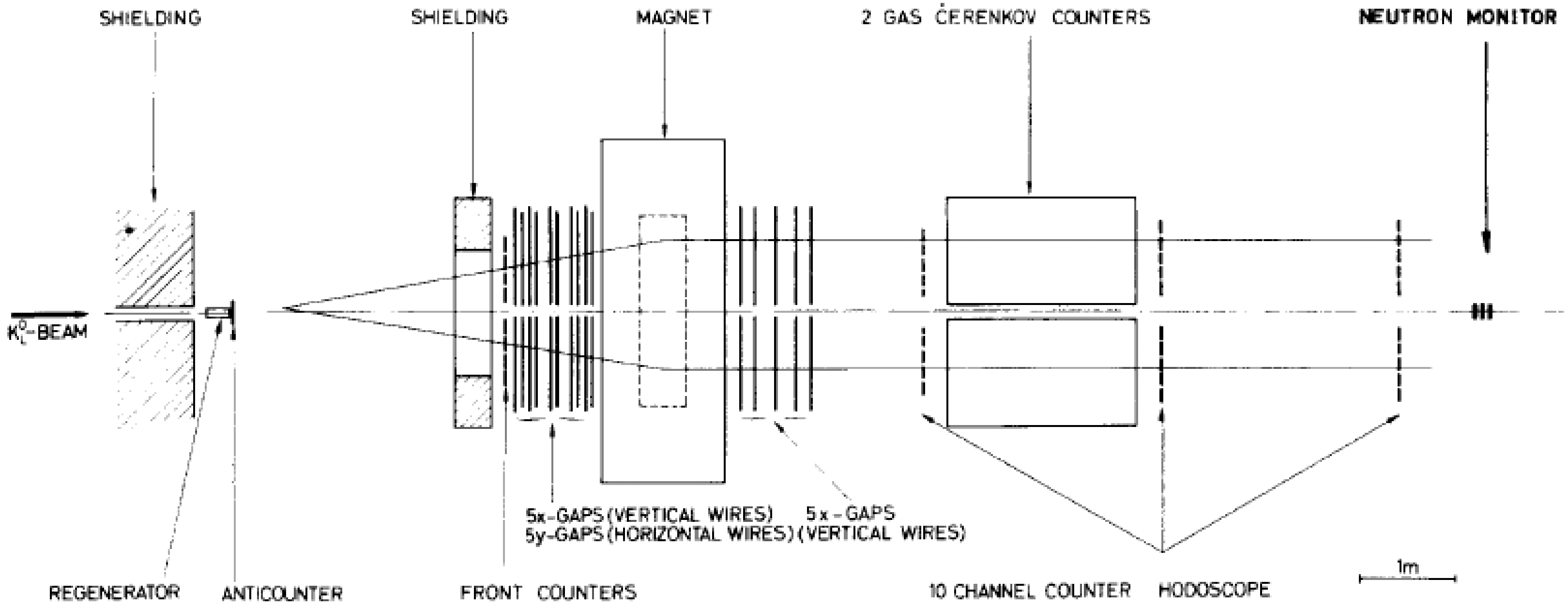
$$2A(p)|\eta_{+-}| e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t} \cos(\Delta m t - \varphi_{+-})$$

$$A(p) = \frac{S(p) - \overline{S}(p)}{S(p) + \overline{S}(p)}$$ ($S(p)$, $\overline{S}(p)$: initial K^0 and $\overline{K}^0$ production intensities);

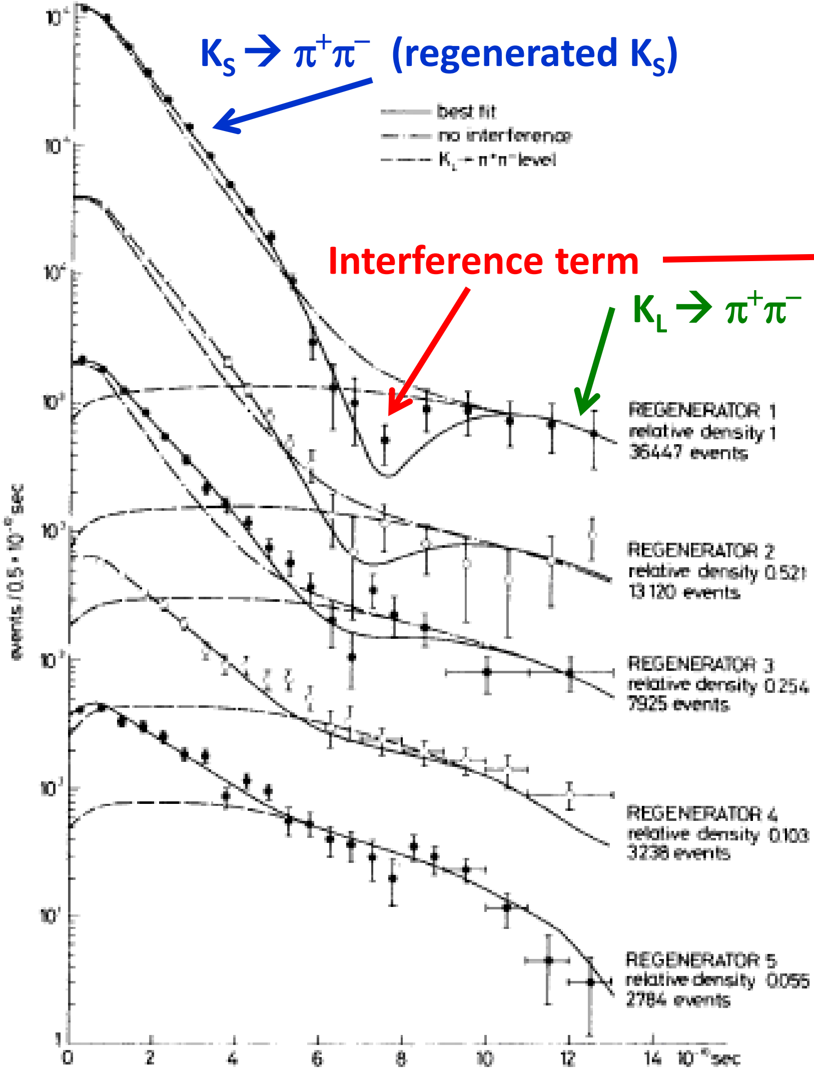
t : time in the $K_{S,L}$ rest frame measured from the K^0 ($\overline{K}^0$) production point

Measurement of the interference between $K_L \rightarrow \pi^+\pi^-$ and $K_S \rightarrow \pi^+\pi^-$ behind a copper regenerator

H. Faissner et al. (Aachen-CERN-Torno coll.), Phys. Lett. **30B** (1969) 204



- **Magnetic spectrometer with magnetic core read-out spark chambers**
- **Trigger counters select events with two charged particles parallel to the beam axis after momentum deflection → high efficiency for $K_{L,S} \rightarrow \pi^+\pi^-$ decays**
- **Five copper regenerators of equal thickness but different densities**



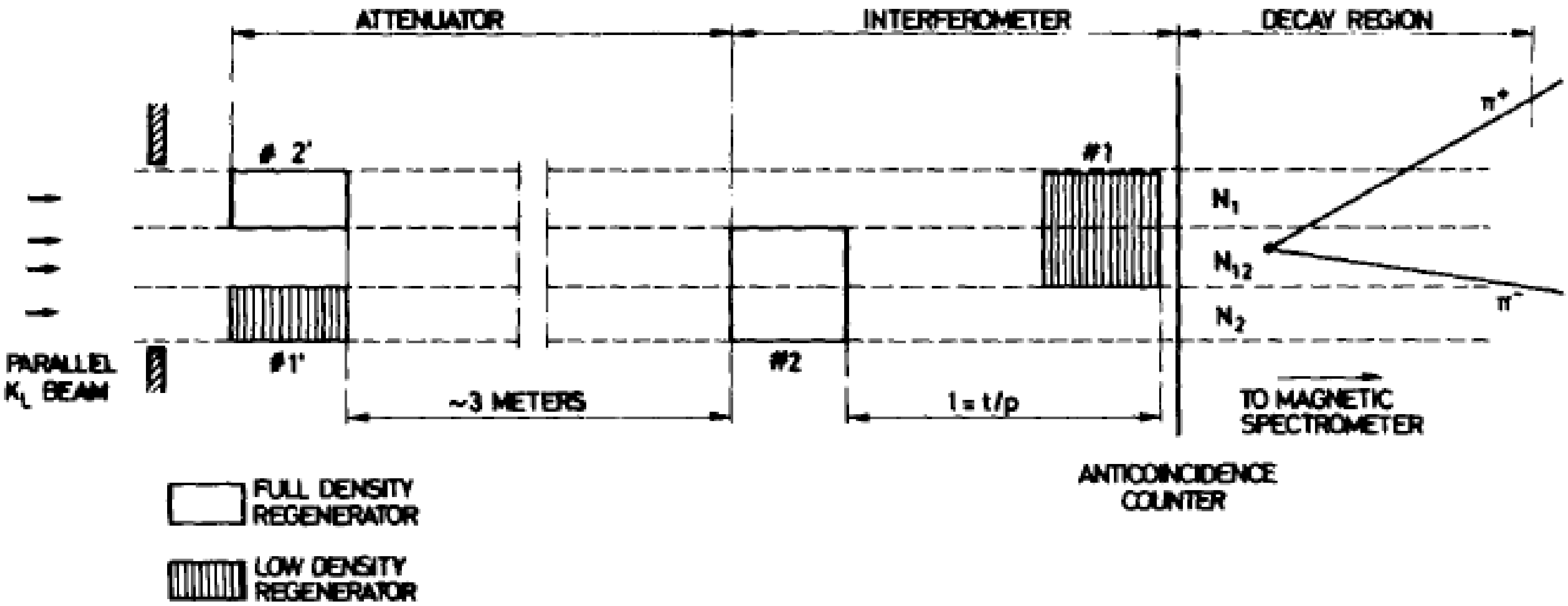
Time in the K rest frame measured from the regenerator exit (units of 10^{-10} s)

$$2|\eta_{+-}\rho|e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t}\cos(\Delta m t+\varphi_\rho-\varphi_{+-})$$

Regeneration amplitude $\rho = f(0) - \bar{f}(0)$: difference between the K^0 and $\bar{K}^0$ forward scattering amplitudes (from other experiments)

Precision measurement of Δm with two regenerators

Aachen –CERN-Torino coll., Phys. Lett. **32B** (1970) 523

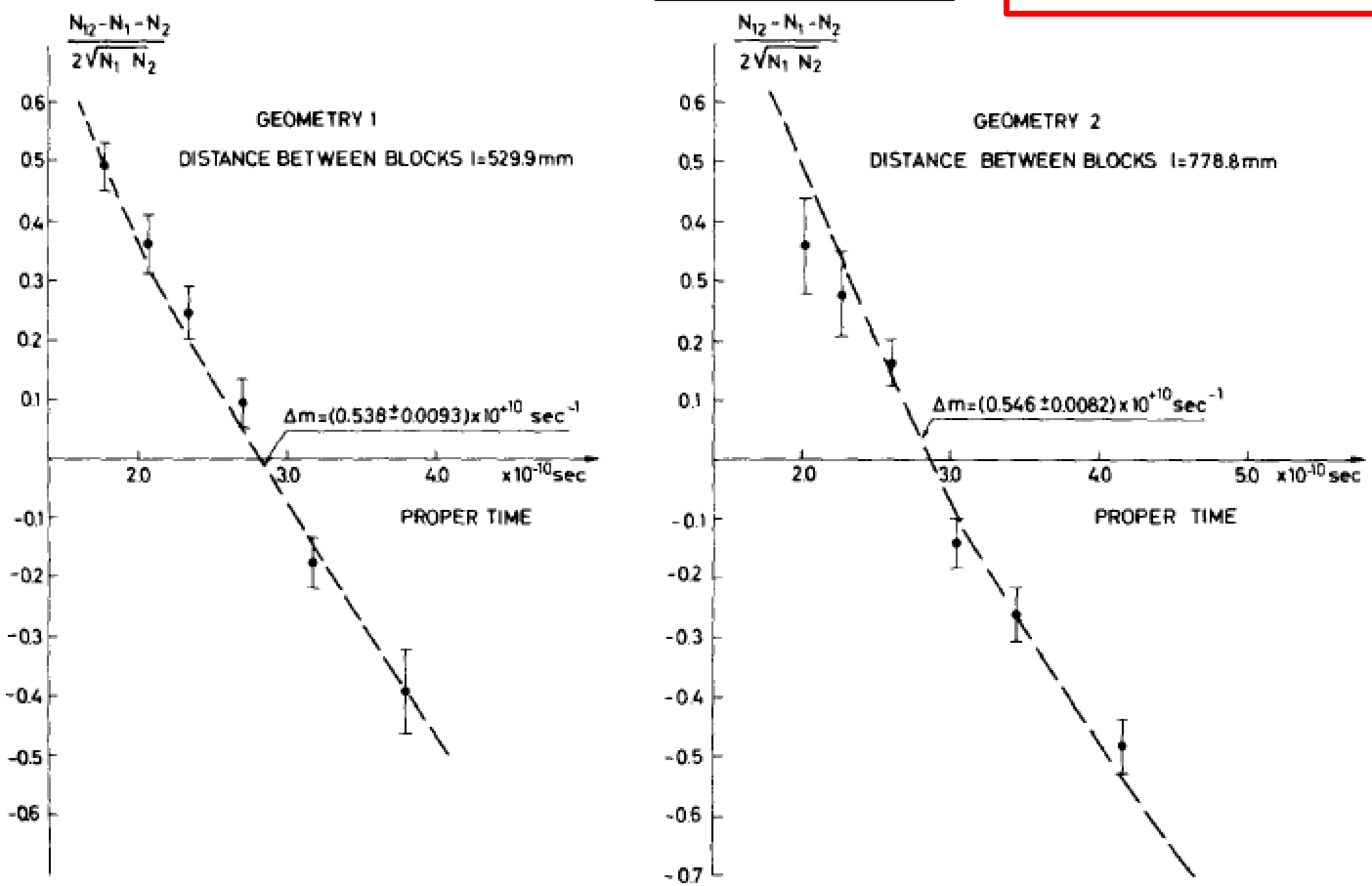


- K_L beam subdivided into three parallel regions with different regenerator configurations
- Equal K_L attenuations for the three regions

$$\Delta N(t) = N_{12}(t) - N_1(t) - N_2(t) + N_0(t) \propto |\rho_1||\rho_2| \cos(\Delta m t)$$

Nb. events no regenerator

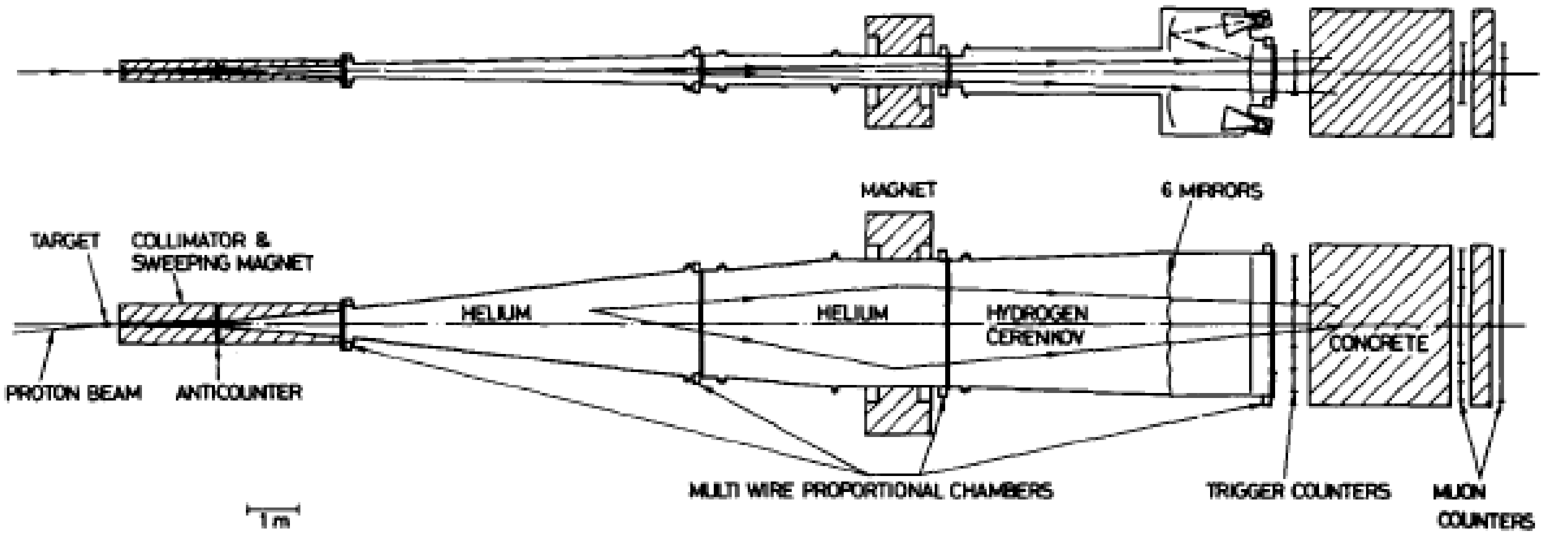
$= 0$ at $t = \pi / 2\Delta m$



$\Delta m = (0.542 \pm 0.006) \times 10^{10}\ s^{-1}$

The CERN "vacuum regeneration" experiment

(CERN – Heidelberg collaboration)



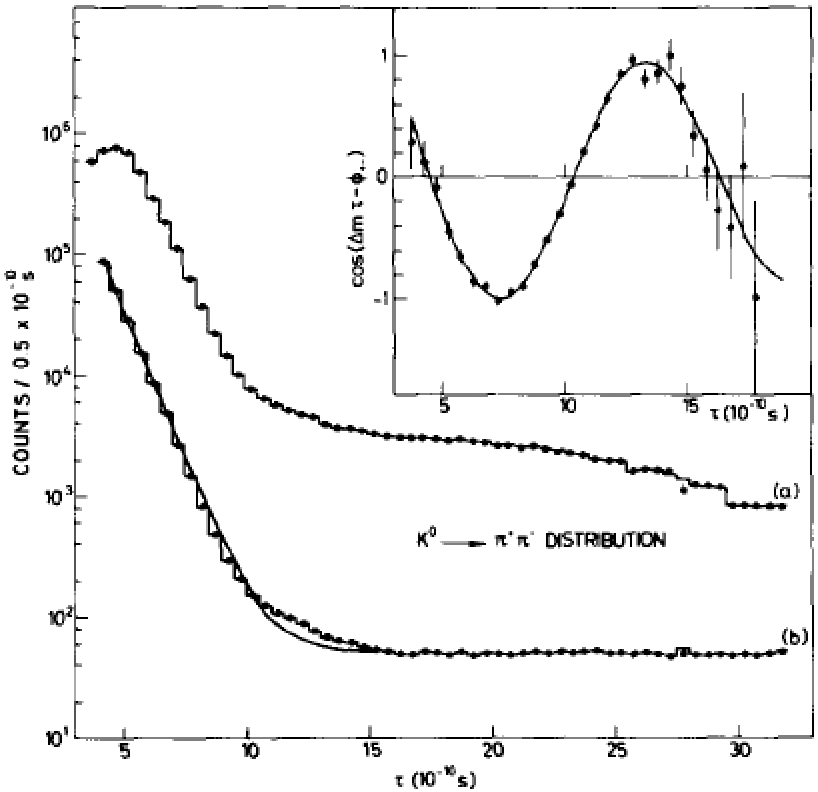
Side view

Top view

- **The first CERN experiment to use large-size multiwire proportional chambers on a large scale for track reconstruction and trigger**
  → ~ 10^3 recorded events / machine cycle (0.35 s)
- **Front face of the decay volume 2 meters from K^0, $\overline{K}^0$ production target**

Time distribution of K → $\pi^+\pi^-$ decays in the "vacuum regeneration" experiment

CERN – Heidelberg coll., Phys. Lett. **B48** (1974) 487



Results :

$|\eta_{+-}| = (2.300 \pm 0.035) \times 10^{-3}$

$\Gamma_S = (1.119 \pm 0.006) \times 10^{10}\ s^{-1}$

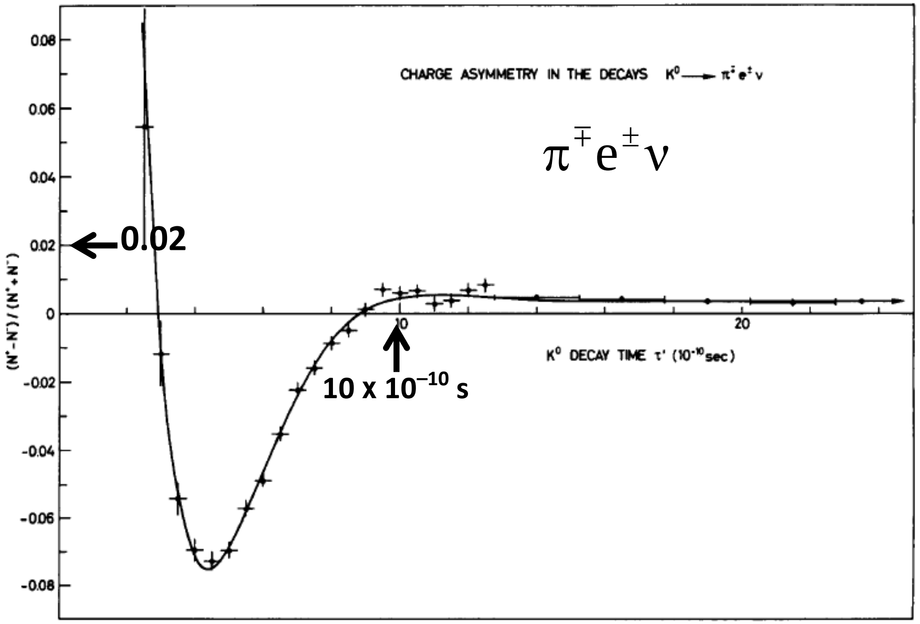
$\phi_{+-} = (49.4 \pm 1.0)^0 + [(\Delta m - 0.540)/0.540] \times 305^0$

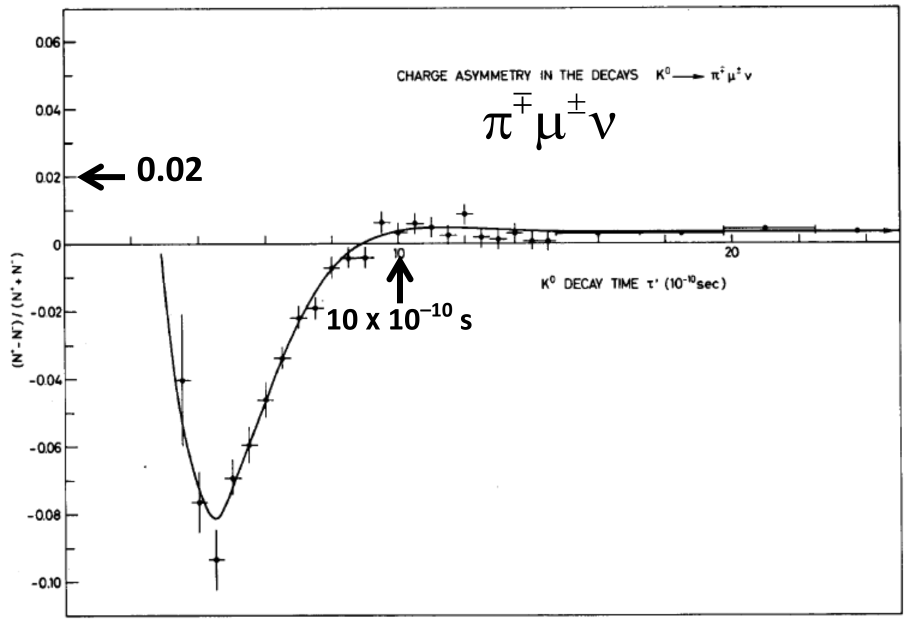
Measurement of Δm from the charge asymmetry in semileptonic K decays

CERN-Dortmund-Heidelberg coll., Phys. Lett. **B52** (1974) 113

Lepton charge asymmetry in the "vacuum regeneration" experiment

$\delta(t) = (N^+ - N^-)/(N^+ + N^-)$ vs. decay time in the K rest frame





$$\delta(t) = 2A(p)e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t}\cos(\Delta m t) + 2\,\mathrm{Re}\,\varepsilon$$

(For K_L semileptonic decay δ = 2Re ε ≈ 0.3 % as a consequence of the ΔS = ΔQ rule)

$\Delta m = (0.5334 \pm 0.0040) \times 10^{10}\ s^{-1}$

The parameter ε describes CP violation in $K^0 - \overline{K}^0$ mixing (the small CP = +1 impurity in the K_L state)

Is there also direct CP violation in the weak decay matrix elements?

Denoting by ε' the parameter describing direct CP violation the ratios of decay amplitudes are

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

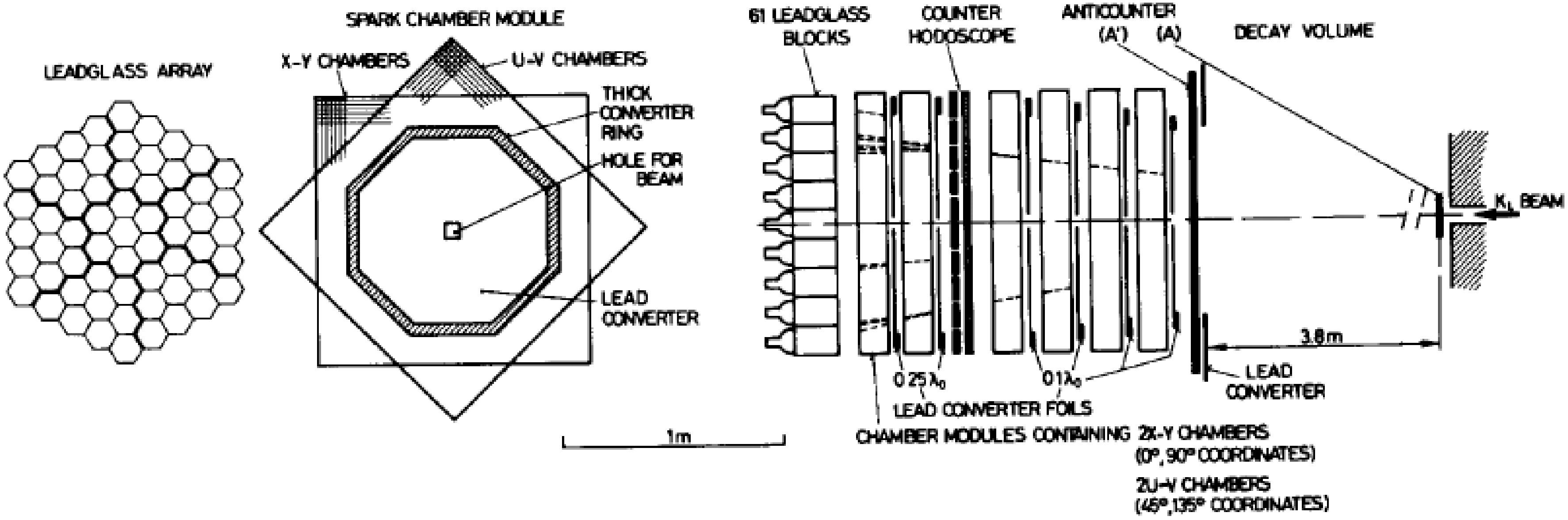
$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

➡ motivation to search for $K_L \to \pi^0 \pi^0$ and measure its rate

Early experiments with 10 – 20 events gave contradictory results.

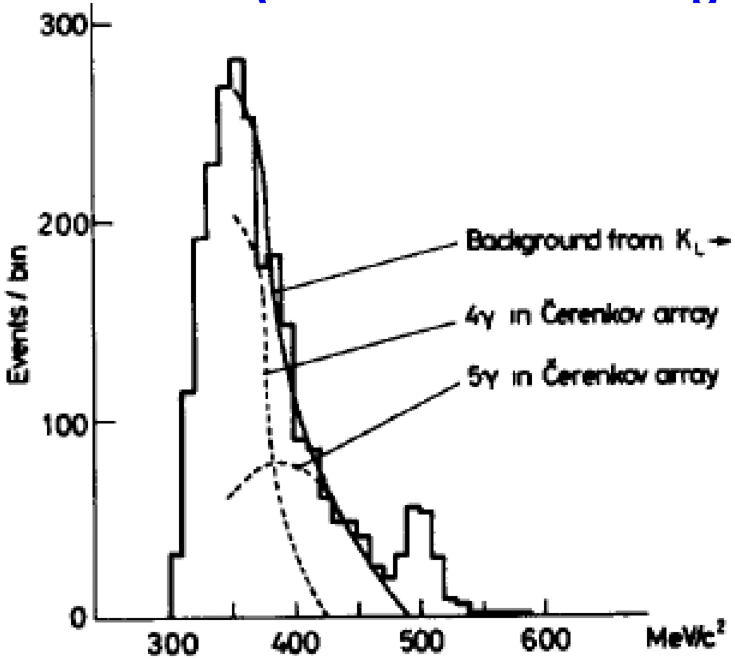
Measurement of the decay $K_L \rightarrow \pi^0\pi^0$

Aachen – CERN – Torino coll., Phys. Lett. B40 (1972) 141

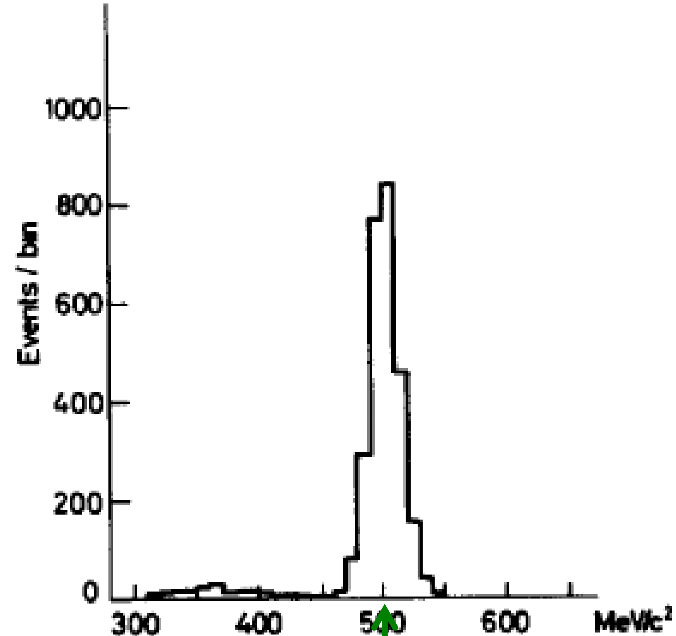


View along beam | Side view

Events with 4 detected photons
(at least 2 converting in the spark chambers)



$K_L \to \pi^0\pi^0$



$K_S \to \pi^0\pi^0$
(regenerated K_S)

Final result: $\left|\dfrac{\eta_{00}}{\eta_{+-}}\right| = 1.00 \pm 0.06$

First evidence for $\varepsilon' \neq 0$ from experiment NA31 at the CERN SPS (1988)
Conclusive result in 1999 from KTEV (Fermilab) and NA48 (CERN):

$$\varepsilon' / \varepsilon = (1.66 \pm 0.23) \times 10^{-3}$$

Hadron spectroscopy

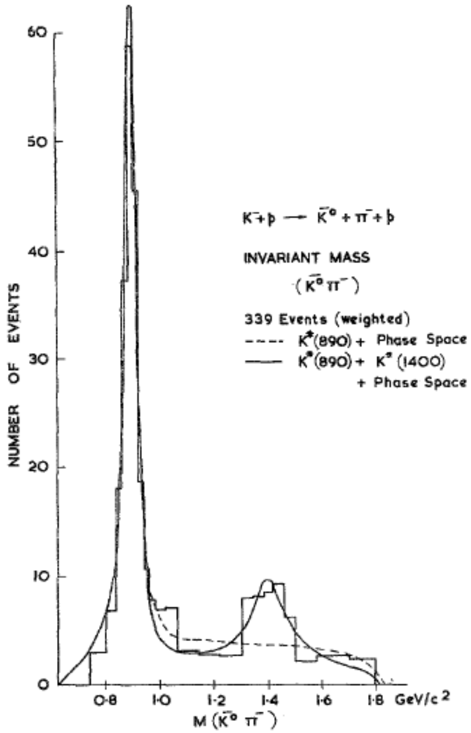
Many important results, mainly from the hydrogen bubble chambers:

- Measurement of the K*(890) spin – parity (1^-) from $\bar{p}$ p annihilation at rest
- Discovery of the f (1270) and measurement of its spin – parity (2^+)
- Discovery of the A_2 (1320) and measurement of its spin – parity (2^+)
- Discovery of the K*(1430) and measurement of its spin-parity (2^+)

$K^- + p \rightarrow \bar{K}^0 + \pi^- + p \rightarrow \pi^+ + \pi^- + \pi^- + p$

3.5 GeV/c K^- beam in the Saclay 80 cm hydrogen bubble chamber

($\bar{K}^0 \pi^-$) invariant mass distribution

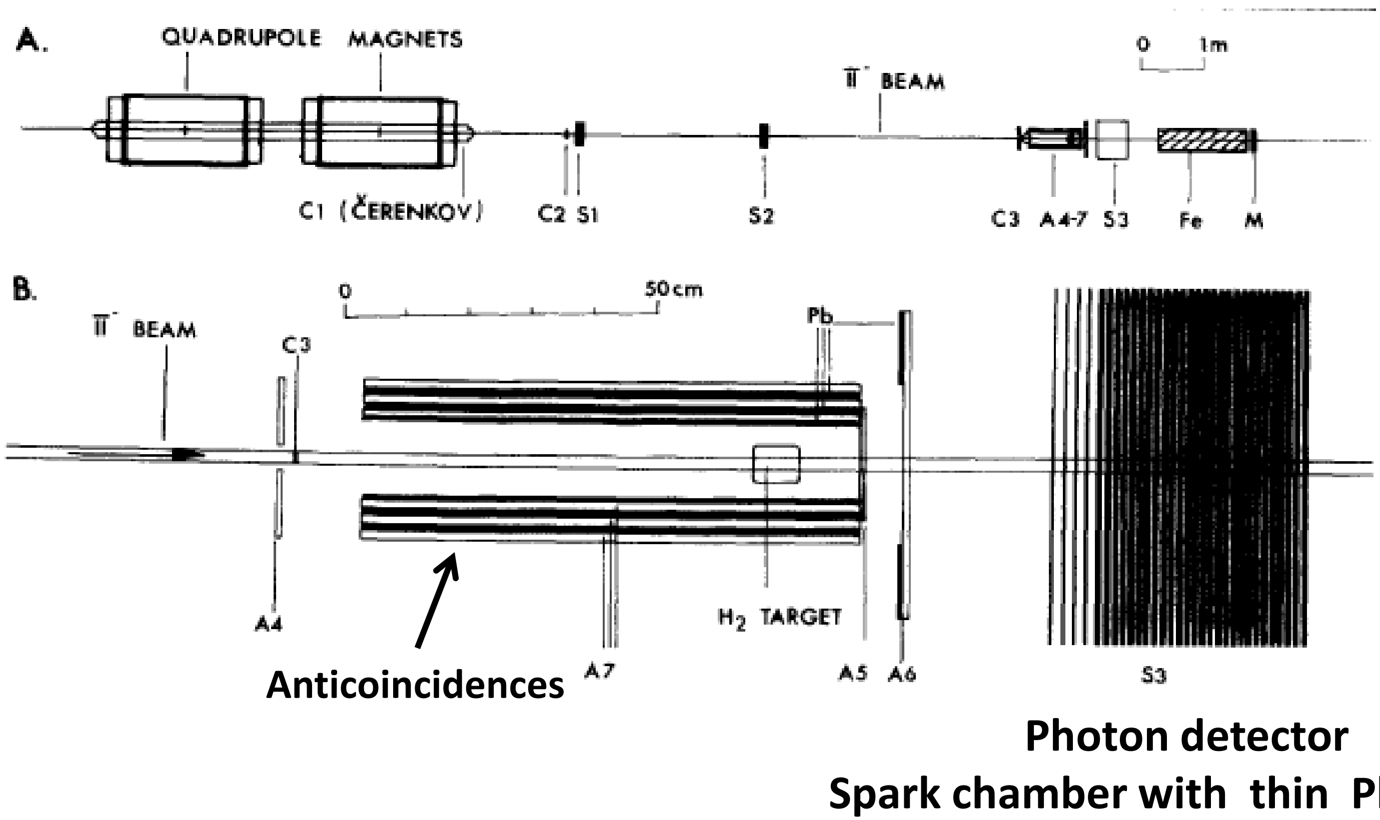


These results provided additional evidence for SU(3) multiplets of hadronic resonances, which led to the formulation of the hadron quark model

Exclusive reactions at high energy

Measurement of the charge exchange reaction $\pi^- + p \rightarrow \pi^0 + n$

Orsay – Saclay coll., Phys. Rev. Lett. 14 (1965) 763 ; Phys. Lett. 20 (1966) 75

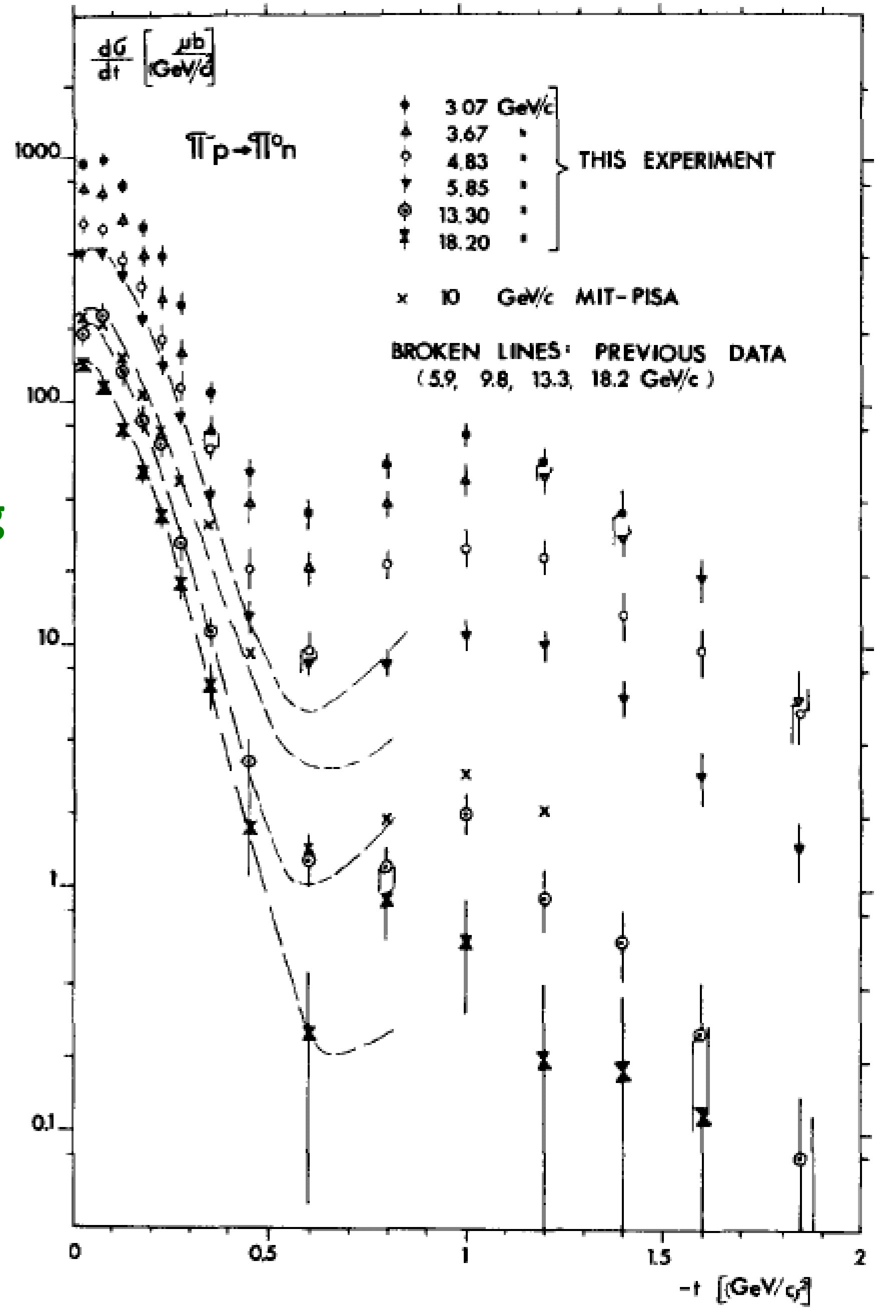


Differential cross – section dσ/d|t|

$$t = (P_{\pi^-} - P_{\pi^0})^2$$

- Minimum at -t ≈ 0.6 (GeV/c)2
- Decrease of dσ/d|t| with increasing energy
- The decrease with energy becomes larger with increasing |t| ("shrinking" of the forward peak)

All features quantitatively described by the Regge pole model (exchange of the ρ – meson Regge trajectory)



Other predictions of the Regge pole model:

- Polarization parameter in pion – proton elastic scattering $P_0 \neq 0$
- Opposite sign for π^+p and π^-p elastic scattering
- $P_0 = 0$ for $\pi^- + p \rightarrow \pi^0 + n$

Differential cross – section for a polarized proton target:

$$\frac{d\sigma}{d|t|} = \left(\frac{d\sigma}{d|t|}\right)_{P_T=0} (1 + \vec{P}_0 \cdot \vec{P}_T)$$

$\vec{P}_T$: polarization of target protons ; $\vec{P}_0$ direction normal to the scattering plane

Crystals containing ~1/16 free, polarized protons with >70% polarization had been developed in Saclay in the early 1960s by A. Abragam and collaborators, and brought to CERN in 1964.

Polarization reversal was achieved by changing a microwave frequency by ~0.3 %, with no need to reverse the magnetic field → no systematic effects

The CERN – Orsay scattering experiment

M. Borghini et al., Phys. Lett. **21** (1966) 114 ;
Phys. Lett. **24B** (1967) 77

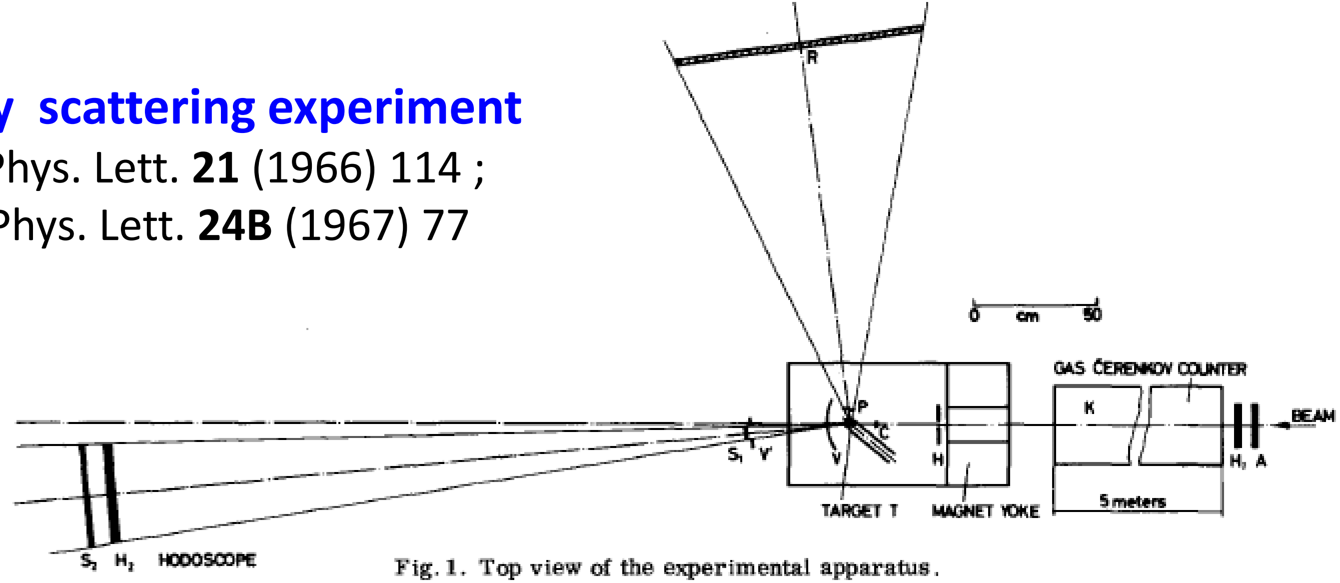
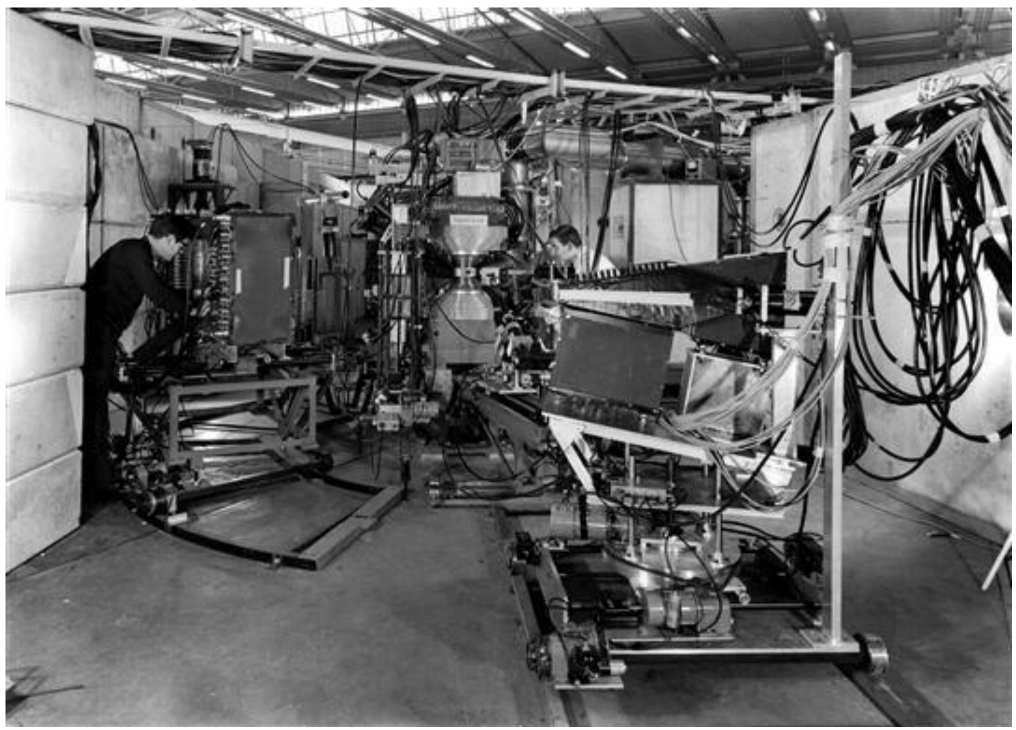


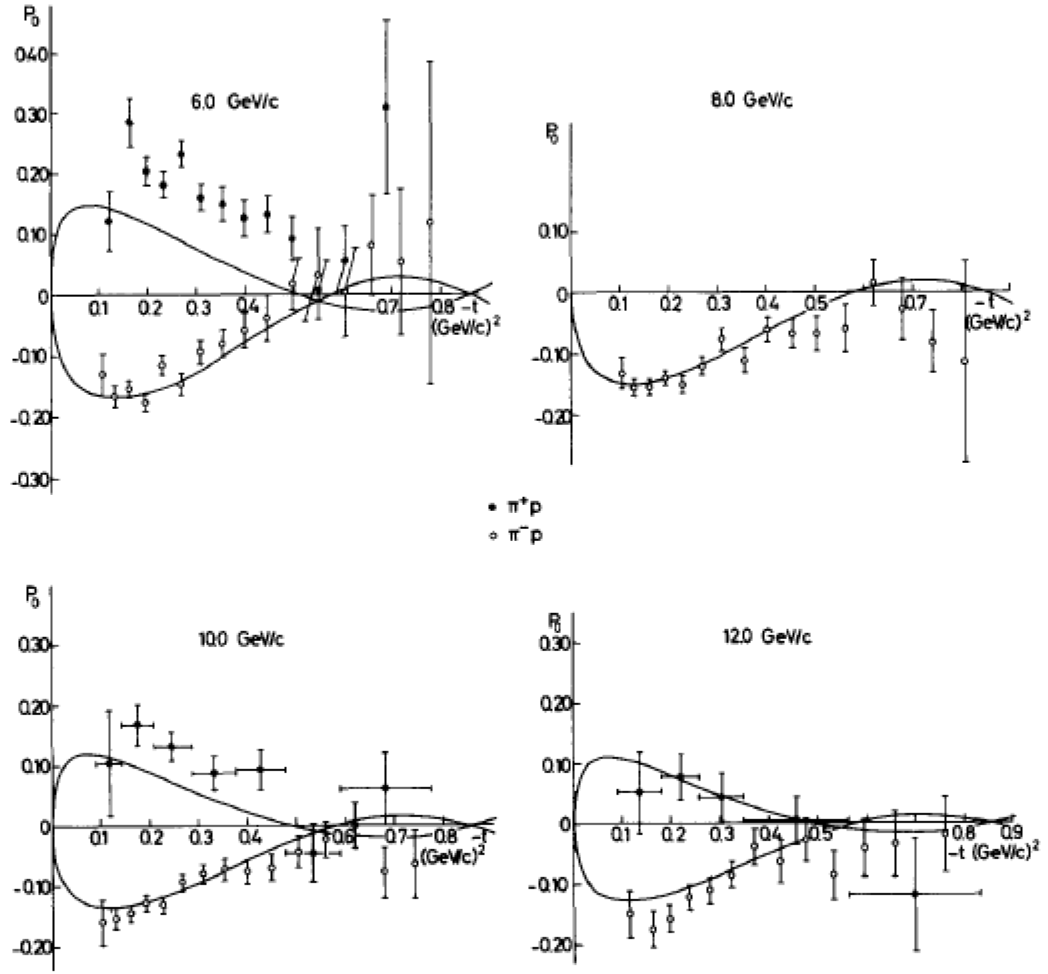
Fig. 1. Top view of the experimental apparatus.



Select scattering on free, polarized protons (1/16) by two-body kinematics (pion – proton coplanarity and $\theta_\pi - \theta_p$ correlation)

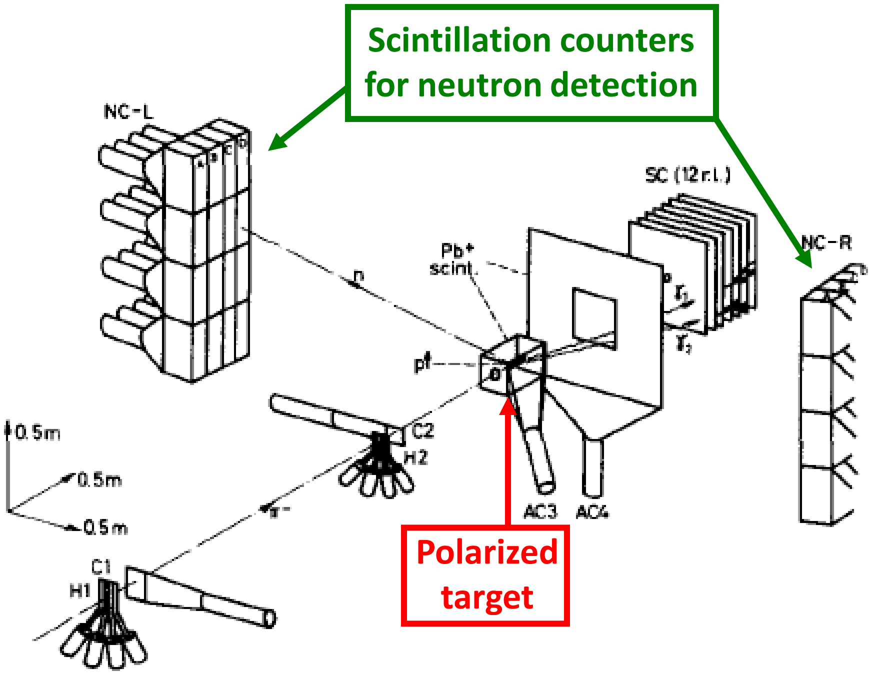
Polarization parameter : $$P_0 = \frac{1}{P_T}\,\frac{N(P_T\ \mathrm{up}) - N(P_T\ \mathrm{down})}{N(P_T\ \mathrm{up}) + N(P_T\ \mathrm{down})}$$

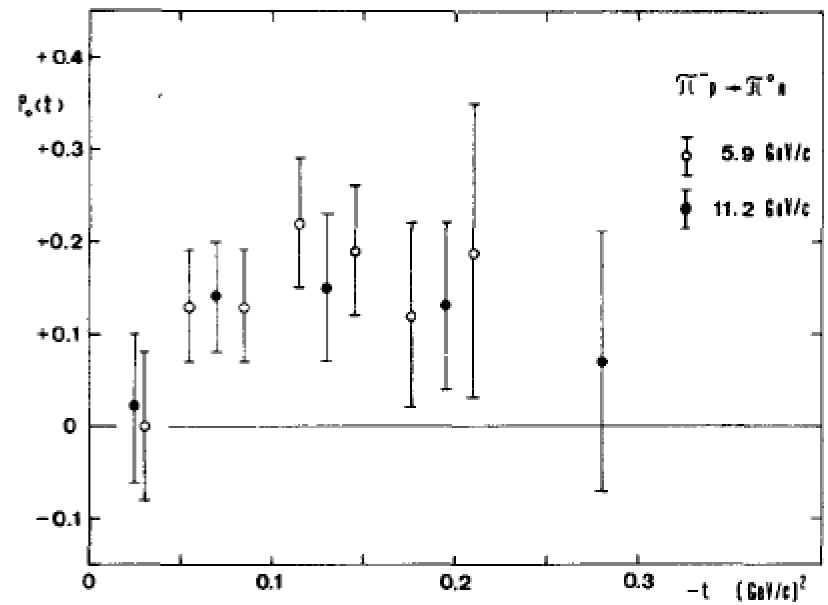
A simple Regge pole model does not describe correctly the polarization parameter in BOTH π^+p and π^-p elastic scattering



Polarization parameter in $\pi^- + p \rightarrow \pi^0 + n$

Orsay – Saclay – Pisa coll., Phys. Lett. **23** (1966) 501





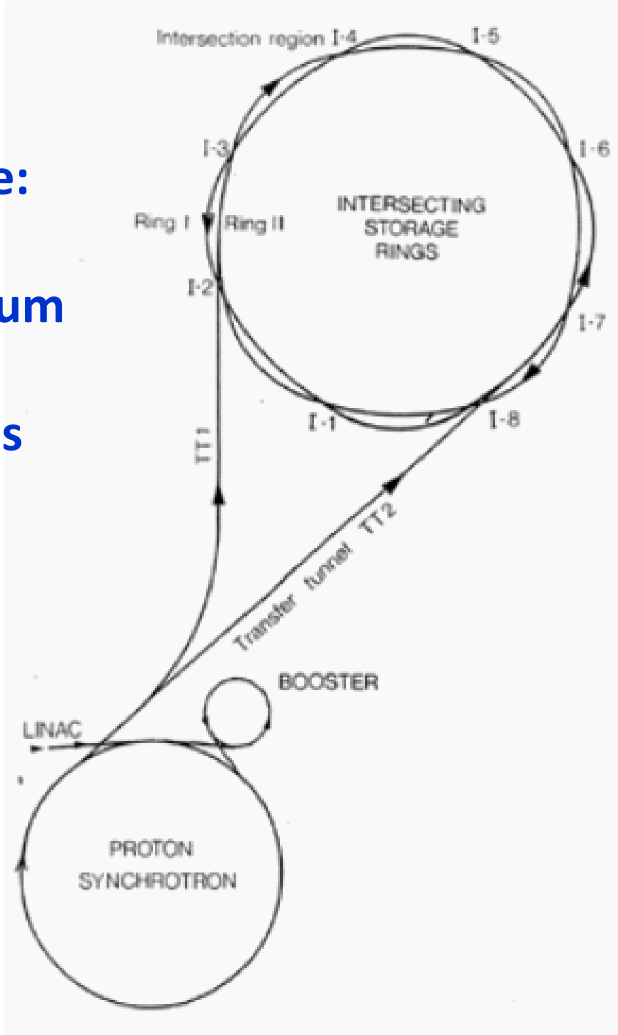
The simple Regge pole model with the exchange of only one trajectory (the ρ – meson) predicted $P_0 = 0$ in disagreement with the experimental results.

It was still possible to describe the polarization results for both $\pi^\pm$ p elastic scattering and π^- p charge exchange using Regge pole models with more trajectories and more fitting parameters.

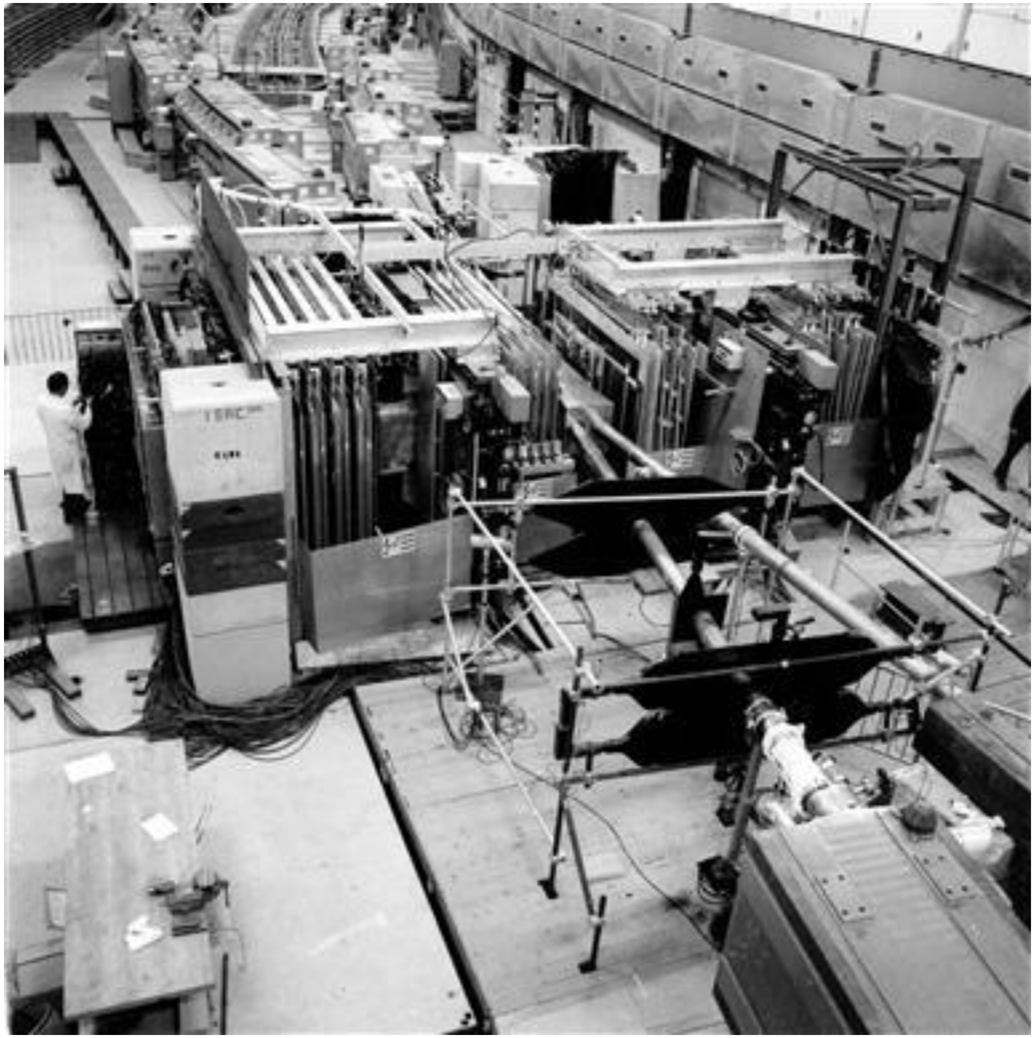
However, by the mid 1970s physicists lost interest in these studies, probably attracted by new, more interesting subjects

The CERN Intersecting Storage Rings (ISR)
The first proton – proton collider ever built

- Two slightly distorted rings intersecting in 8 points
- Average radius 78.6 m
- Proton accumulation by RF stacking in momentum space: the first proton pulse from the PS is accelerated by the ISR RF system up to the highest acceptable momentum (the orbit with largest radius), successive pulses are accumulated on orbits of lower and lower average radius
- Circulating beams are ribbon – shaped (few cm wide), crossing at a 14° angle, with no time structure
- Max. proton energy 31 GeV
  → collision energy 62 GeV corresponding to
  ~ 2.05 TeV protons on a stationary target
- Design vacuum 10^{-10} Torr, soon improved to 2×10^{-12}
- Design luminosity 4×10^{30} cm^{-2} s^{-1} reaching > 2×10^{31} with low-β insertions
- First collisions 27 January 1971; end of collider operation 1984



View of an ISR crossing region
with a double – arm detector at 90 degrees



1964 : Presentation of the ISR design report to CERN Council

End of 1965: approval ("a window to investigate the highest energies")

1968: Study groups to prepare for experiments (Which physics should be studied at the ISR?)

Emphasis on: measurement of proton – proton total cross – section;
elastic scattering including Coulomb interference region;
isobar production p + p → p + N*;
particle production.

Cosmic ray experiments had shown that the main feature of pion production at very high energies is the limited transverse momentum p_T

$$\frac{dN}{dp_T} \propto p_T e^{-6 p_T}$$ (p_T in GeV/c)

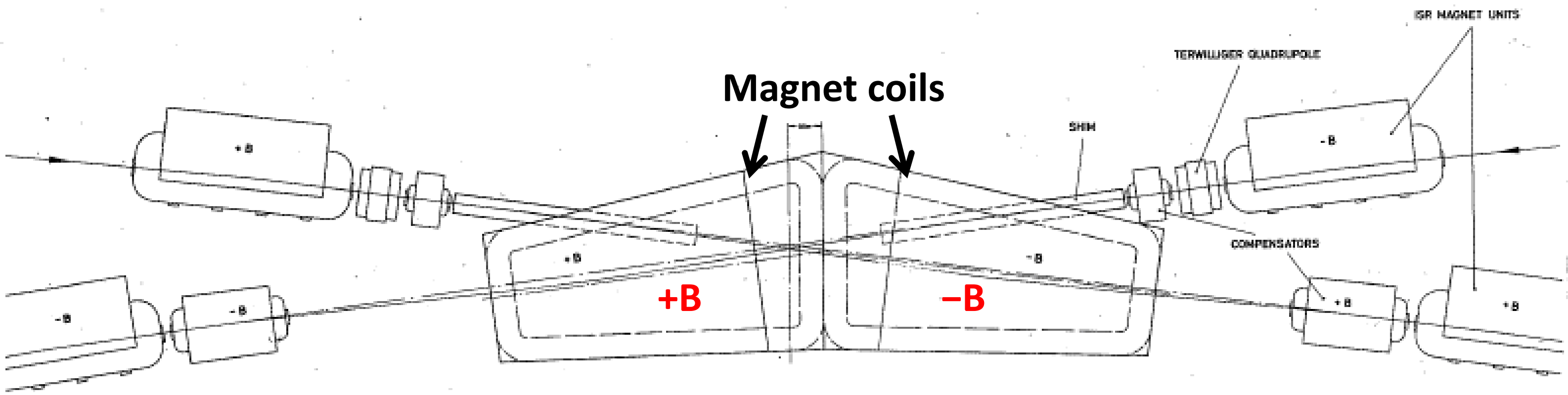
giving $\langle pT \rangle \approx$ 300 MeV/c

The prevailing opinion :

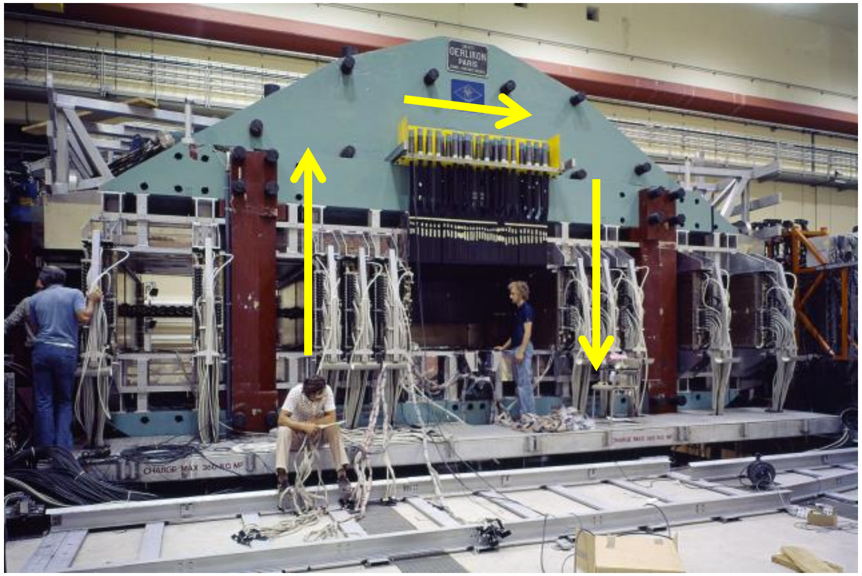
"Nothing happens at 90° in proton - proton collisions at the ISR"

The typical example of this "school of thought": the design of the general – purpose magnetic spectrometer for the ISR

The Split Field Magnet: maximum bending power in the angular regions at small angles to the beams, with minimal perturbation to the beams



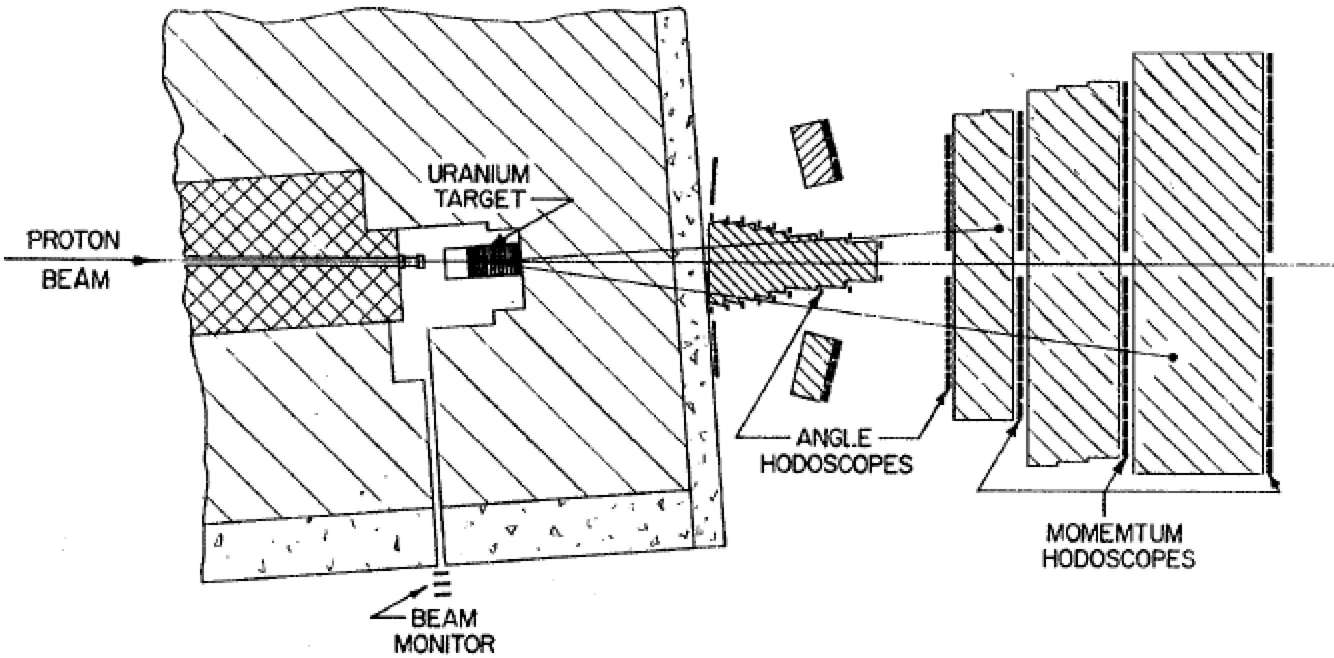
Split Field Magnet with magnetic field directions

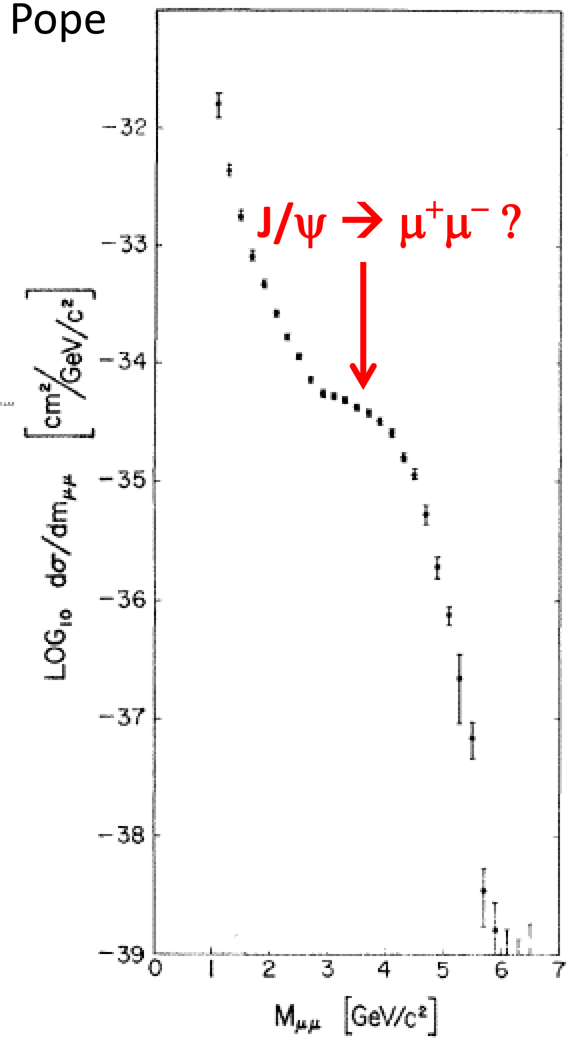


The story of an ISR discovery which prevented a more important discovery

1970: a "beam dump" experiment at the Brookhaven AGS observing the production of high – mass muon pairs

J.H. Christenson, G.S. Hicks, L.M. Lederman. P.J. Limon, B.G. Pope and E. Zavattini, Phys. Rev. Lett. **25** (1970) 1523





Measurement of the muon angle by counter hodoscopes and of muon energy by residual range in iron

→ poor resolution on the dimuon invariant mass

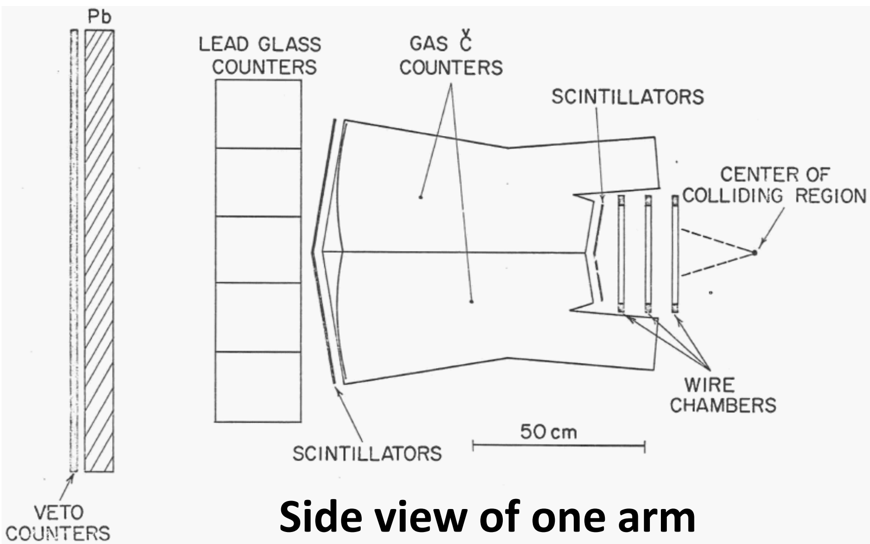
CERN/ISRC/69-43
20 June 1969

INTERSECTING STORAGE RINGS COMMITTEE

Preliminary Proposal

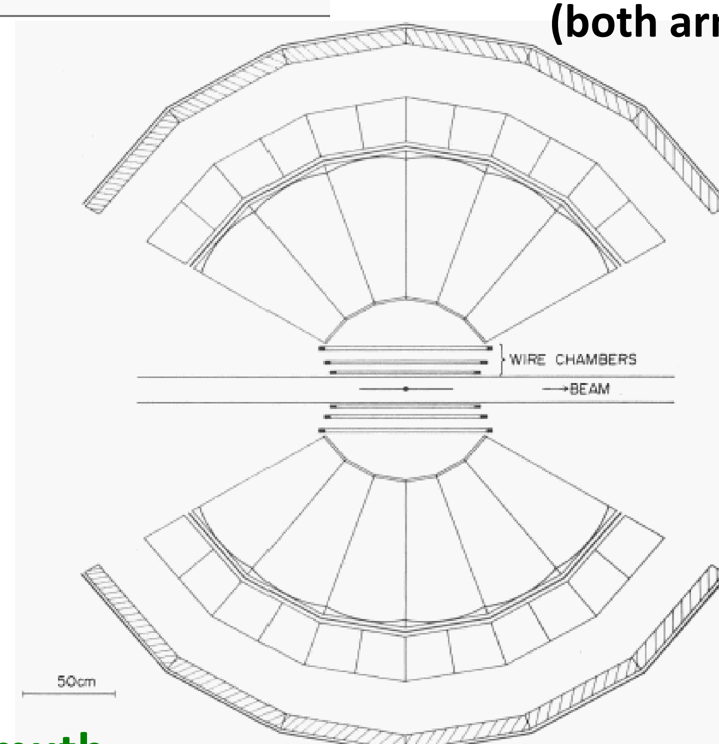
INTERSECTING STORAGE RINGS STUDY OF DILEPTONS

R. Cool, Brookhaven National Laboratory
L. DiLella, CERN-Columbia
L. Lederman, Columbia University
E. Zavattini, CERN



Side view of one arm

Top view (both arms)



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

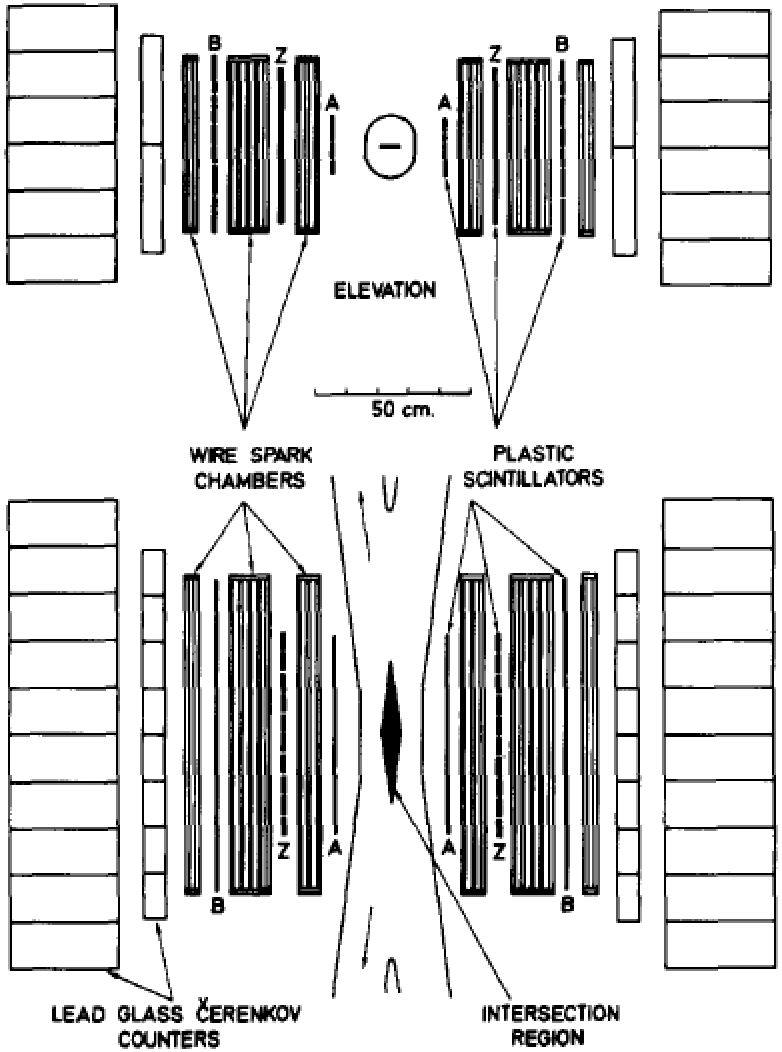
Detect electrons near 90° at opposite azimuth

Good invariant mass resolution (wire spark chambers + lead glass counters)

The preliminary proposal had gas Čerenkov counters for electron / pion separation.

The final set-up had no gas Čerenkov counters (only low p_T pions were expected around 90°), but the solid angle was much increased (about 1 sr on each side of the beams)

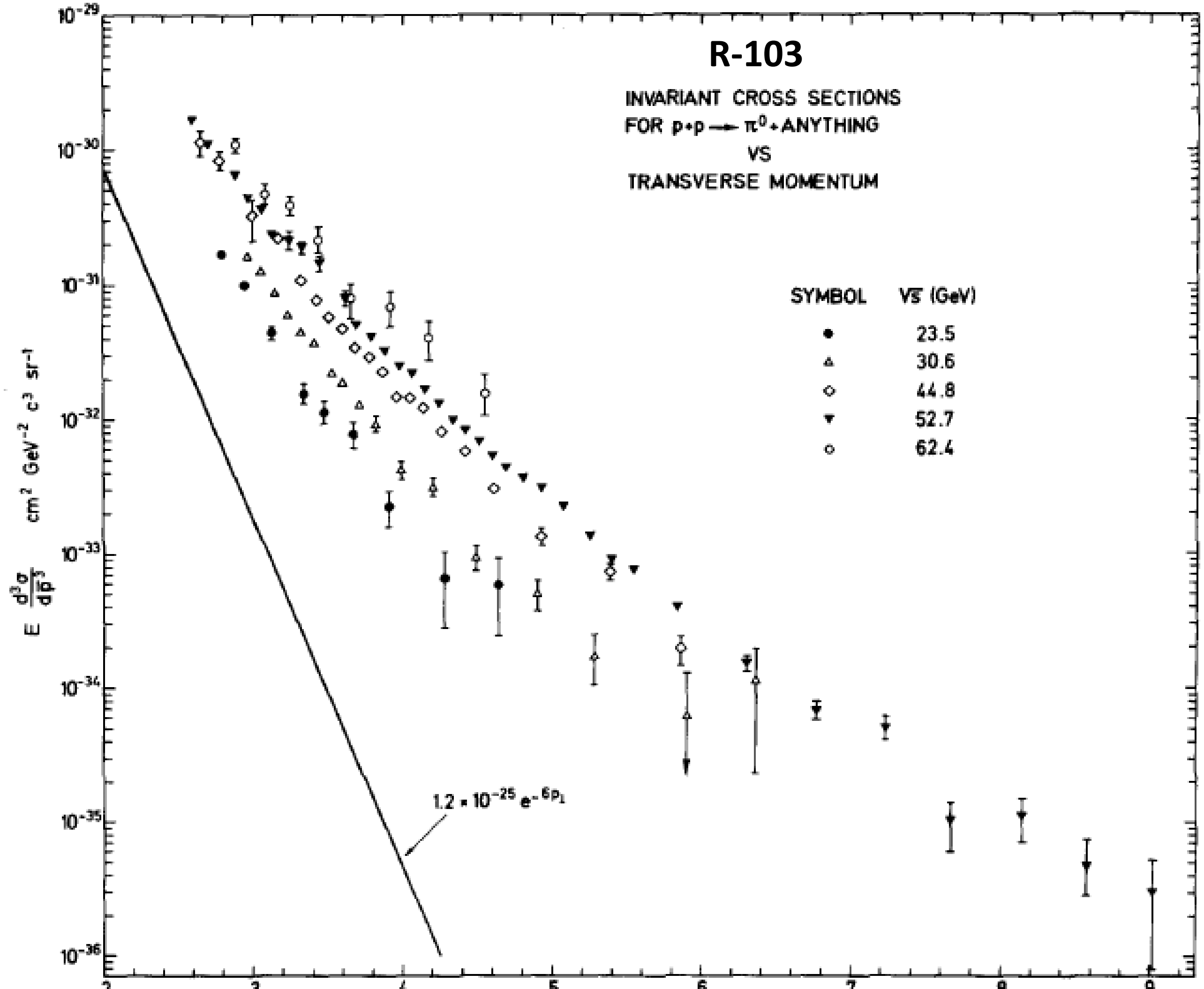
ISR experiment R-103
Final set-up



OBSERVATION OF π^0 MESONS WITH LARGE TRANSVERSE MOMENTUM IN HIGH-ENERGY PROTON-PROTON COLLISIONS

CERN– Columbia – Rockefeller coll., Phys. Lett. B46 (1973) 471

Results presented at the 1972 Int. Conf. on High Energy Physics

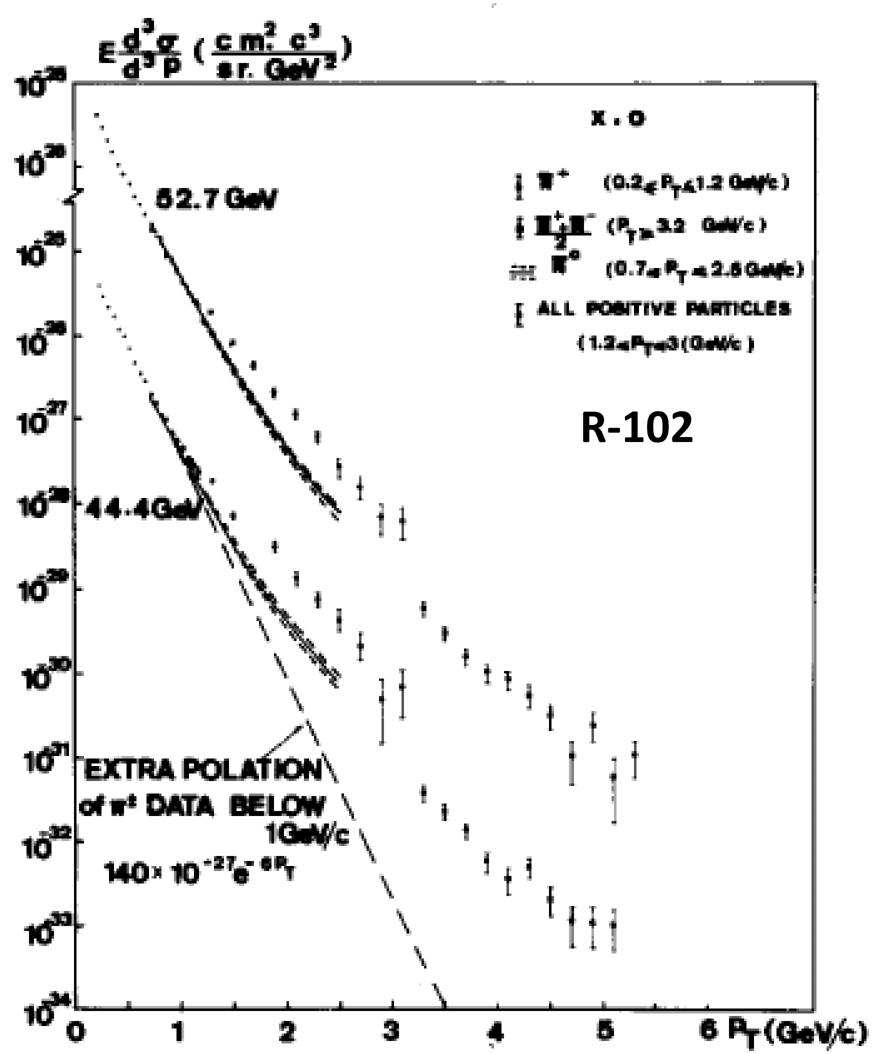


π^0 transverse momentum (GeV/c)

The production of high transverse momentum $\pi^{\pm}$ was also observed at the ISR in two experiments with single-arm magnetic spectrometer

British-Scandinavian collaboration
(ISR experiment R-203),
Phys. Lett. **B44** (1973) 521

Saclay-Strasbourg collaboration
(ISR experiment R-102),
Phys. Lett. **B44** (1973) 537



The production of high transverse momentum hadrons at the ISR was interpreted as the result of hard scattering between point – like proton constituents ("partons", first observed in deep – inelastic electron – nucleon scattering at SLAC).

It had been predicted to occur in high-energy proton-proton collisions:
Inclusive Processes at High Transverse Momentum, S.M. Berman, J.D. Bjorken and J.B. Kogut, Phys. Rev. D4 (1971) 3388.
However, the production cross-section of high p_T hadrons calculated in this paper assumed photon exchange between partons (electromagnetic interaction), too small to be observed at the ISR.

The ISR experiments have demonstrated that partons behave as point-like objects also when they interact strongly.

These results have opened the way to the study of jet production in high energy hadron collisions (the only process occurring to leading order in perturbative QCD).

In experiment R-103 (the large solid angle double-arm lead-glass array) the rate of two-arm coincidences used for trigger was dominated by the production of high pT π^0 pairs emitted at opposite azimuth . It was limited to ~10 Hz by the spark chambers (and also by the rate of event writing onto magnetic tape). The only way to keep the trigger rate under control was to increase the trigger energy threshold.

A SEARCH FOR ELECTRON PAIRS AT THE CERN ISR

F.W. BÜSSER*[1], L. CAMILLERI, L. Di LELLA, G. GLADDING*[2], A. PLACCI,
B.G. POPE, A.M. SMITH, J.K. YOH*[3] and E. ZAVATTINI
CERN, Geneva, Switzerland

B.J. BLUMENFELD*[4] and L.M. LEDERMAN*[5]
Columbia University, NY, USA *[6]

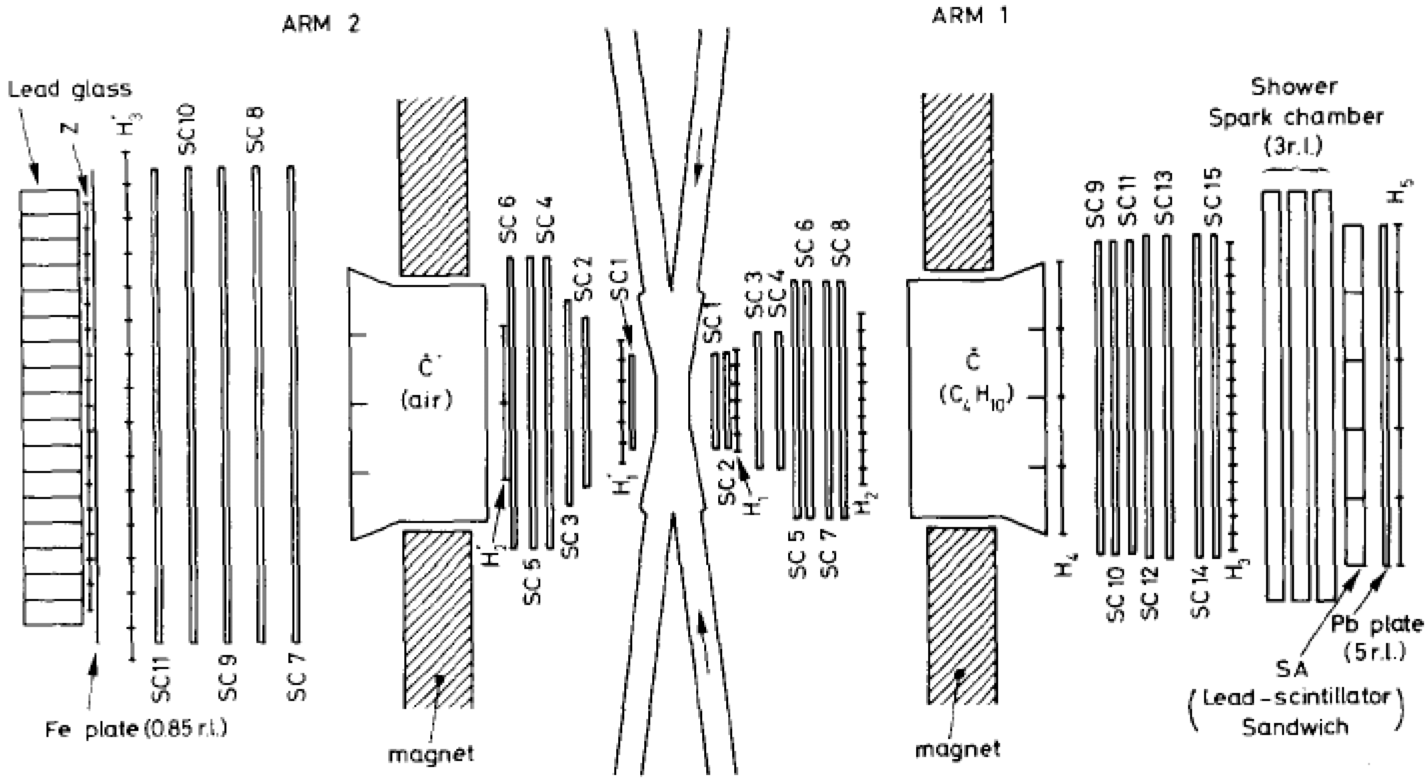
R.L. COOL*[5], L. LITT and S.L. SEGLER
Rockefeller University, NY, USA *[7]

Received 20 December 1973

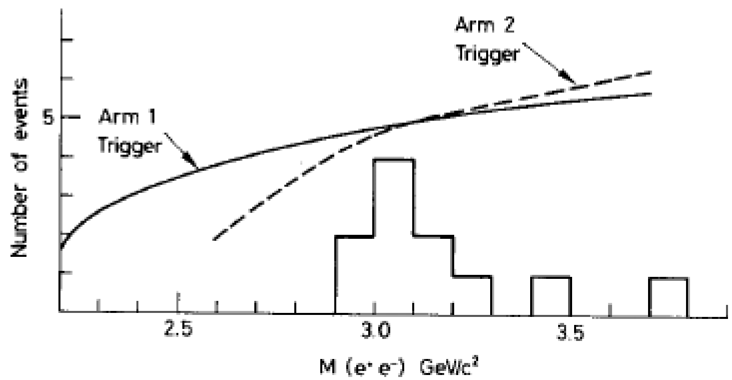
The analysis of runs corresponding to 2×10^{10} inelastic interactions at $\sqrt{s} = 52.7$ GeV yielded five events in which two tracks, on opposite sides of the apparatus, were found to satisfy all of the above requirements. The invariant mass of each pair was calculated from the relation $m^2 = 2p_1 p_2(1 - \cos\theta)$, where θ is the opening angle of the two electrons, and p_1 and p_2 are their momenta. The pair masses were distributed above a threshold of 3.1 GeV/c^2. This threshold was due to the energy cuts imposed on each electron and to the requirement that the two electrons be on opposite sides of the apparatus. No pair was observed with an effective mass greater than 4.2 GeV/c^2.

ISR experiment R-105 (two-arm spectrometer)

CERN-Columbia-Rockefeller-Saclay collaboration



e^+e^- invariant mass distribution



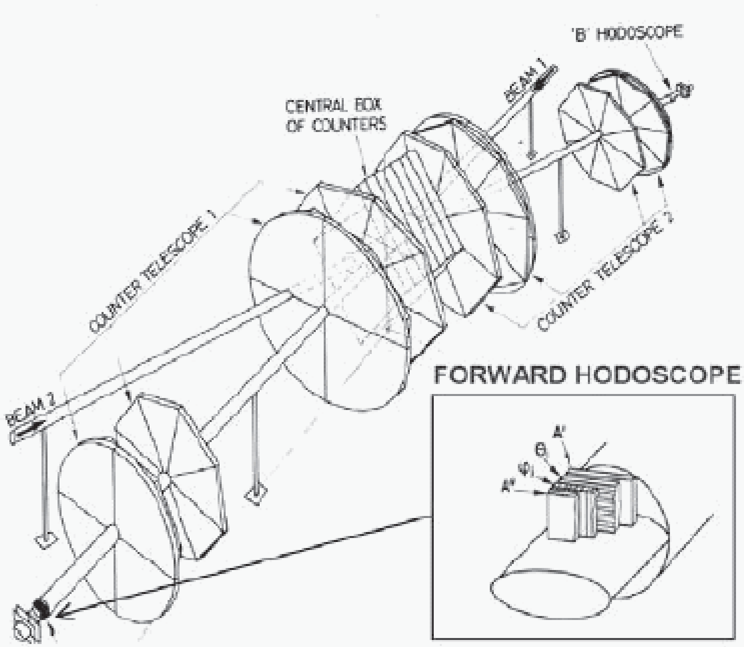
Phys. Lett. **B56** (1975) 482

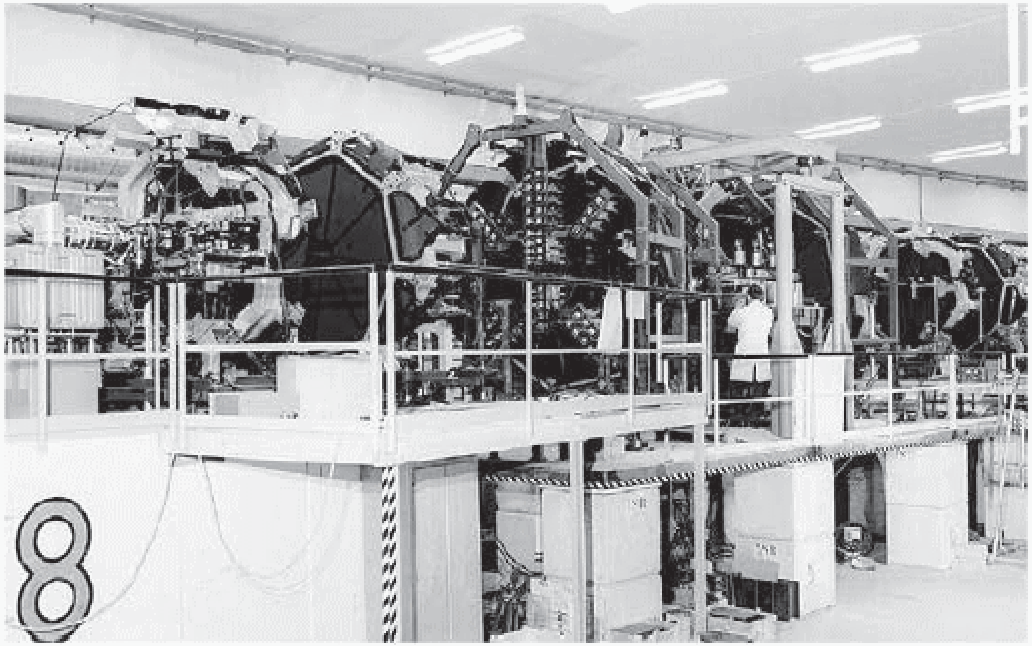
A clear $J/\Psi \rightarrow e^+e^-$ few months after its discovery at BNL and SLAC

The rise of the proton – proton total cross – section at the ISR

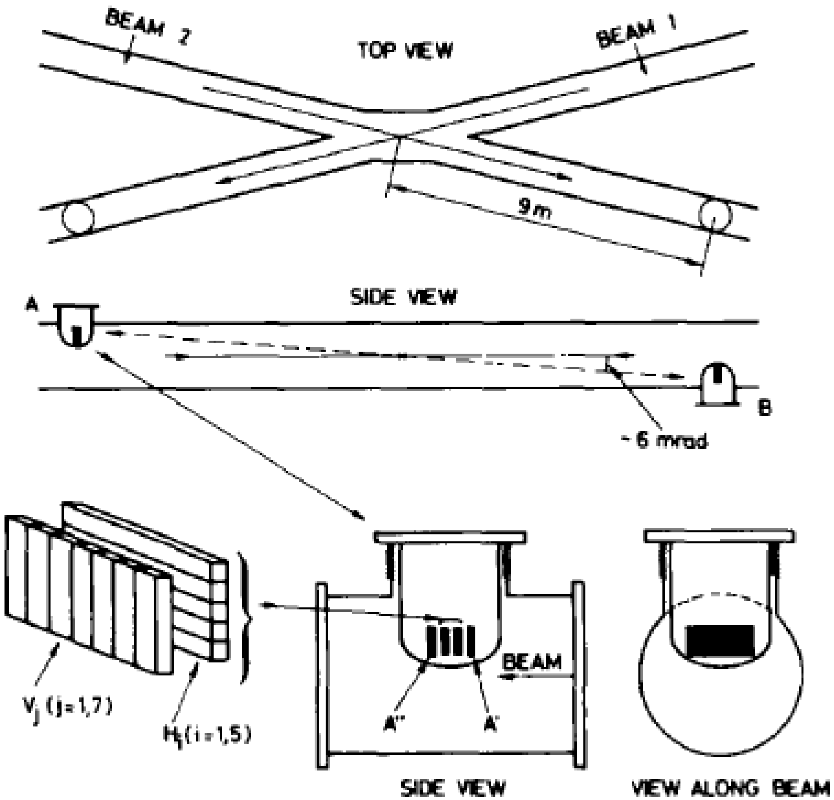
Three experiments:

R – 801 (Pisa – Stony Brook collaboration)
Scintillation counter hodoscopes covering a solid angle of almost 4π





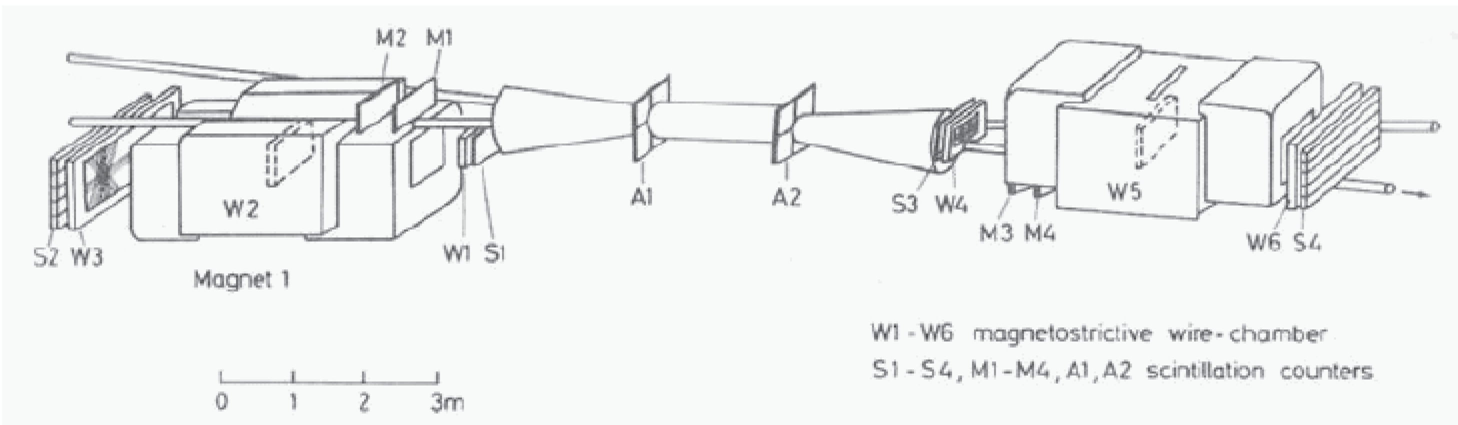
R – 601: CERN – Rome collaboration
Measurement of proton – proton elastic scattering at very small angles, including the Coulomb interference region



An original system of "pots" equipped with scintillator hodoscopes moving as close as possible to the beams under stable beam conditions

The technique of movable "pots" (with different types of detectors) has since been used in all measurements of elastic and total cross-sections at all hadron colliders: the $\bar{p}$ p colliders at CERN and Fermilab, and the LHC (TOTEM experiment)

R – 602 : Aachen – CERN – Harvard – Genova – Torino collaboration
Measurement of proton – proton elastic scattering using
two septum magnets (dipoles)



Relation between elastic scattering at small angles and the total cross-section

$$\frac{d\sigma}{d|t|} = \frac{\pi}{k^2}\frac{d\sigma}{d\Omega^*} = \frac{\pi}{k^2}\left|A(\theta^*)\right|^2$$

$A(\theta^*)$ strong interaction scattering amplitude;

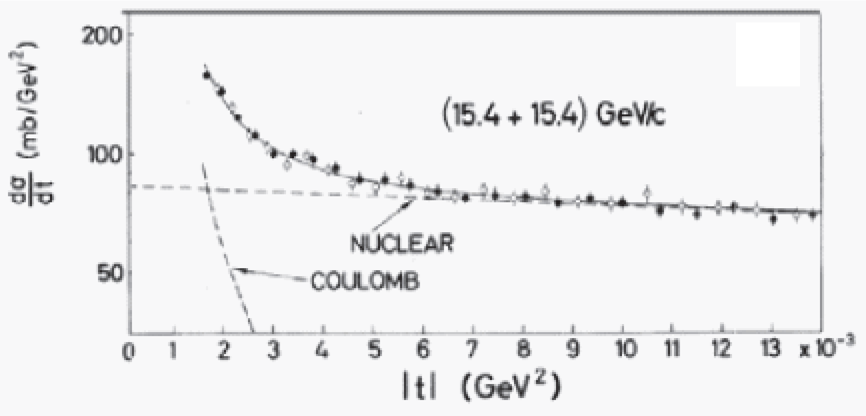
$t = -2k^2(1 - \cos\theta^*)$ (4 –momentum transfer)^2 ; k : momentum
θ^* : scattering angle
} in the centre-of-mass reference frame

Extrapolation to $t = 0$ ($\theta^* = 0$) gives $|A(0)|^2 = [\mathrm{Re}A(0)]^2 + [\mathrm{Im}A(0)]^2$

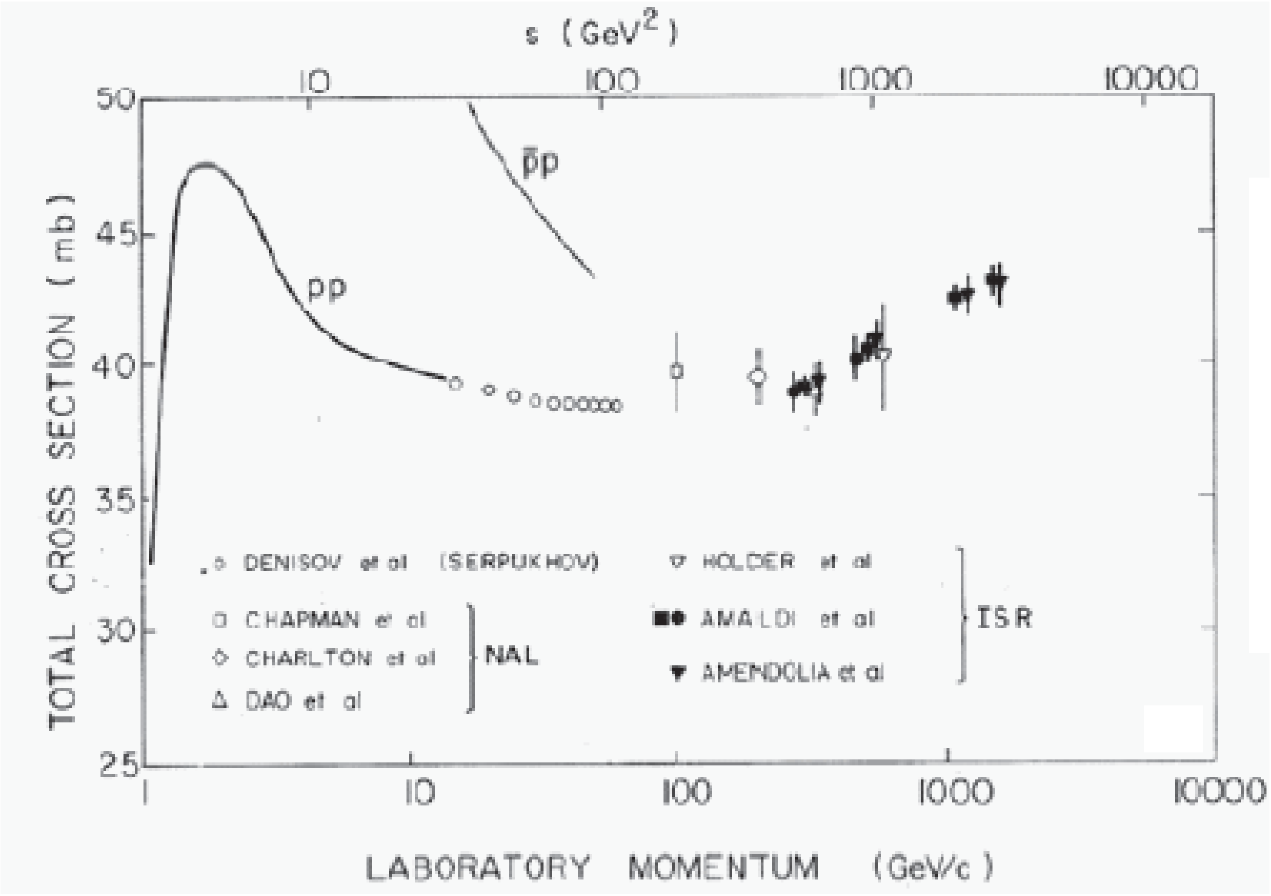
"Optical" theorem: $$\sigma_{TOT} = \frac{4\pi}{k}\mathrm{Im}A(0)$$

The measurement of $d\sigma/d|t|$ in the Coulomb interference region gives $\rho = \frac{\mathrm{Re}A}{\mathrm{Im}A}$

$$\sigma_{TOT} = 4\sqrt{\frac{\pi}{1+\rho^2}\left(\frac{d\sigma}{d|t|}\right)_{t=o}}$$



The proton – proton total cross – section at the end of 1973



M. Holder et al. (Aachen – CERN – Harvard – Genova – Torino coll.), Phys. Lett. **B36** (1971) 400
U. Amaldi et al. (CERN – Rome coll.), Phys. Lett. **B43** (1973) 231; Phys. Lett. **B44** (1973) 112
R. Amendolia et al. (Pisa – Stony Brook coll.), Phys. Lett. **B44** (1973) 119

The invention of the hadronic calorimeter

NUCLEAR INSTRUMENTS AND METHODS 106 (1973) 189–200; © NORTH-HOLLAND PUBLISHING CO.

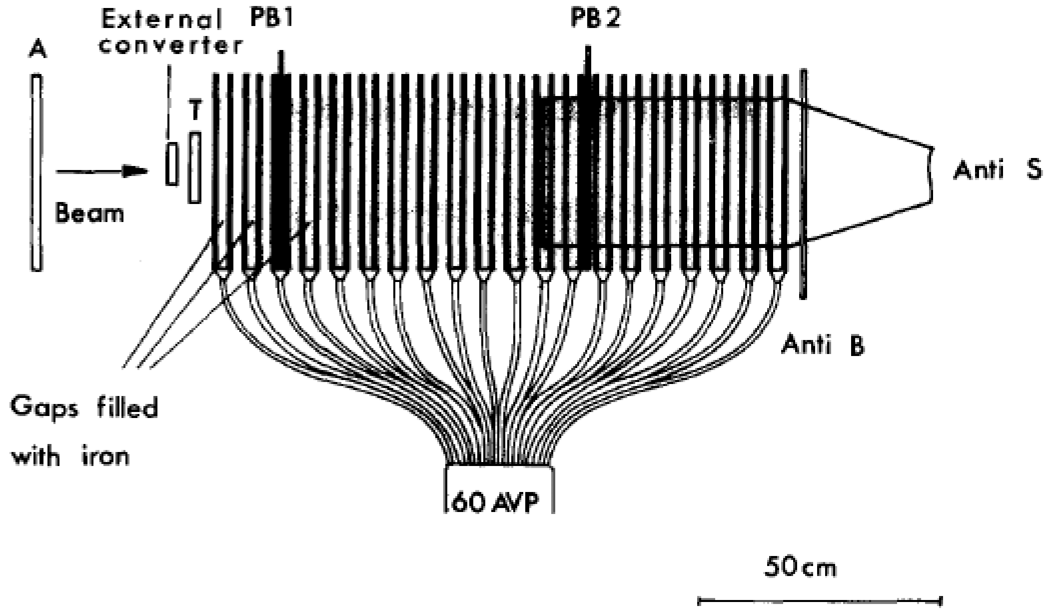
A TOTAL ABSORPTION SPECTROMETER FOR ENERGY MEASUREMENTS OF HIGH-ENERGY PARTICLES

J. ENGLER, W. FLAUGER, B. GIBBARD, F. MÖNNIG, K. RUNGE and H. SCHOPPER

CERN, Geneva, Switzerland, and Institut für Experimentelle Kernphysik, Karlsruhe, Germany

Received 18 August 1972

A sampling total absorption counter (STAC) is described, which consists of a sandwich of iron and scintillator plates. It permits the energy determination of neutrons or other strongly interacting particles with energies above 3 GeV. The optimization of the energy resolution and other properties of the counter are reported. At 24 GeV/c an energy resolution of $\pm 11\%$ was achieved.



Searches for free quarks

Searches for free quarks with fractional electric charge started in 1964, as soon as the quark model of hadrons based on SU(3) symmetry was proposed

The main detector methods:

- **Low ionization density (for relativistic free quarks expect dE/dx between 1/9 and 4/9 of $(dE/dx)_{MIP}$ (MIP = Minimum Ionizing Particle)**
- **Measured momentum (assuming |charge| = e) higher than average beam momentum**

Searches for free quarks at the CERN PS:

- **Exposure of the 80 cm H_2 bubble chamber to a 20 GeV beam**
  (average bubble density for 1 MIP = 25 bubbles / cm)
- **Exposure of a heavy liquid (Freon) bubble chamber to a 16 GeV beam**
  (average bubble density for 1 MIP = 20 bubbles / cm)

Observe no track consistent with fractional electric charge particles

Assuming that free quark production mechanism is dominated by $p + \text{nucleon} \rightarrow p + \text{nucleon} + q + \bar{q}$, obtain typical upper limits of the order of < 1 free quark produced in 10^8 p – nucleon collisions

The most sensitive search for free quarks at the PS:
a counter experiment in a beam from an internal target

J.V. Allaby et al., Nuovo Cim. **A64** (1969) 75

A secondary beam from a PS internal target bombarded by 27 GeV protons

T : trigger counters

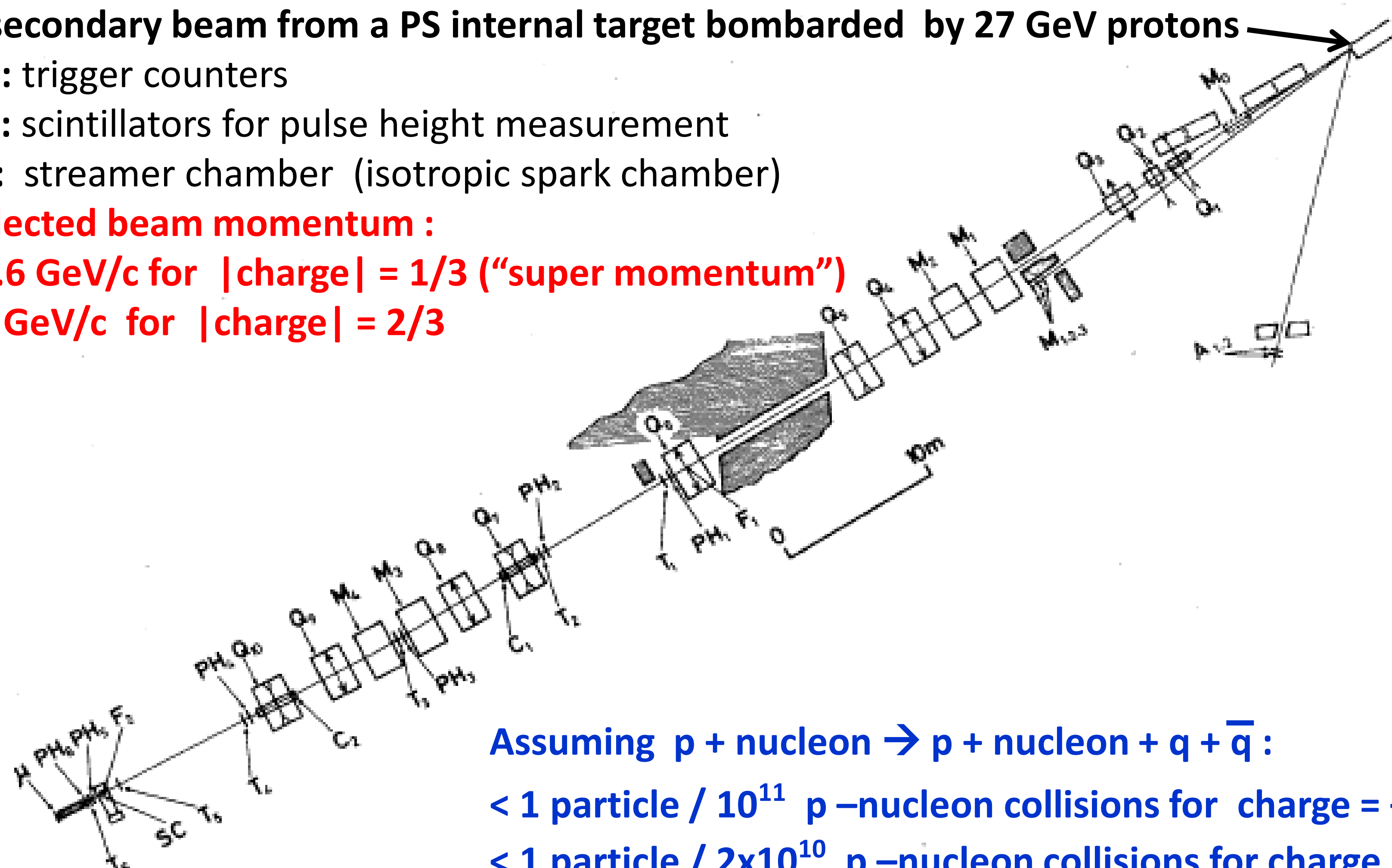
PH: scintillators for pulse height measurement

SC: streamer chamber (isotropic spark chamber)

Selected beam momentum :

32.6 GeV/c for |charge| = 1/3 ("super momentum")

22 GeV/c for |charge| = 2/3



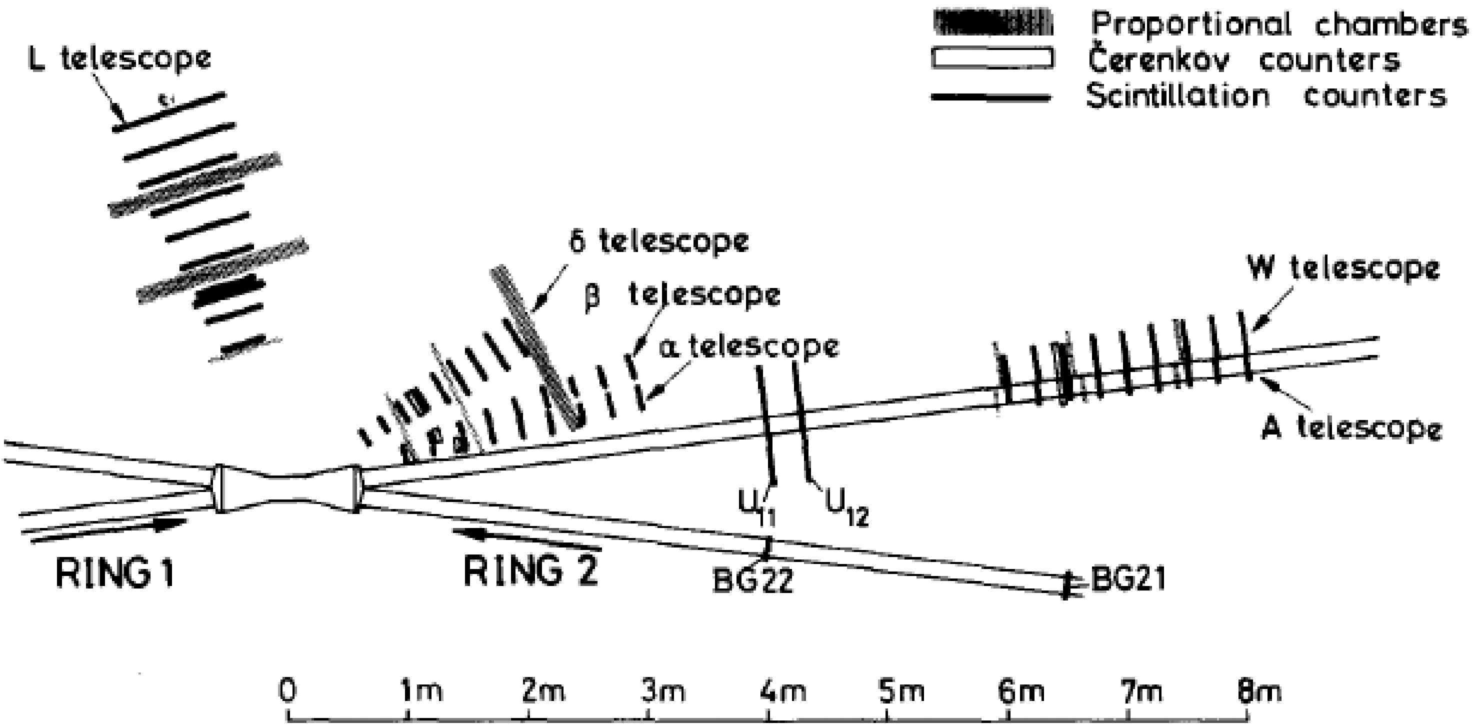
Assuming p + nucleon → p + nucleon + q + $\bar{q}$:

< 1 particle / 10^{11} p –nucleon collisions for charge = –1/3

< 1 particle / $2x10^{10}$ p –nucleon collisions for charge = –2/3

Search for free quarks at the ISR

CERN – MPI coll., Nucl. Phys. **B101** (1975)349



Assuming p + p→ p + p + q + $\overline{q}$:

< 1 particle / 10^9 p –p collisions for |charge| = 1/3

< 1 particle / $5x10^8$ p –p collisions for |charge| = 2/3

at a collision energy of 53 GeV

The three "g – 2" experiments

Measurement of the muon anomalous magnetic moment

For a review see F.J.M. Farley and E. Picasso, Ann. Rev. Nucl. Part. Science **29** (1979) 243

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:

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

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

Original motivation to measure a_μ in the early 1960s:
to understand the difference between muon and electron
(mass difference associated with different interaction?)

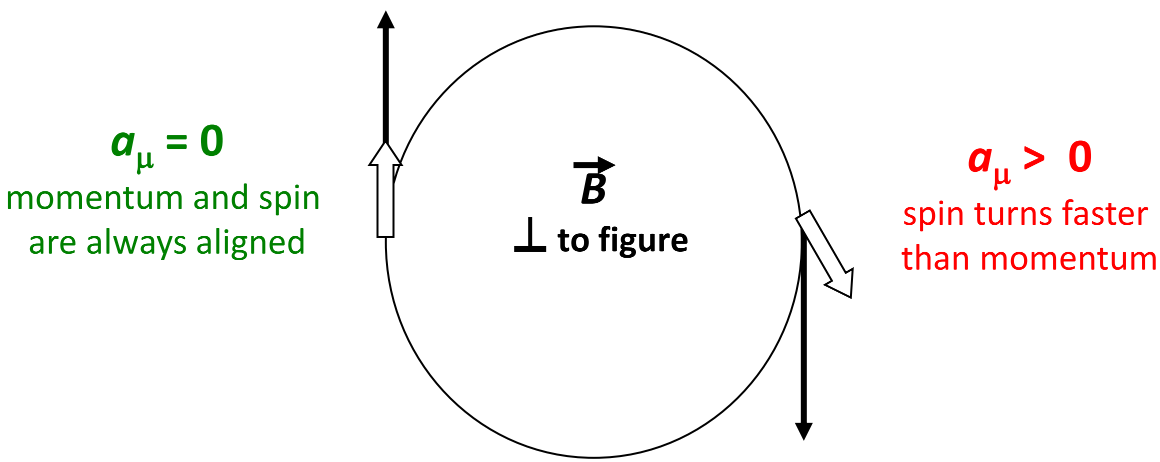
Inject longitudinally polarized muons with momentum $\vec{p}$ into a uniform magnetic field $\vec{B}$

$$\vec{\omega}_c = -\left(\frac{e}{mc}\right)\frac{\vec{B}}{\gamma}$$ 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

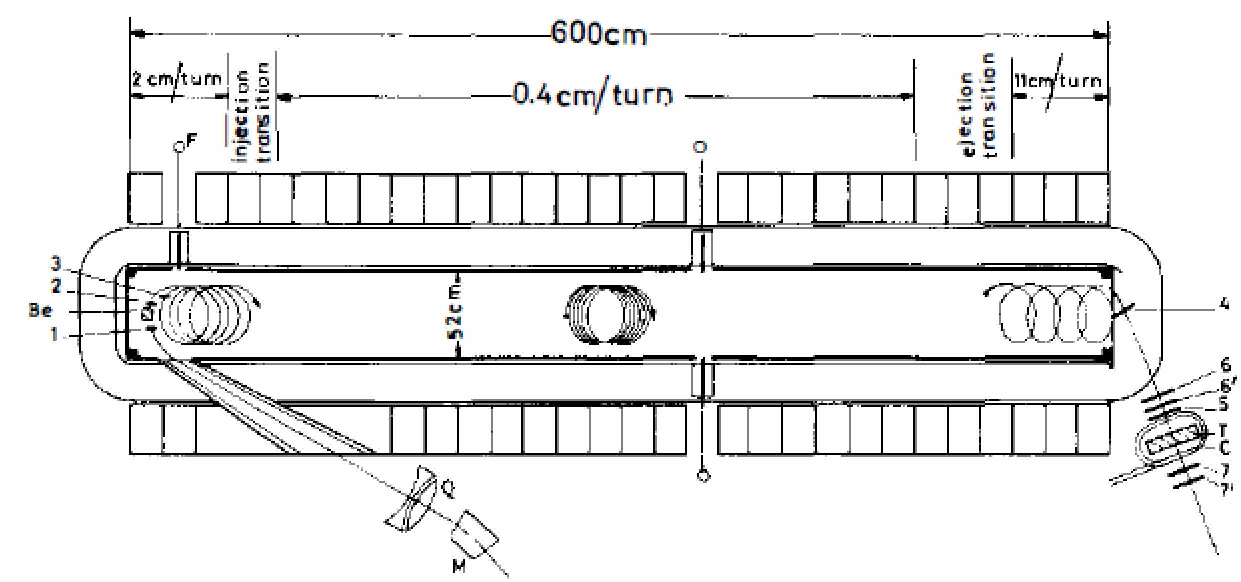
$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{e}{mc}\right)a_\mu \vec{B}$$ spin precession relative to the momentum vector

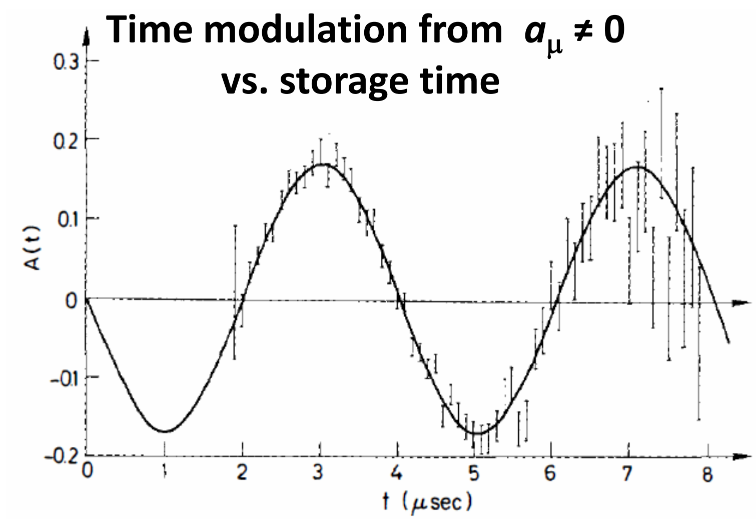
An independent, precise measurement of the muon spin precession at rest provides the value of $g_\mu (e / mc)$ – B is measured precisely using proton magnetic resonance



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

1962 – 65: First CERN experiment with slow muons from the 600 MeV syncrocyclotron
Special dipole magnet with gradients for muon focusing and orbit horizontal movement
Measure muon polarization after 440 turns





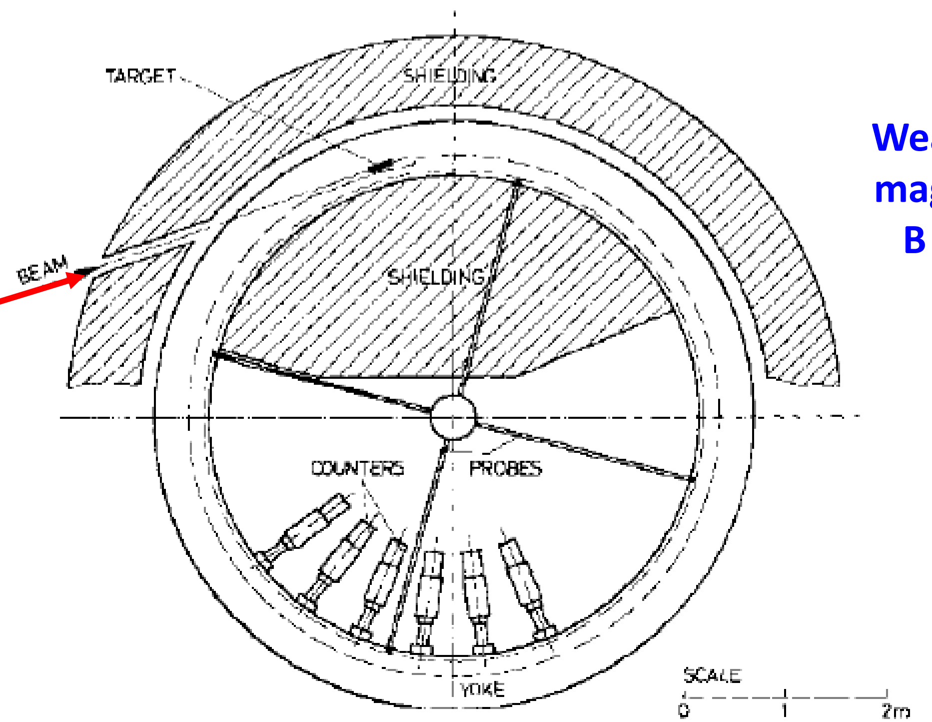
Time modulation from $a_\mu \neq 0$ vs. storage time

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

1966 – 70: 1st muon storage ring at CERN (orbit diameter 5 m)

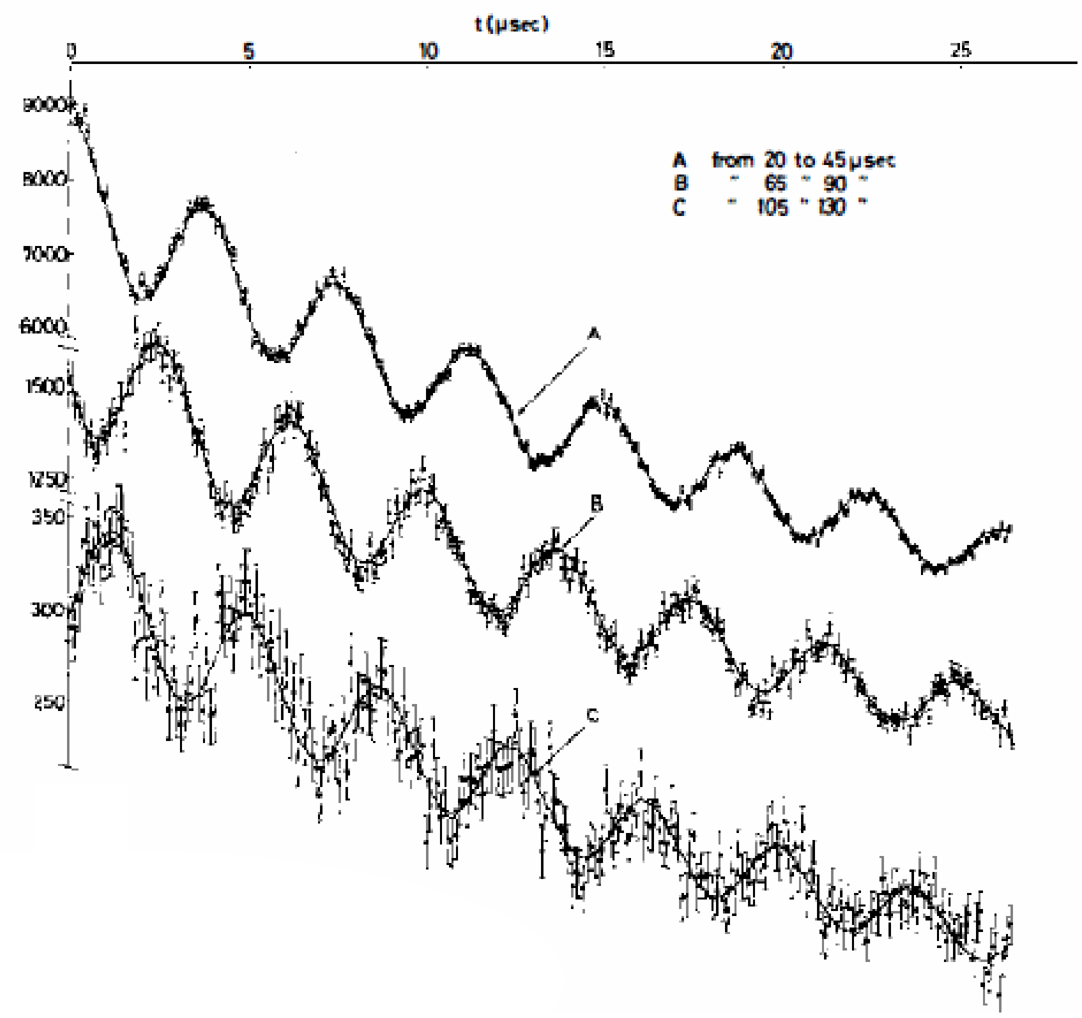
p = 1.28 GeV/c, γ = 12, measure muon polarization over 2500 turns

10.5 GeV/c protons from the CERN PS (10 ns pulses)



Weak focusing magnetic field B = 1.711 T

Time modulation from $a_\mu \neq 0$ vs. storage time



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

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

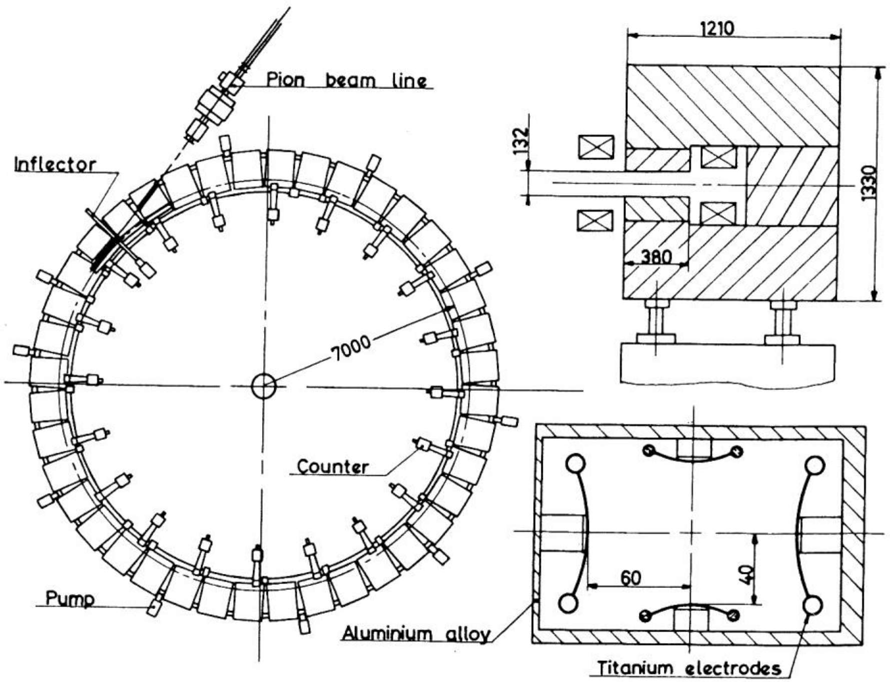
New idea: use uniform magnetic field and electrostatic focusing

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

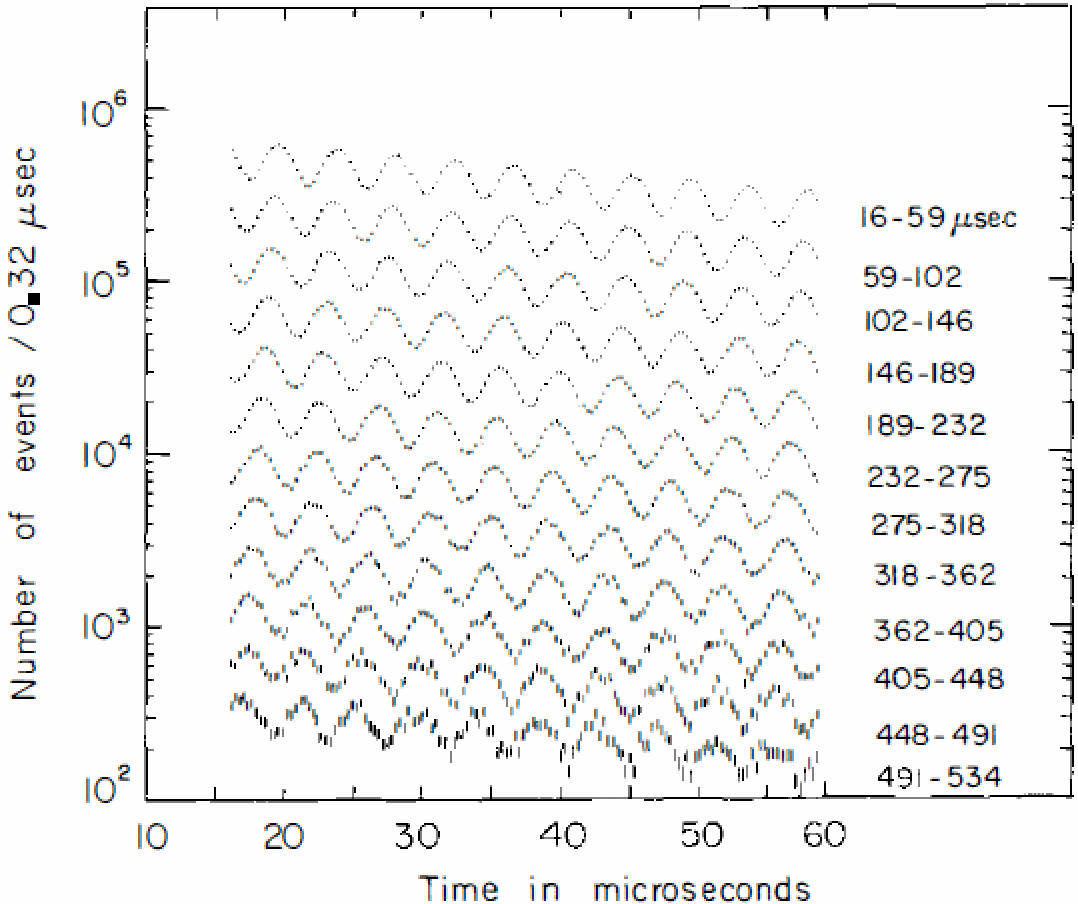
$$\vec{\omega}_a = -\left(\frac{e}{mc}\right)\left[a_\mu \vec{B} + \left(\frac{1}{\gamma^2 - 1} - a_\mu\right)\vec{\beta}\times\vec{E}\right]$$

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

Idea first implemented in the 2nd muon storage ring at CERN (1972 – 76 , bending radius 7 m)



Time modulation from $a_\mu \neq 0$ vs. storage time



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

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

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

CONCLUSIONS

The way to do particle physics experiments has changed a lot during the years 1964 – 74.

- **Improvements of detector technology:**
  - – from small volume to large volume bubble chambers;
  - – from spark chambers to MWPCs and drift chambers;
  - – development of calorimetry;
  - – development of fast electronics and computers.
- **More theoretical guidance when proposing and designing new experiments, thanks to a better understanding of the laws of Nature (e.g., hadron compositeness and the development of the Standard Model)**