Scattering and annihilation electromagnetic processes
18-22 février 2013 ECT* Trento

Historical aspects of nucleon form factors

Paola Dalpiaz

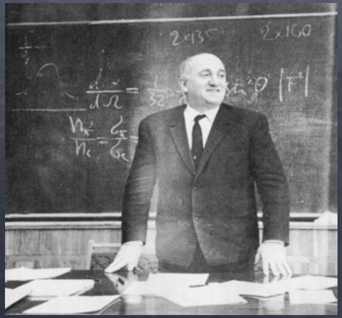
………. our efforts (since 1957) were focused on physics development, design and construction of electron-electron collider VEP-1.

Many laboratories throughout the world became active in the direction, and, **upon the first beams storing at AdA (Frascati)**, two of them, Stanford-Princeton group and Novosibirsk group, were the first in reaching……….

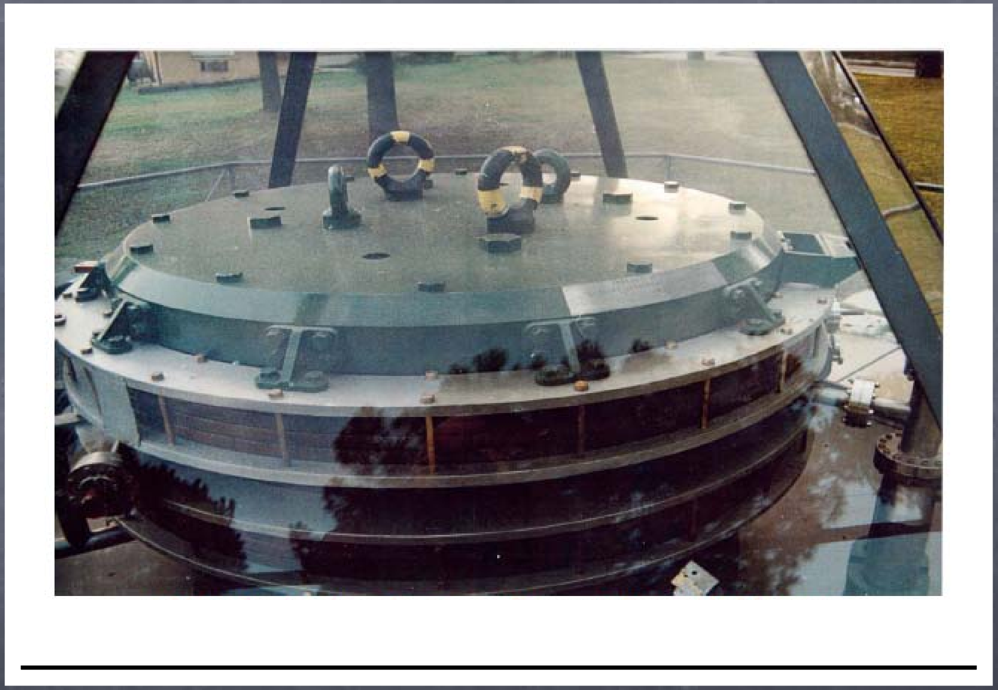
ELECTRON-POSITRON COLLIDERS AT NOVOSIBIRSK

N. Dikansky

Budker Institute of Nuclear Physics, Novosibirsk, 630090, Russia



Why this dimension?



AdA under its glass showcase. Frascati, Open Air Museum

AdA dimensions are strictly connected to nucleon form factors, as measured by Robert Hofstadter and collaborators in the fifty's

Brief History of Early Electron Scattering Experiments

1951 Early electron scattering experiments are performed at University of Illinois. A 15.7 MeV beam allows for confirmation of Rutherford's earlier approximation.

From Hofstadter Nobel lecture:

"a nucleus could be represented by a model of a uniformly charged sphere. The radius (R) of the sphere would be given by the relation

$$R \sim 10^{-13} A^{1/2}$$

where A is the mass number of the nucleus.
This is the point from which the present studies began."

Brief History of Early Electron Scattering Experiments

1953 Standford and Michigan have electron beams running at energies up to 190 MeV. Lots of new experimental data becomes available

1956 The nucleon form factors are measured. The finite nucleon radius and form of the e.m interaction is given . The form factor fitted well with a "dipole" function

.

It was a surprise, immediately interpreted as the demonstration of the existence of a neutral "vector meson", called the

$$\rho, J^{PC} = 1^{--}$$

Brief History of Early Electron Scattering Experiments

1956

THURSDAY AFTERNOON AT 2:00

Physics 320

(S. T. STEPHENSON, presiding)

Contributed Papers

11. Electron Scattering from Hydrogen, Deuterium, and Carbon at 190 Mev.* J. A. MCINTYRE AND R. HOFSTADTER, *Department of Physics, and W. W. Hansen, Laboratories of Physics, Stanford University.*—The recoil of the proton or deuteron permits solid targets of light and heavy polyethylene to be used in studying the elastic scattering of high energy electrons from the nuclei of hydrogen and deuterium, as distinguished from the elastic scattering from carbon nuclei. Inelastic electron scattering peaks have been observed in carbon at 4.5 Mev and 9.7 Mev and add a background below the carbon elastic peak which must be subtracted from the hydrogen and deuterium peaks. Angular distributions of the elastic electron scattering have been observed in hydrogen between 35° and 100° at 190 Mev in the laboratory frame. The proton appears to be a point charge since the experimental points fit the Mott formula. The deuteron definitely appears as not a point charge. Its finite size is exhibited by a fivefold reduction from the Mott formula at 105° in the center-of-mass system. The rms radius of the observed charge distribution is $1.5\pm0.2\times10^{-13}$ cm. This "radius" is a measure of the rms distance between the center of mass of the deuteron structure and the position of the proton.

* This research was supported jointly by the U. S. Navy (Office of Naval Research) and the U. S. Atomic Energy Commission, and by the U. S. Air Force through the Office of Scientific Research of the Air Research and Development Command. It was also aided by a grant from the Research Corporation.

12. Electron Scattering in Hydrogen and Helium.* R. HOFSTADTER, R. MCALLISTER, AND E. WIENER,† *Department of Physics, and W. W. Hansen, Laboratories of Physics, Stanford University.*—To investigate the elastic scattering of high-energy electrons from hydrogen, helium, and other gases we have constructed a stainless steel scattering chamber containing gas at high pressure. The target is a right cylinder of length 2½ inches, diameter ¾ inch with walls 15 mils and end windows of thickness 5 to 10 mils. Operation at psi has proved quite convenient. The end effects are subtracted out by emptying the gaseous contents and are not important except at small angles (~35°). Studies of the angular distribution in hydrogen and helium have been carried out at 190 Mev in the laboratory frame of coordinates and show agreement with the Mott point-charge formula for hydrogen but distinct deviations from the Mott formula for helium. These studies thus demonstrate the finite size of the helium nucleus (the alpha particle). A preliminary estimate of the size of the alpha particle gives $1.40\pm0.3\times10^{-13}$ cm for the rms radius of the alpha particle. The rms radius is taken with respect to charge.

* This research was supported jointly by the U. S. Navy (Office of Naval Research) and the U. S. Atomic Energy Commission, and by the U. S. Air Force through the Office of Scientific Research of the Air Research and Development Command. It was also aided by a grant from the Research Corporation.

† Miss Eva Wiener met a tragic death in an automobile accident

13. The *K*-Capture/Positron Ratio of Na^{22}. W. E. AND C. SHARP COOK, *U. S. Naval Radiological Defense Laboratory.*—Using a gamma-ray scintillation spectrometer, annihilation radiation and 1.3 Mev gamma ray from have been studied with a view toward determining the K-capture/positron ratio for this isotope. The ratios of have been studied with a view toward determining *K*-capture/positron ratio for this isotope. The ratios of peak to total areas for a 4-in. diameter, 4-in. high NaI crystal have been measured using collimated gamma rays from six sources.[1] Using these data and mental measurements of the photopeak areas associated the annihilation radiation and the 1.3-Mev gamma from Na^{22}, the relative intensities of these two

Possible connection between these form factors and multi π-meson resonances

$$G(t) = \alpha + \frac{\beta}{1 - t/t_0}$$

α, β, t_0 are phenomelogical constants that can be extracted from the data

$\sqrt{t_o}$ vector meson mass: the "dipole mass"

Possible connection between these form factors and multi π-meson resonances

$$G_E^V(0) = \frac{1}{2} = \alpha_E^V + \beta_E^V \qquad G_E^S(0) = \frac{1}{2} = \alpha_E^S + \beta_E^S$$

$$G_M^V(0) = \frac{1}{2}\left(1 + \mu_{proton} - \mu_{neutron}\right) = \alpha_M^V + \beta_M^V = 2.353$$

$$G_M^S(0) = \frac{1}{2}\left(1 + \mu_{proton} + \mu_{neutron}\right) = \alpha_M^S + \beta_M^S = 0.440$$

Fitting the data $\sqrt{t_o}$ **is determined**

Brief History of Early Electron Scattering Experiments

$$350 \leq \sqrt{t_o} \leq 500 MeV$$

THE VECTOR MESON MASS SUGGESTED BY THE FORM FACTORS DISTRIBUTION HAS BEEN UNDEREVALUATED IN THE FIRST FITTING PROCEDURES

Bruno Touschek in the 1940s (courtesy of Bruno Touschek's family).

Bruno Touscheck

Bruno Touscheck has conceived (and later designed) the first electrons collider "to discover the ρ", a vector meson resonance

Bruno Touscheck arrived in Rome in 1952.

He decided to stay in Rome permanently, receiving the position of researcher at the National laboratories of INFN in Frascati. He was also appointed as a part-time lecturer at the University of Rome-La Sapienza.

He rented a room from the Alberigi-Quaranta in the same building in via Senafe' 19, where I was living with my family, and where the Pancini famiily had a flat too. Untill his mariage, in 1955, Bruno Touscheck partecipated with enthusiasm to the life of these physicist families.

In this period the Sunday lunch at home with Bruno Touscheck became an habit. After lunch he and my father discussed physics until dinner time. I remember the enthusiasm and the evident enjoiement they hade.

One argument of interest for Bruno Touscheck was the existence of vectorial neutral heavy mesons (the mesotrons)

Touscheck were deeply convinced of their existence, and very interisted in the possibility to discover them

Bruno's view, as he put it, was that a physical system can be characterized appropriately by investigating its "geometry" and its "dynamics."

Its geometry, its size and shape, is observable by employing space-like photons as in electron-proton scattering experiments ("diffraction of electron waves");

This was precisely what Robert Hofstadter was doing at Stanford using the Mark III Linac to measure form factors of nuclear particles.

No one, however, had as yet observed the dynamics; for this one needed to produce time-like photons of sufficiently large energy to excite resonant modes of the vacuum corresponding to the masses of the vector mesons.

Touschek concluded that one should make electrons and positrons collide and annihilate in the center-of-mass system to produce time-like photons

Why e+e- collisions?

While electrons just electromagnetically scatter off electrons, electrons and positrons mutually annihilate.

One of the leading motivations for planning e+e– colliding beam experiments (rather thane–e– or p-p) was that in such an experiment one could

‘observe’ the virtual time-like photon “

Why e+e- collisions?

The great attraction of colliding electron-positrons beams was that they produce pairs of strongly interacting particles and antiparticles with time-like momenta in the particular $J^{PC} = 1^{--}$ channel and free of any other couplings.

In Touschek's own words: " **The quantum numbers of e+e– allowed to speak with the hadronic world, in admitting as clean a separation between strong and electromagnetic interactions as nature will allow**"

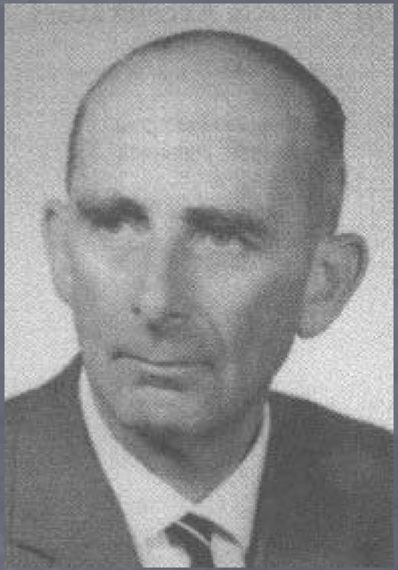
But he had an argument for “managers and political people”

Why e+e- collisions?

Colliding beam arrangements will have to deal with either equal or opposite charges. Equal charges require two rings, opposite charges can be stored in one ring, provided that their masses are equal.

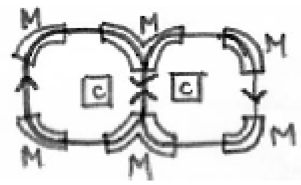
Touscheck argument: " Italy being a poor country cannot afford an experiment which requires two rings. If we cannot even afford one ring we have the synchrotron which can be converted into one."

The idea of exploring collisions in the center-of-mass system to fully exploit the energy of the accelerated particles had been given serious consideration by the Norwegian engineer and inventor Rolf Wideröe, who had constructed a 15-MeV betatron in Oslo and had patented the idea in 1943 after considering the kinematic advantage of keeping the center of mass at rest to produce larger momentum transfers.



Rolf Wideröe
(1902–1992)

This idea was also taken seriously by a Princeton-Stanford group that included William C. Barber, Bernard Gittelman, Gerry O'Neill, and Burton Richter, who in 1959, following a suggestion of Gerry O'Neill in 1956, proposed to build a couple of tangent rings to study Møller Scattering.



O'Neill's rings drawn by Bruno Touschek

Andrei Mihailovich Budker (1918–1977) initiated a somewhat similar project at Novosibirsk, wherethe VEP-1 electron-electron collider was underconstruction in 1961

Donald W. Kerst (1911–1993), who had constructed the first successful betatron at the University of Illinois in 1940, also was considering colliders, particularly for protons, in 1959 using the Fixed-Field Alternating-Gradient(FFAG) concept

The attention of these people was apparently focused on the kinematic advantage of colliding beams

That was precisely Bruno Touschek's starting point at Frascati. He considered the kinematics as rather obvious; to him the possible physics to be learned from colliding particles was far more significant:

To discover a "dipole" with mass ~500 MeV 250 MeV electron beams were needed

I prefer to think of it as an experiment rather than as a machine [...]
Talking of it as an experiment I propose to study the reactions

$$e^+ + e^- \to 2\gamma \quad (A)$$
$$e^+ + e^- \to \mu^+ + \mu^- \quad (B)$$
$$e^+ + e^- \to \pi^+ + \pi^- \quad (C)$$

And I admit that I think that there is nothing else of importance, which can be studied with the same set up.

The first of the processes listed is two quantum annihilation. The cross section for this process is

$$\sigma(A) = 6.3 . 10^{-30} cm^2$$

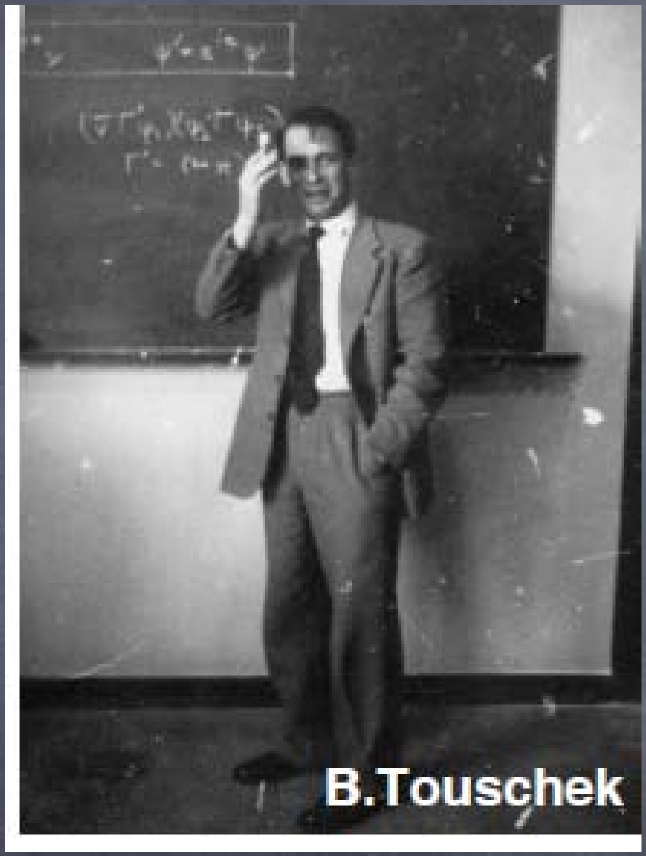
At 250 MeV[...]I propose to use (1A) as a monitoring process[...]

1957-1960

Bruno Touscheck is intetrested in symmetries and conservations laws.
He was very impressed by the discovery of the non conservation of parity.
Collaborate with Pauli

In 1960 he was tired of pure theorethical physics

He decided a full immersion in e+e- collider development



Bruno Touschek gave a seminar on March 7, 1960, at Frascati in which he guaranteed that an electron and a positron necessarily meet in a single orbit because QED is CP (charge-parity) invariant.

His skeptical colleagues did not have the courage to doubt him.

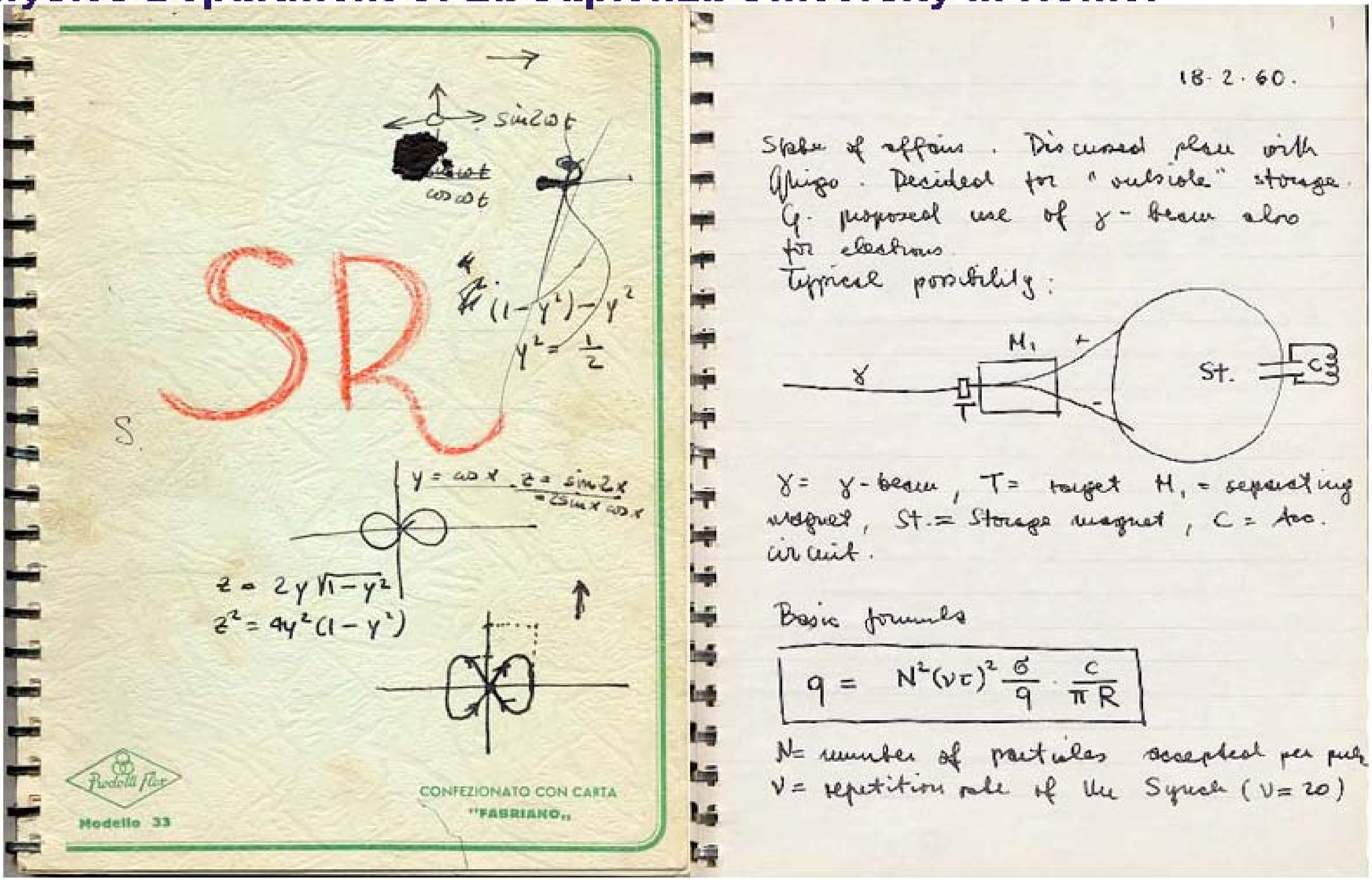
Bruno Touschek remarked that

an e+e- machine could be realized in a single ring, 'because of the CTP theorem' "

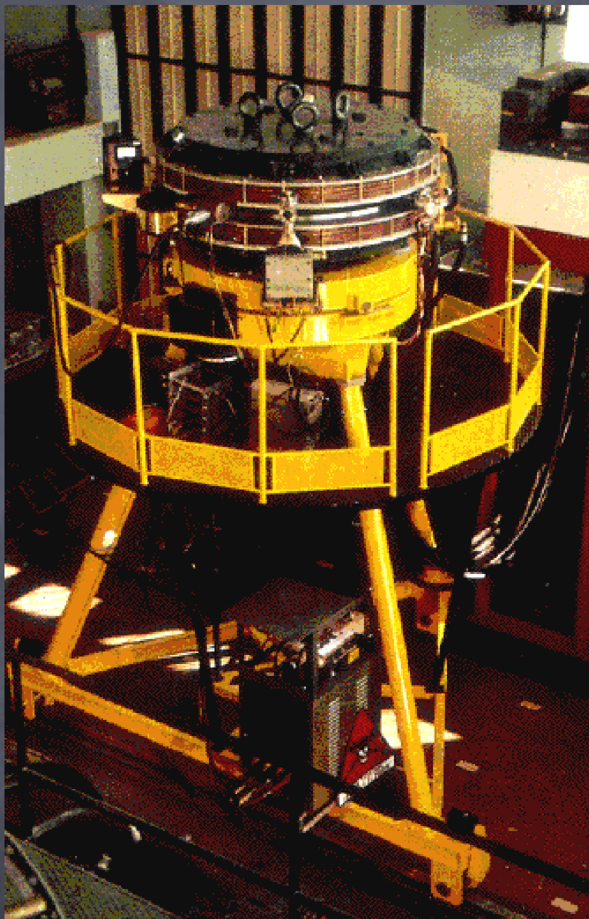
He kept insisting that CPT invariance would grant the same orbit for electrons and positrons inside the ring

At the time, and until it was experimentally demonstrated in 1964, many people doubted that electrons and positrons traveling in a single ring would really meet.

Touschek's seminar appears to have been thoroughly prepared during the whole period going from February 18 to March 7, as can be inferred from his notebook preserved in the archives of the Physics Department of La Sapienza University in Rome.



AdA (Anello di Accumulazione) 1960-1965



AdA consis of a a weak focusing magnet, Capable to let circulate(e+/e-) with an energy of *250 MeV*.

IL NUOVO CIMENTO

The Frascati Storage Ring.

C. Bernardini, G. F. Corazza, G. Ghigo
Laboratori Nazionali del CNEN - Frascati

B. Touschek
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 7 Novembre 1960)

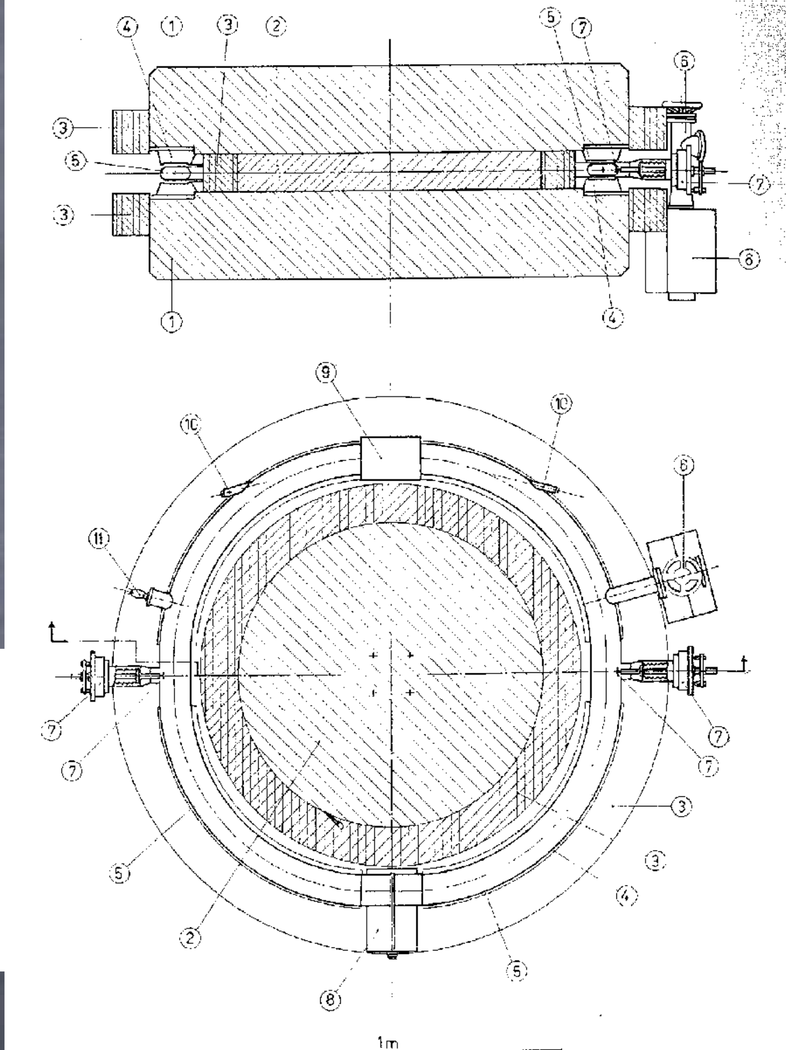
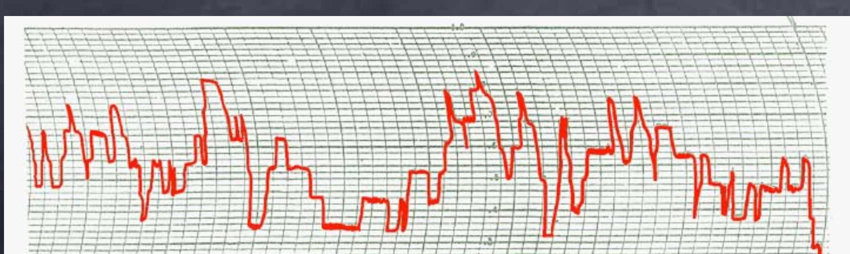
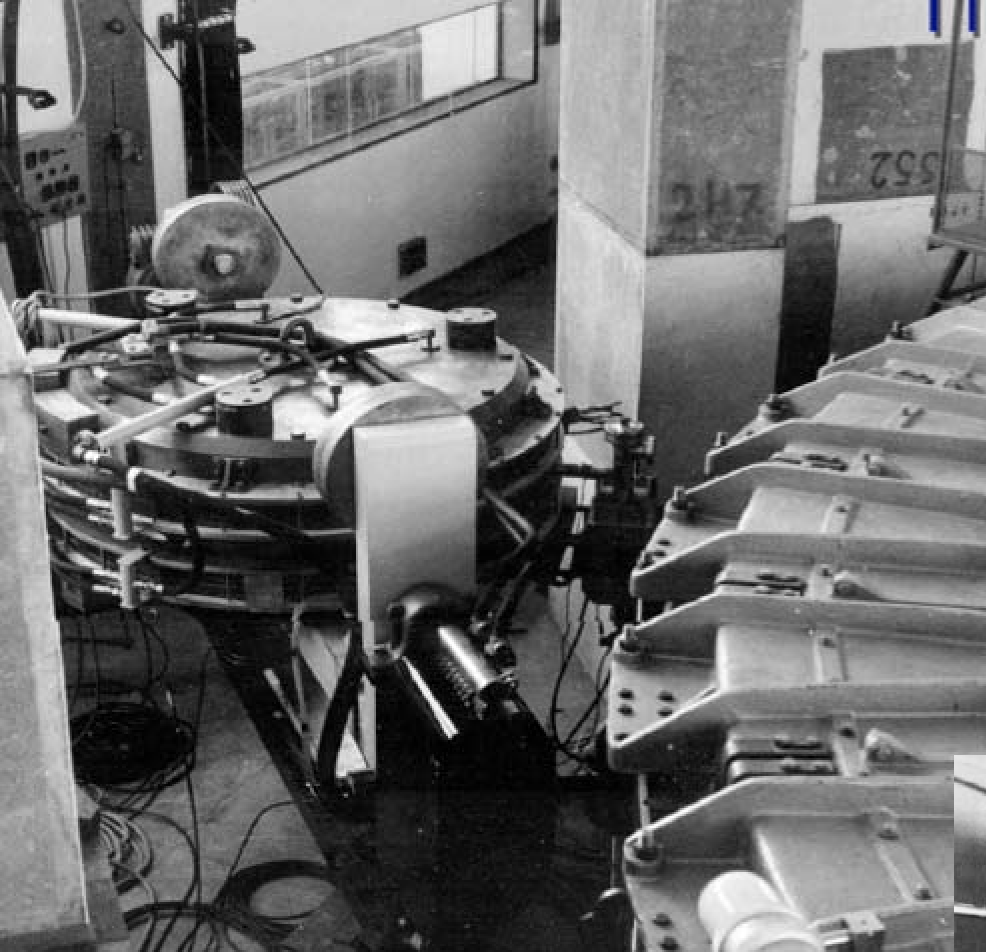


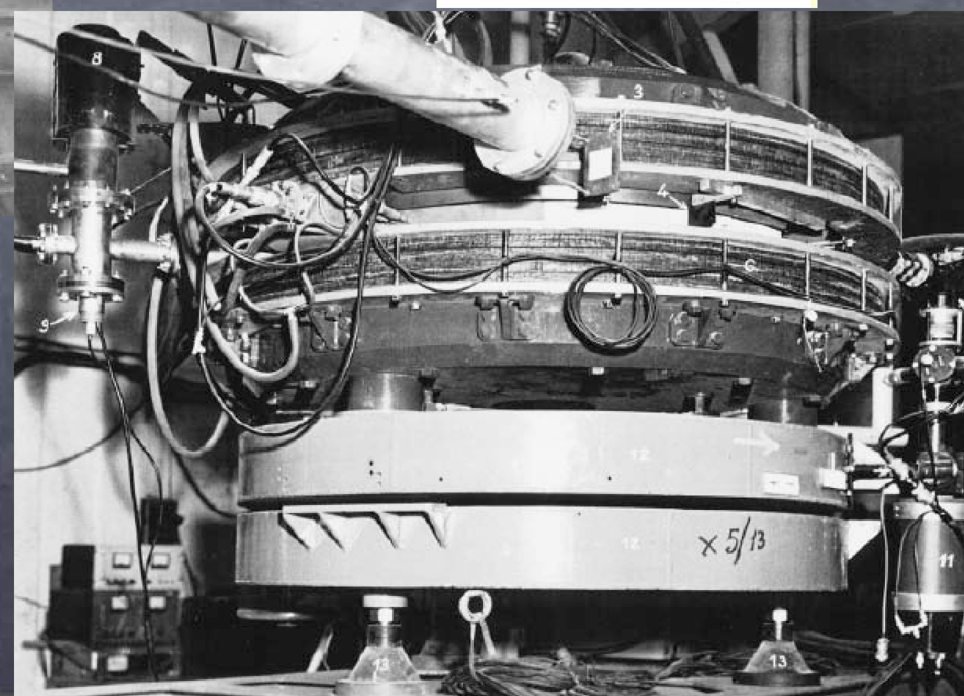
Fig. 1. – Elevation and plan section of the Frascati Storage Ring (anello di accumulazione = AdA): 1) magnet yoke; 2) magnet core; 3) coils; 4) polepieces; 5) doughnut; 6) titanium pump; 7) injection ports; 8) RF cavity; 9) experimental section; 10) windows for the observation of the synchrotron radiation; 11) vacuum gauge.



Registration of the first electrons circulating ina AdA.

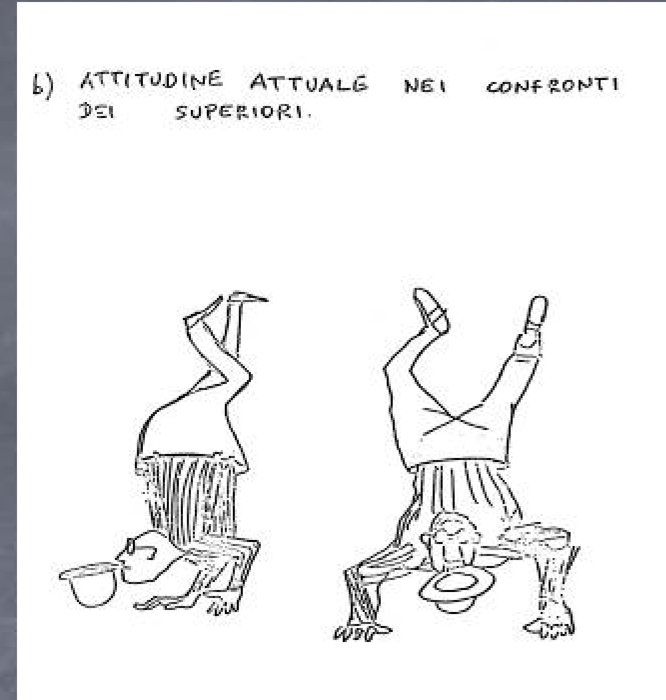


Frascati



Orsay

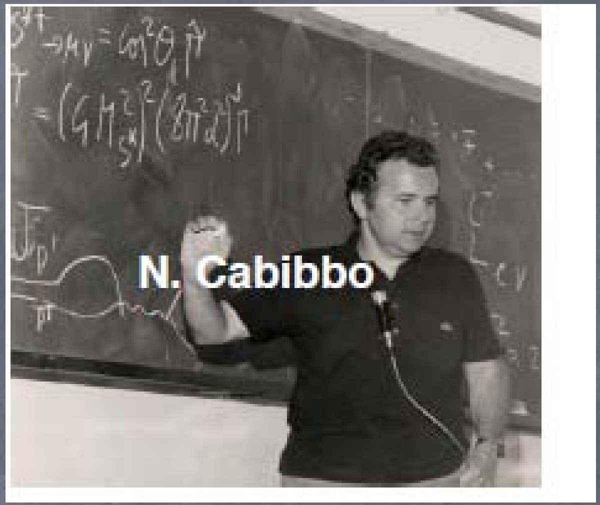

Direzione dell' Istituto di Fisica Maria Montessori.
la Scelta del Direttore.
CB


b) ATTITUDINE ATTUALE NEI CONFRONTI DEI SUPERIORI.


CARCERI.


SIAMO TUTTI DIRETTORI
CAN-CAN CHIMICO

His seminar was attended by many people, among them Raul Gatto, who with Nicola Cabibbo immediately began to investigate all possible electronpositron reaction cross sections and derived formulas describing the relevant parameters,particularly in hadronic physics. The central question was many or few hadrons be produced?



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N. Cabibbo and R. Gatto
1° Aprile 1961
Il Nuovo Cimento
Serie X, Vol. 20, pag. 185-193

Theoretical Discussion of Possible Experiments with Electron-Positron Colliding Beams.

N. Cabibbo and R. Gatto

Istituti di Fisica delle Università - Roma e Cagliari
Laboratori Nazionali di Frascati del CNEN - Frascati (Roma)

(ricevuto il 2 Febbraio 1961)

1. – We discussed recently the possible determination of the pion form factors from the reactions $e^+ + e^- \to n\pi$ (1). There is at present a definite interest, particularly in Frascati, in the realization of electron-positron colliding beams. In this note we shall briefly present some further theoretical considerations on high energy electron-positron experiments.

2. – High energy e^+-e^- experiments can test the validity of quantum electrodynamics at small distances. There are two other aspects of such experiments that we want to stress:

i) The possibility of exploring form factors of strong interacting particles. These form factors are explored for timelike momentum transfers. Electron scattering experiments — whenever possible — can only explore spacelike momentum tranfers.

ii) The possibility of carrying out consistently a « Panofsky program », *i.e.* the exploration of the spectrum of masses of elementary particles through their interaction with photons. This program can be extended to include the exploration of particular classes of unstable states.

(1) N. Cabibbo and R. Gatto: *Phys. Rev. Lett.*, **4**, 313 (1960). The same results have also been derived by Yung Su Tsai: *Phys. Rev.*, **120**, 269 (1960).

4. – Production of strong-interacting particles.

We consider the lowest order graph in the electromagnetic interaction but including all strong interaction effects.

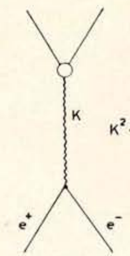


Fig. 4.

The form of the $PP\gamma$ vertex is only limited by Lorentz- and gauge-invariance.

a) for $e^+ + e^- \to f + \bar{f}$ where f is a charged or neutral fermion of spin $\frac{1}{2}$

$$\frac{d\sigma}{d(\cos\theta)} = \frac{\pi}{8}\alpha^2\lambda^2\beta_f F(\cos\theta)\,,$$

where

$$F(\cos\theta) = |F_1^{(f)}(-4E^2) + \mu_f F_2^{(f)}(-4E^2)|^2(1+\cos^2\theta) + \\ + \sin^2\theta\left|\frac{m_f}{E}F_1^{(f)}(-4E^2)|^2 + \frac{E}{m_f}\mu_f|F_2^{(f)}(-4E^2)\right|^2.$$

Here μ_f is the static anomalous magnetic moment of f, and $F_1^{(f)}(k^2)$, $F_2^{(f)}(k^2)$ are the analytical continuation of the electric and magnetic form factors of f for negative values of k^2. The situation is illustrated in the following graph for the special case of the isotopic vector part of the nucleon electromagnetic vertex.

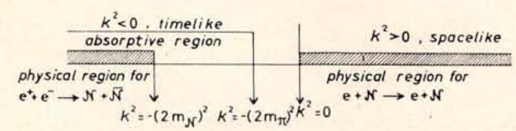


Fig. 5.

In the graph we have reported the physical regions and the absorptive region on the k^2 real axis.

However...

1961

Robert Hofstadter wins Nobel Prize for "his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

Albert Erwin discovered with William Walker the rho-meson in a bubble-chamber experiment at the Madison physics departement, measuring its mass at 750MeV

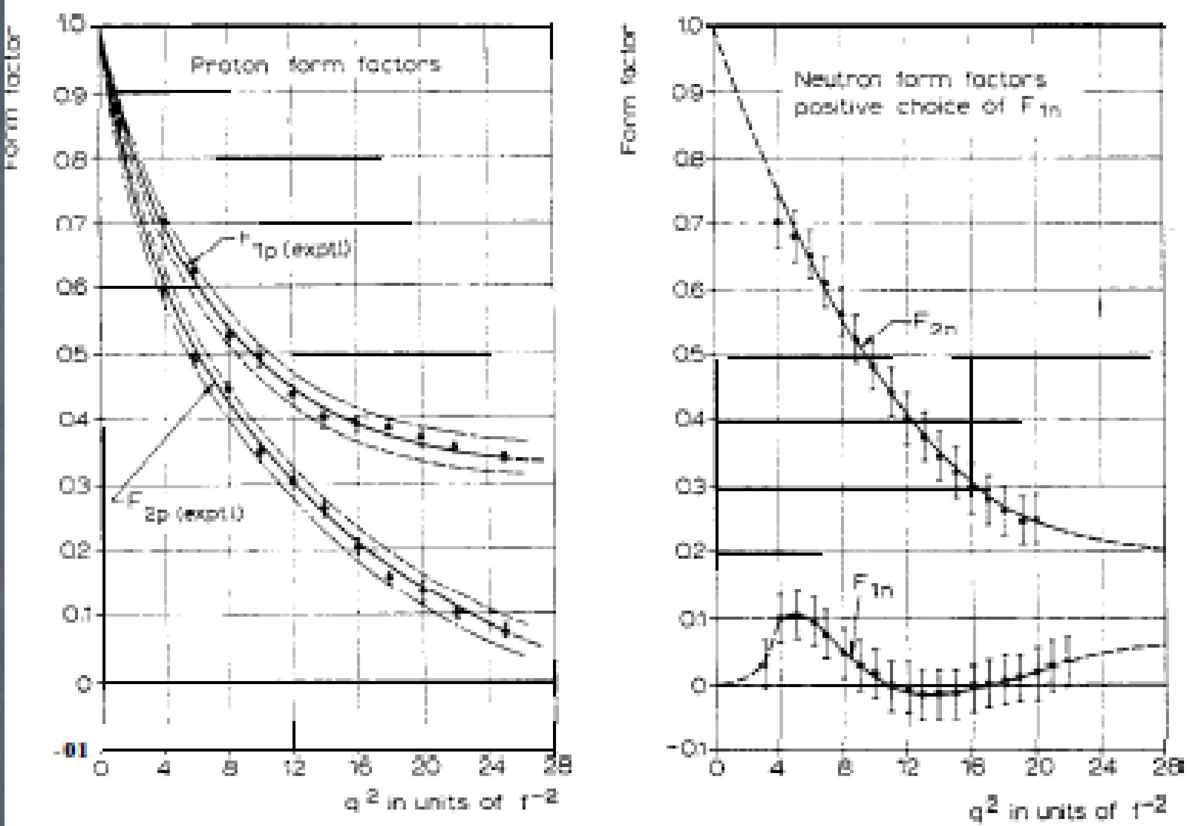


Fig. 12. This figure shows the most recent Stanford results[17,18] for both the neutron and the proton for the positive choice of sign of F_{1n}. The regularity of the neutron curves arises from the fact that the experimental deuteron curves were smoothed before putting the corresponding data into the theoretical formulae from which the form factors are deduced. The four curves of this figure can be fit approximately with dispersion theory or Clementel-Villi curves corresponding to the newly discovered heavy mesons. It is interesting that the newer neutron data agree very well with older result[16] and many of the present conclusions could have been drawn in 1958.

fall of $F_{2\pi}$ would be very surprising and is not expected.

If the first choice of values of F_{1s} is made, which seems much more likely, an understanding of all the proton and neutron data can be obtained along the lines of the heavy-meson or pion-resonance theory of Bergia, *et al*[27]. An interpretation of the early data in terms of Clementel-Villi form factors, using Yukawa clouds of different ranges and delta functions, was also given by the present author and Herman[23]. These initial and approximate theoretical interpretations are probably correct in principle but incomplete in detail and it now seems likely that it is necessary to add to them the effects on the form factors of a third heavy meson (η-meson)[28]. Such a particle has recently been discovered by A. Pevsner, *et al.*[29]. Its existence was also predicted by Sakurai[30].

Attempts are now being made to fit the data of Fig. 12 in terms of the heavy-meson theory in a way similar to that given in Refs. 23 and 27 but now employing three mesons (ρ, ω, η) instead of only two. I hesitate to show the results of the studies since the exact mass values of the heavy mesons are not yet definite and small variations of these values affect the relative importance of the mesons in the form factor equations in a sensitive way.

"POSSIBLE EXISTENCE OF HEAVY NEUTRAL MESONS"

Y. Nambu, Phys. Rev., 106 (1957) 1366.

S. Drell, Proc. 1958 Intern. Conf. High Energy Physics CERN,pp. 27-33.

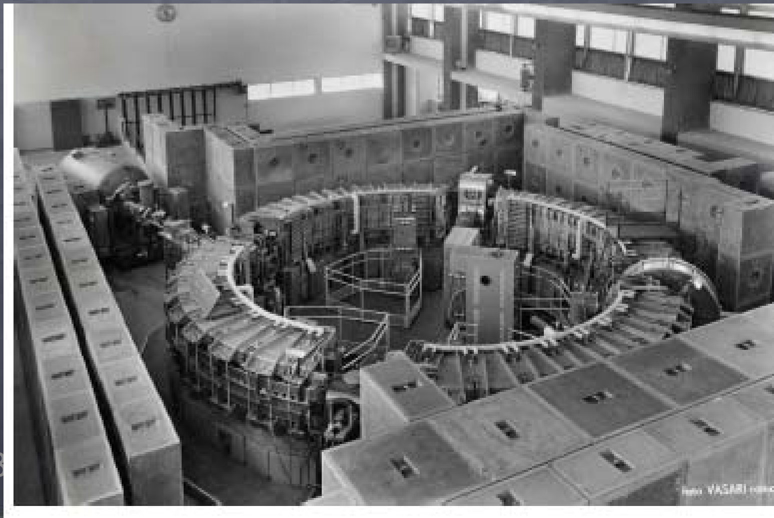
W. R. Frazer and J. R. Fulco, *Phys. Rev. Letters, 2 (1959) 365; Phys. Rev., 117*(1960) 1609.

S. Bergia, A. Stanghellini, S. Fubini, and C. Villi, *Phys. Rev. Letters, 6 (1961) 367;*
S. Bergia and A. Stanghellini, *Nuovo Cimento, 21 (1961) 155.*

Touschek tried to convince Salvini and Amaldi to immediately convert the Frascati electron synchrotron into a collider ring (as actually was done ten years later for the Cambridge Electron Synchrotron)

He has always regretted the impossibility to implement this solution in Frascati..

(Amaldi and Salvini however warmly agreed with the proposal to prepare a new machine.)



Bruno Touschek did not like much of the theoretical machinery of that time (dispersion relations, Regge poles, S-matrix…), but he regarded as quite important

the problem of analyticity of form factors and their analytical continuation to time-like values of squared-momentum transfer.

Stemming from Touscheck School

ADONE

ADONE has had an important role in the determination of the “time-like” form-factors:

- The first time-like point

$$e^+e^- \rightarrow \bar{p}p$$

- The neutron form factors

Fernando Amman

Adone, a 3000-MeV electron-positron collider at Frascati (each beam had an energy of 1500 MeV)

The proton-antiproton experiments

$$\bar{p}p \to e^{+}e^{-}$$

The proton-antiproton experiments

IL NUOVO CIMENTO Vol. XXIV, N. 1 1° Aprile 1962

Proton-Antiproton Annihilation into Electrons, Muons and Vector Bosons.

A. Zichichi and S. M. Berman (*)
CERN - Geneva

N. Cabibbo and R. Gatto
Università degli Studi - Roma e Cagliari
Laboratori Nazionali di Frascati del CNEN - Roma

(ricevuto il 20 Gennaio 1962)

Summary. — The possibility of achieving relatively high intensity antiproton beams has prompted some considerations on the rather rare annihilation channels of the proton-antiproton system. We propose i) to study the two-electron mode as a means of investigating the electromagnetic structure of the proton for time like momentum transfers; ii) to study the two-muon mode and compare with the two-electron mode to investigate whether the muon behaves like a heavy electron for large time like momentum transfers; iii) to investigate the existence of weak vector bosons by the modes $p+\bar{p}\to B+\bar{B}$ and $p+\bar{p}\to B+\pi$. Although no precise theoretical predictions can be made, crude estimates indicate that the cross-section for these four channels could be roughly of the same order of magnitude.

1. – The electromagnetic annihilation $p+\bar{p}\to e^{+}+e^{-}$, $p+\bar{p}\to\mu^{-}+\mu^{+}$.

One of the significant programmes in high-energy physics has been the systematic study of the electromagnetic structure of nucleons carried out by Hofstadter (1) and co-workers, and by Wilson (2) and co-workers. The theo-

(*) Now at Stanford Linear Accelerator Center, Stanford, Cal.
(1) For example: R. Hofstadter and R. Herman: *Phys. Rev. Lett.*, **6**, 293 (1961).
(2) R. M. Littauer, H. F. Schopper and R. R. Wilson: *Phys. Rev. Lett.*, **7**, 141 (1961).

retical explanation of these experiments has been one of the outstanding pro[blems] in the theory of strong interactions and has led to many new and inte[rest]ing ideas (3). These experiments measure the form factors of the nucle[on] for spacelike momentum transfers where the form factors are real and [ap]parently decreasing with increasing momentum transfers up to highest valu[es] thus far measured of order $q^2 \approx 2(M)^2$ (M = nucleon mass).

The advent of antiproton beams of relatively high intensity ($\approx 10^4$ pa[r]ticles per pulse) allows the possibility of further investigation of the elect[ro]magnetic structure of the proton in a region thus far completely unexplor[ed]. This is accomplished by the study of the reaction

$$p+\bar{p}\to e^{-}+e^{+}. \qquad (1)$$

Reaction (1) is the inverse of proton-antiproton pair production fr[om] electron-positron clashing beams (4).

Figures 1-*a*) and 1-*b*) show the diagrams for proton-electron scattering a[nd] proton-antiproton annihilation into an electron pair, respectively, in the o[ne] photon channel.

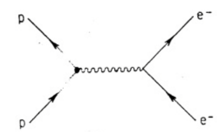


Fig. 1-*a*.

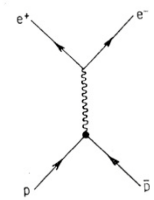


Fig. 1-*b*.

For the proton-electron scattering experiment the four-momentum carri[ed] by the photon is purely spacelike, *i.e.* $q^2>0$, whereas in the annihilati[on] the photon four-momentum is purely timelike, $q^2<-4M^2$. This is clea[rly] demonstrated in the c.m. of target and projectile, in which case the fou[r-]momentum transfer has only space components for the scattering experime[nt] and only a time component for the annihilation.

The momentum transfer for process (1) is determined uniquely by the an[ti]proton energy $\mathscr{E}$ in the laboratory system, $q^2=-2M(\mathscr{E}+M)$. Beginning [at] $q^2=-4M^2$, when the antiproton is at rest, the momentum transfer contin[ues] to as negative a value of q^2 as can be achieved with the highest possible an[ti]proton energy.

(3) S. D. Drell and F. Zachariasen: *Electromagnetic Structure of Nucleon[s]* (Oxford, 1961).
(4) N. Cabibbo and R. Gatto: *Phys. Rev.*, **124**, 1577 (1961).

The proton-antiproton experiments

crude guess for the cross-section which in fact could very well be ten times bigger or ten times smaller than the estimate given here.

An experiment on the annihilation at rest would involve the branching ratio for the electromagnetic modes to the total annihilation rate. In order to go from this experimental number to the evaluation of the form factors either the atomic physics of the capture must be eliminated or a separate experiment to determine the complex s-wave phase shifts in $p\bar{p}$ elastic scattering must be performed. Note that the 2e (or 2μ) annihilation through the one-photon cha[illegible] only occur, in general, from ${}^3S_1$ and ${}^3D_1$. In view of these difficulties it appears that the results of the in-flight experiment can be interpreted in a much more unambiguous manner.

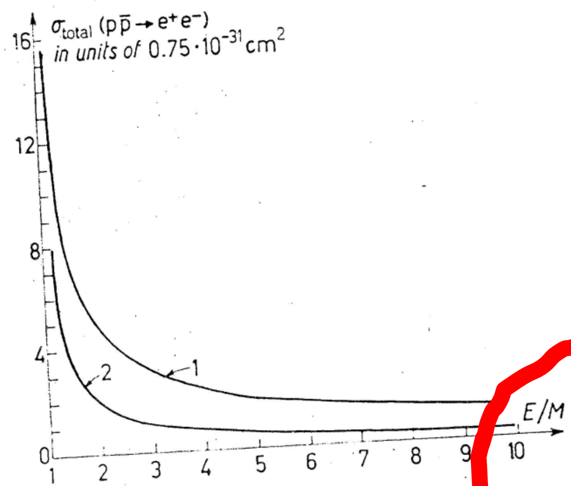


Fig. 3. – In units of $0.75 \cdot 10^{-31}$ cm². Upper curve (1) is for pointlike proton with $\mu_p = 1.79$, lower curve (2) is obtained by extrapolating the form factors of reference (7).

However, for the determination of the 2μ to 2e ratio, and the consequent exploration of the validity of electrodynamics, formula (8) also applies to annihilation at rest.

The proton-antiproton experiments

BNL ~1965-1969

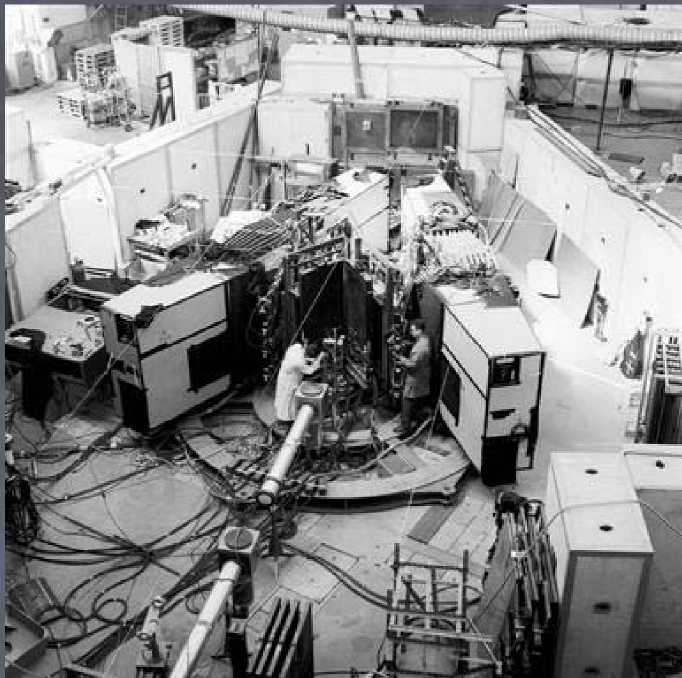
Tollerstrup and collaborators

antiproton beam at 1.47,2.40 GeV/c

CERN ~1963-1967

Zichichi and collaborators

antiproton beam at 3GeV/c



Papep experiment ,CERN

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Date: 12 January 1965

M E M O R A N D U M

To : The members of the Nuclear Physics Research Committee

From : The EEC

Subject : Minutes of the Electronics Experiments Committee Meeting of January 12, 1965.

Present : J. Bell, A. Diddens, H.J. Gerber, B. Gregory, W. Lock, G. Munday, W. Paul, P. Preiswerk, G. Puppi, J.C. Sens and V.F. Weisskopf.

1. PS; present period

For weeks no. 6 and 7, when the CERN/ETH group runs in the d-beam and Paplep in the m_4-beam, the EEC recommends to consider Paplep as the main user.

For weeks no. 8 → 11, the EEC recommends allocating to the Maglić group (d-beam) week no. 8 (set up), no. 9 (parasite time), no. 10 + 11 (full time). Concerning use of the m_4-beam during weeks no. 10 + 11 by either the Σ parity group or the Paplep group, no recommendation is presently made. The deadline for taking this decision is February 10.

2. PS; post-shut down period

Large angle πp scattering (Lundby/Goldzahl)

It is recommended to await analysis of the results before considering a continuation at higher energies.

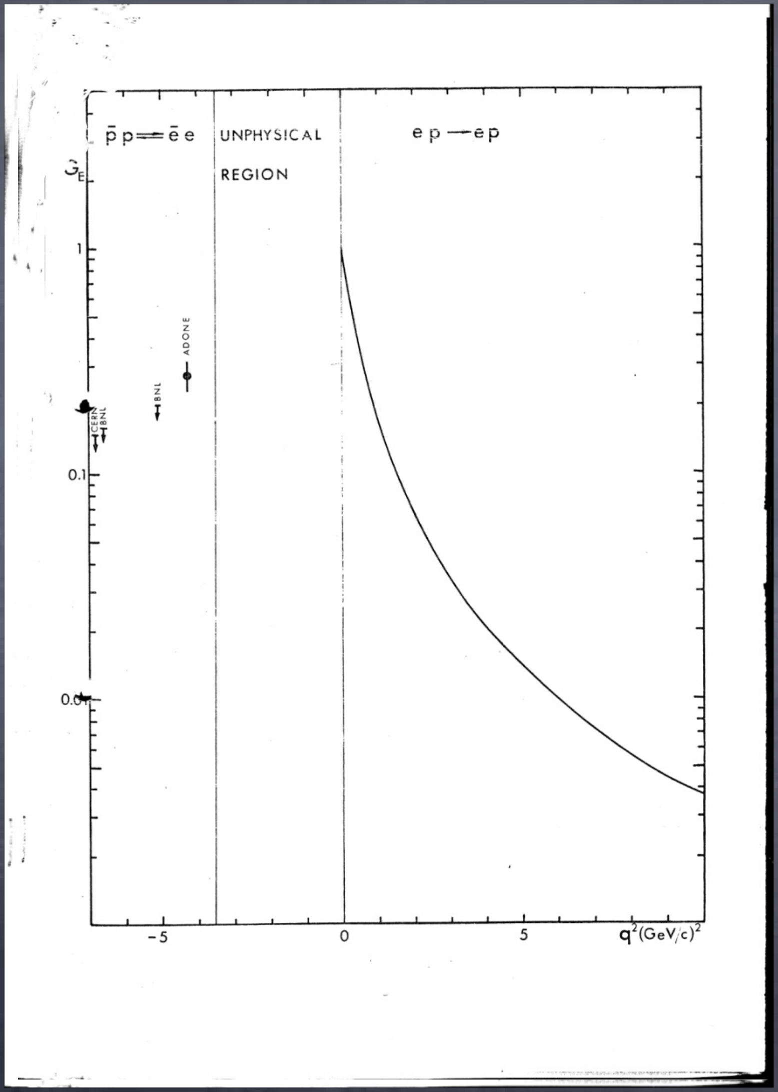
Charge exchange at high energy with polarized target (Falk-Vairant et al.)

This experiment is recommended for presentation in a Tuesday seminar.

56/67/3

1971

$$\bar{p}p \to \mu^+\mu^-$$



$$\bar{p}p \to e^+e^-$$

at threshold

ELPAR

(Torino Strasbourg collaboration)

The hadron rejection was very efficace, based on shower evolution and kinematic :

$$\bar{p}p \to e^{+}e^{-}$$

rejection 10^{-8}

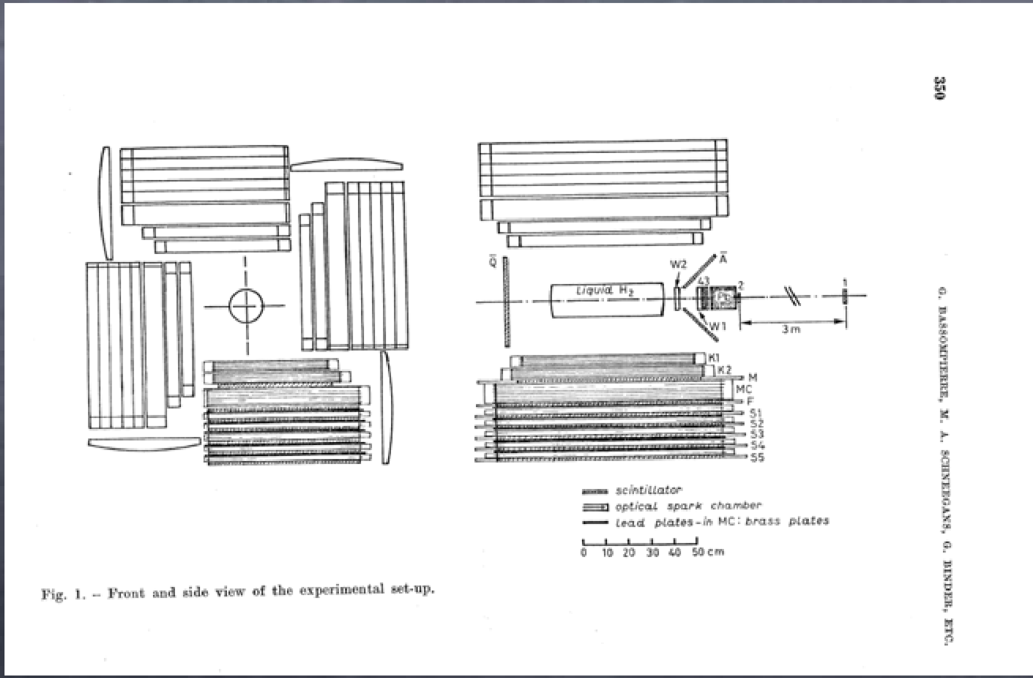
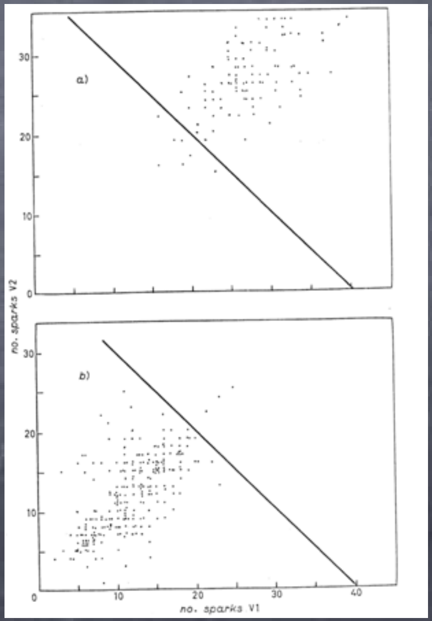
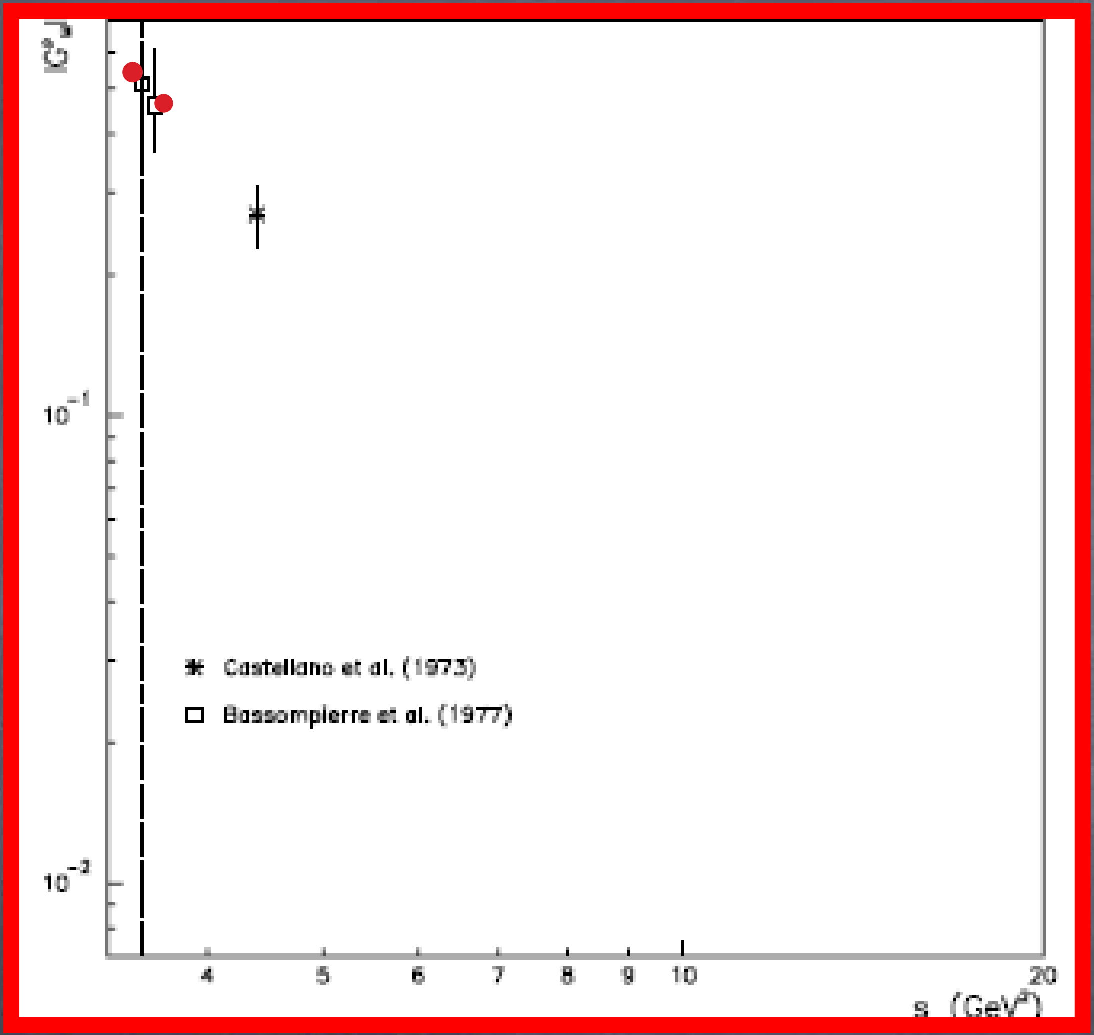


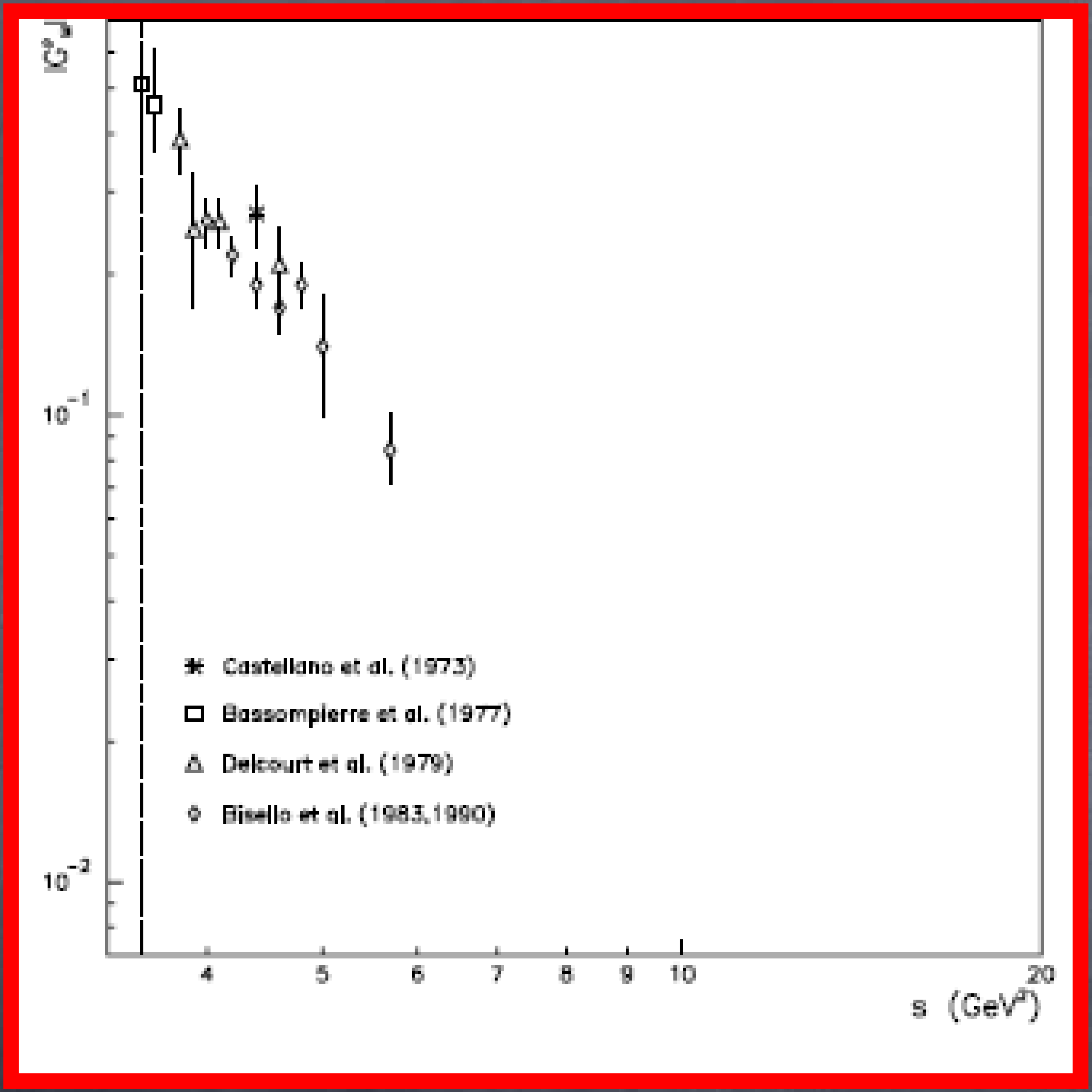
Fig. 1. – Front and side view of the experimental set-up.



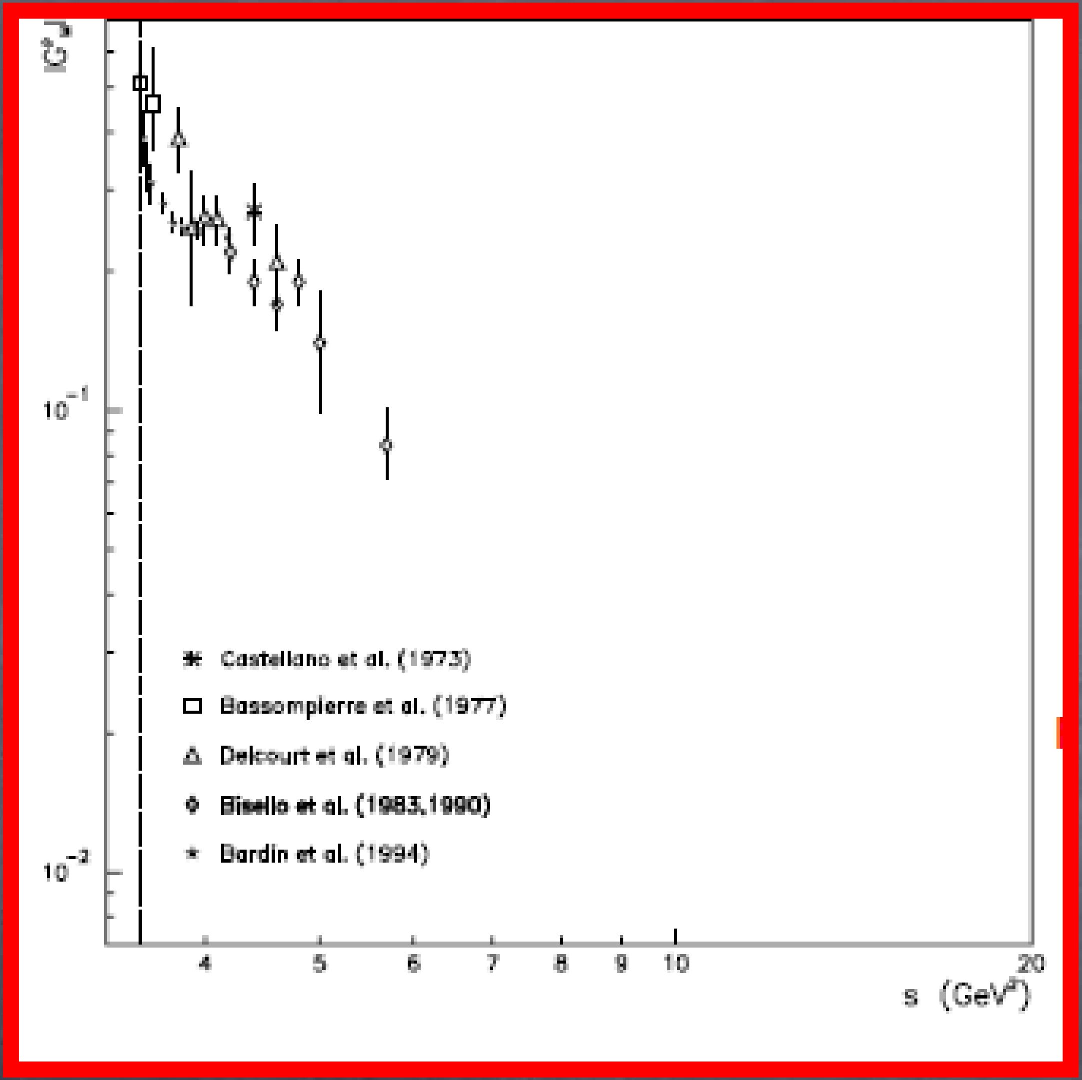


ELPAR experiment at CERN. Observed 45 events of antiproton-proton annihilation at rest in a liquid H_2 target.
The measurement assumes $|GE|=|GM|$

The high value of G was a surprise

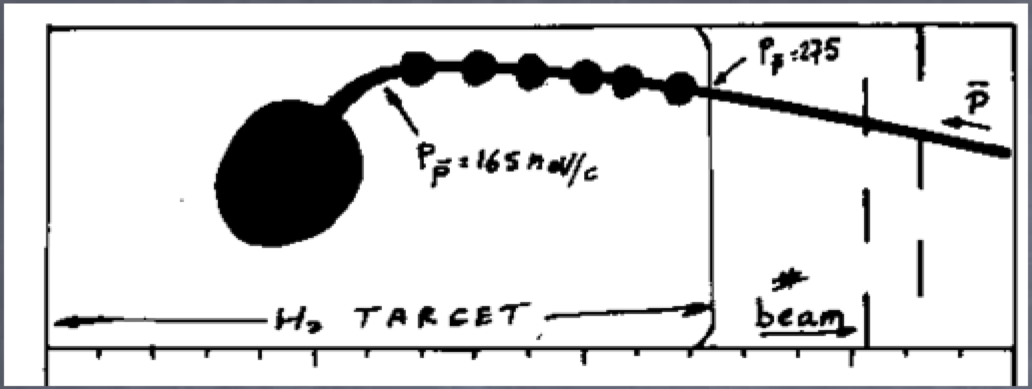


At DCI in ORSAY
the DM2 collected data
in three data taking runs
for a total of 0.7= **pb**$^{-1}$
With a total of 112 events
in 6 points they
attempted to measure the
angular distribution, from
which they could fit
|GM|/|GE|=0.34,
but |GE|=|GM| was still
allowed

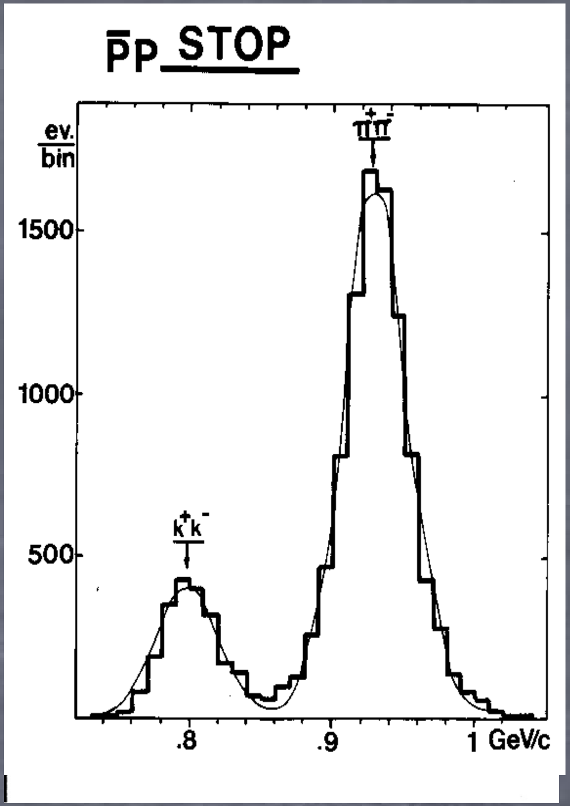


At LEAR the PS 170 Experiment recorded a total of 3667 $\overline{p}p \to e^{+}e^{-}$ events in 9 data points.

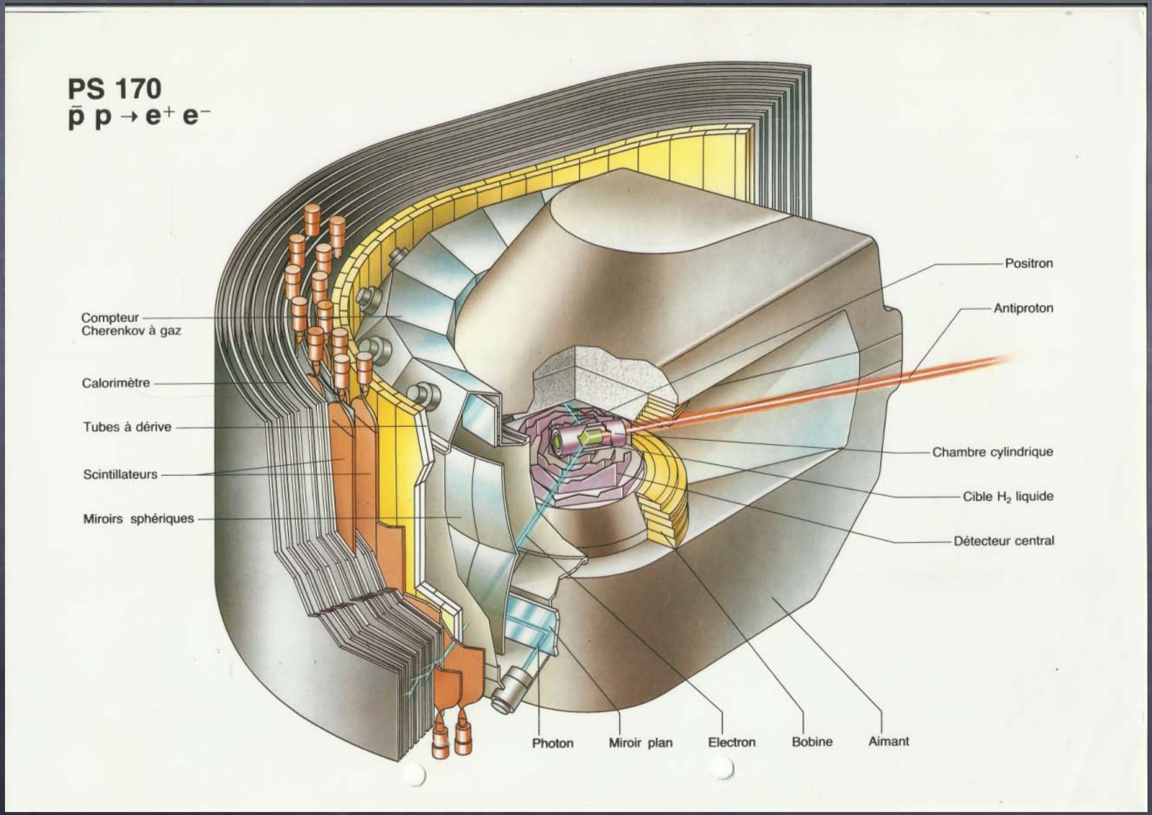
First indication of steep rise near threshold.



$P_{\bar{p}}$=275
$\bar{p}$
$P_{\bar{p}}$=165 MeV/c
H_2 TARGET
beam



$\bar{p}p$ STOP
ev.
bin
1500
1000
500
$\pi^+\pi^-$
k^+k^-
.8
.9
1 GeV/c



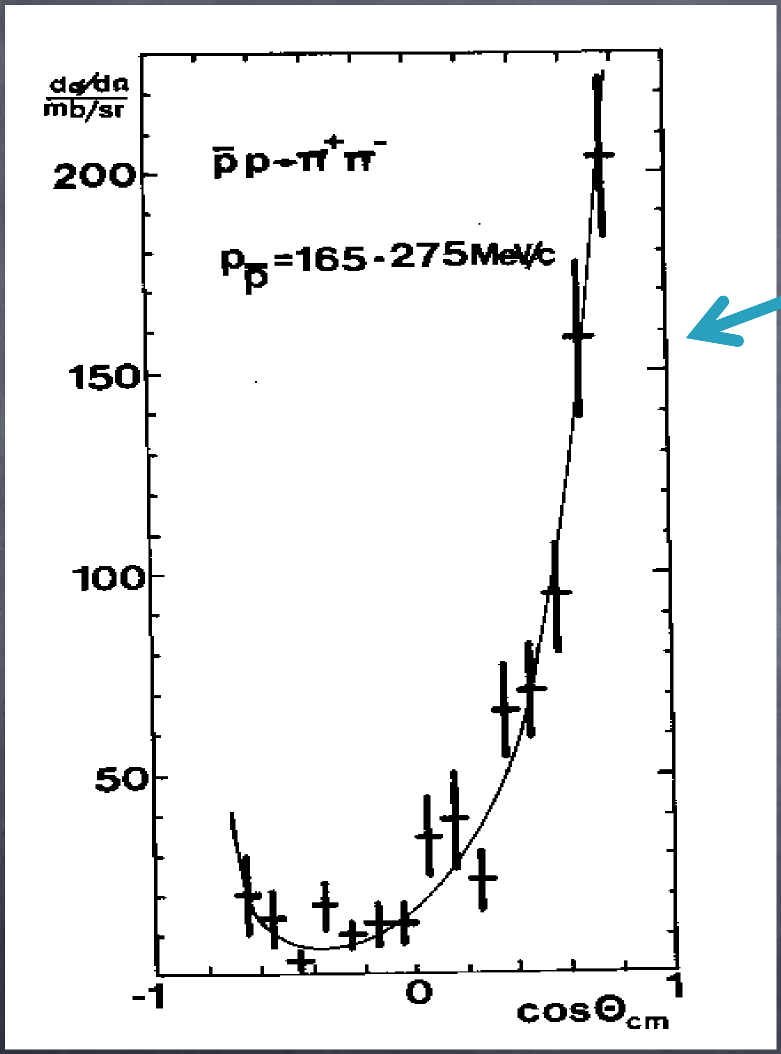
PS 170
$\bar{p}\,p \rightarrow e^+ e^-$
Compteur Cherenkov à gaz
Calorimètre
Tubes à dérive
Scintillateurs
Miroirs sphériques
Positron
Antiproton
Chambre cylindrique
Cible H_2 liquide
Détecteur central
Photon
Miroir plan
Electron
Bobine
Aimant

PS170 rejection toward hadrons

$\overline{p}p \to e^+e^-$ **rejection** $10^{-10} - 10^{-12}$

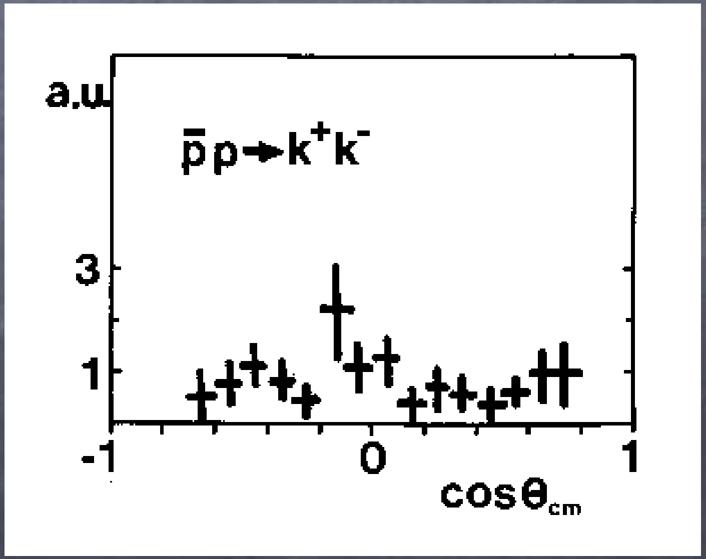
Tested in a dedicated beam test

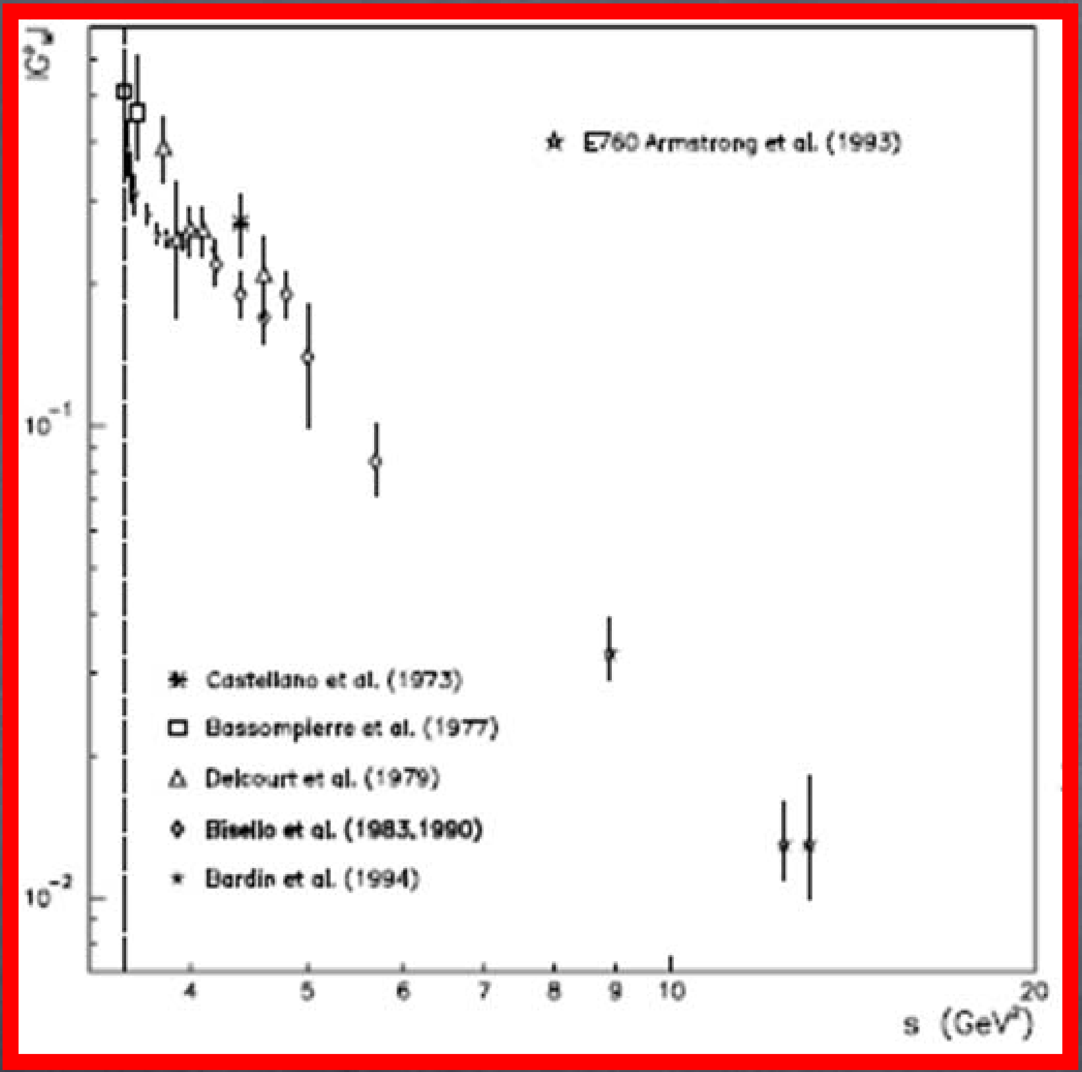
PS170 ANGULAR DISTRIBUTION



Antiproton-proton annichilation

The valence quarks interact directly

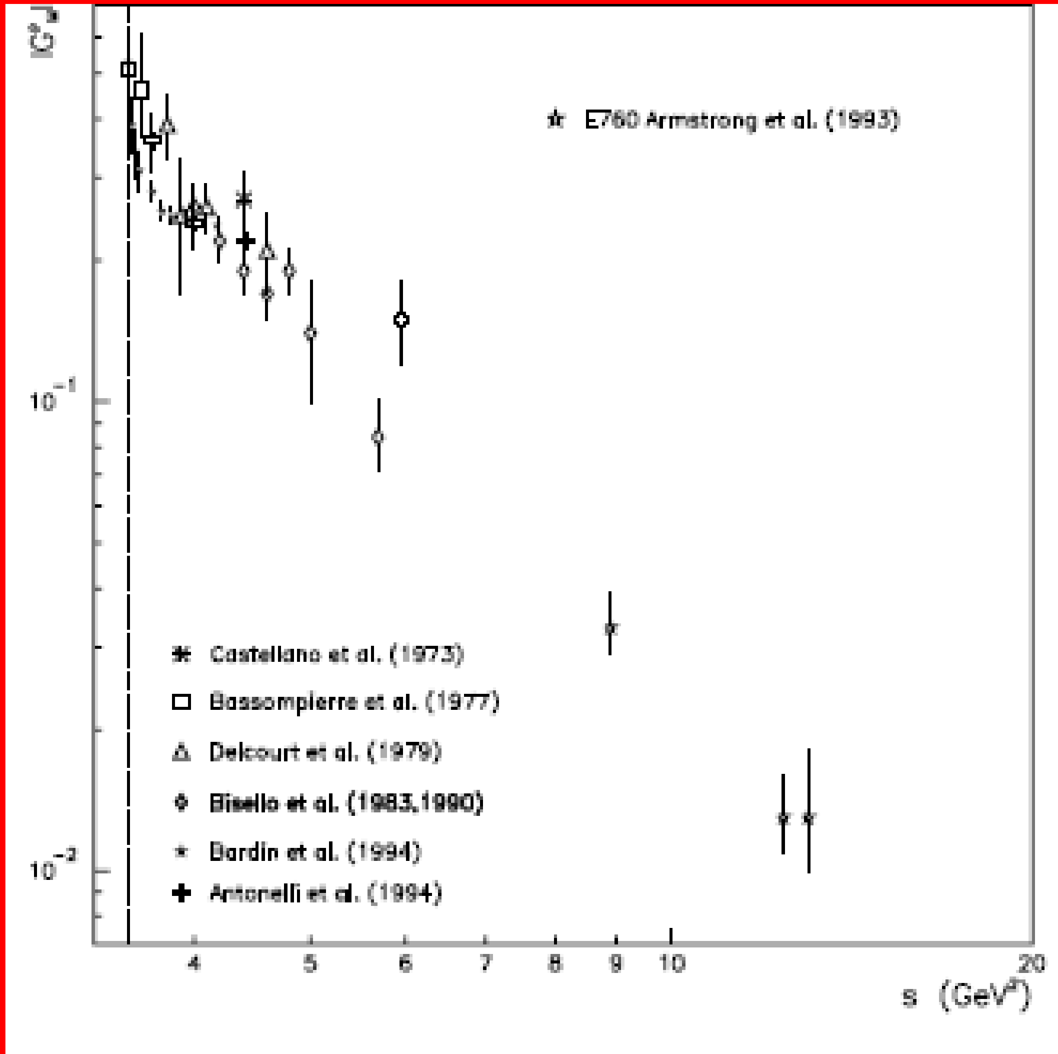




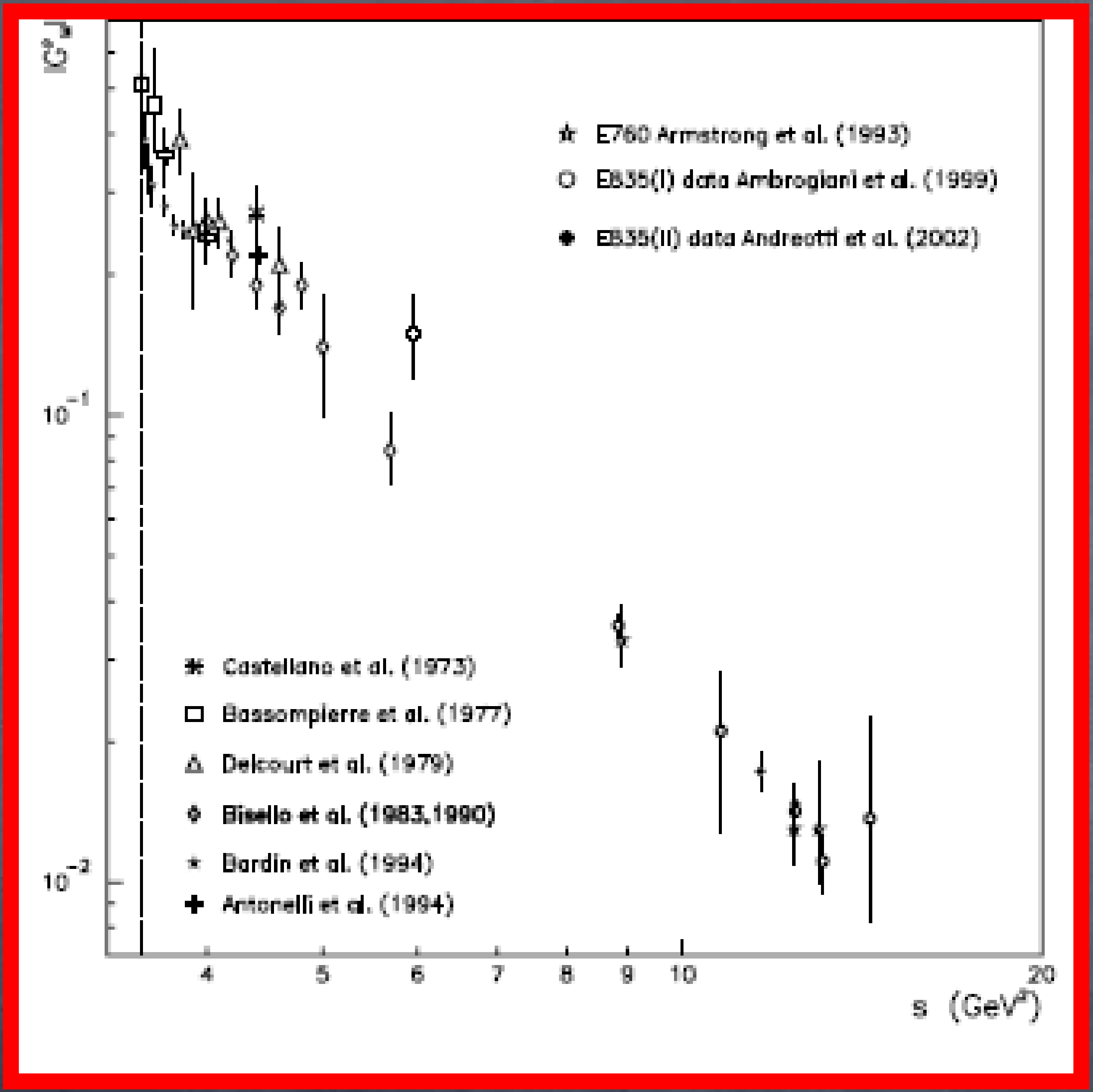
The E760 experiment at Fermilab produced the first measurement of the form factors at high Q2

$$\bar{p}p \to e^+e^-$$

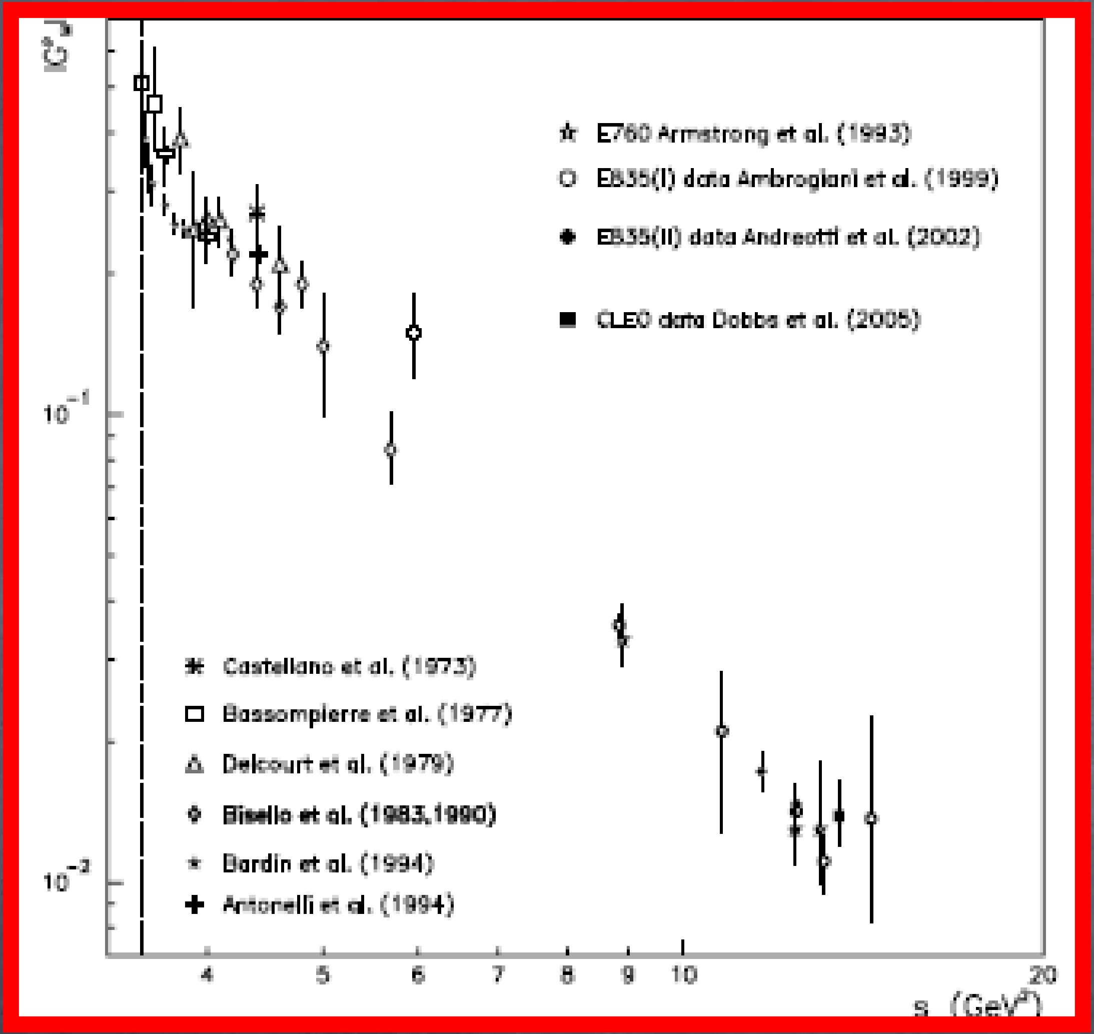
They recorded 29 events. The measurement assumes |GE|=|GM|. Proton



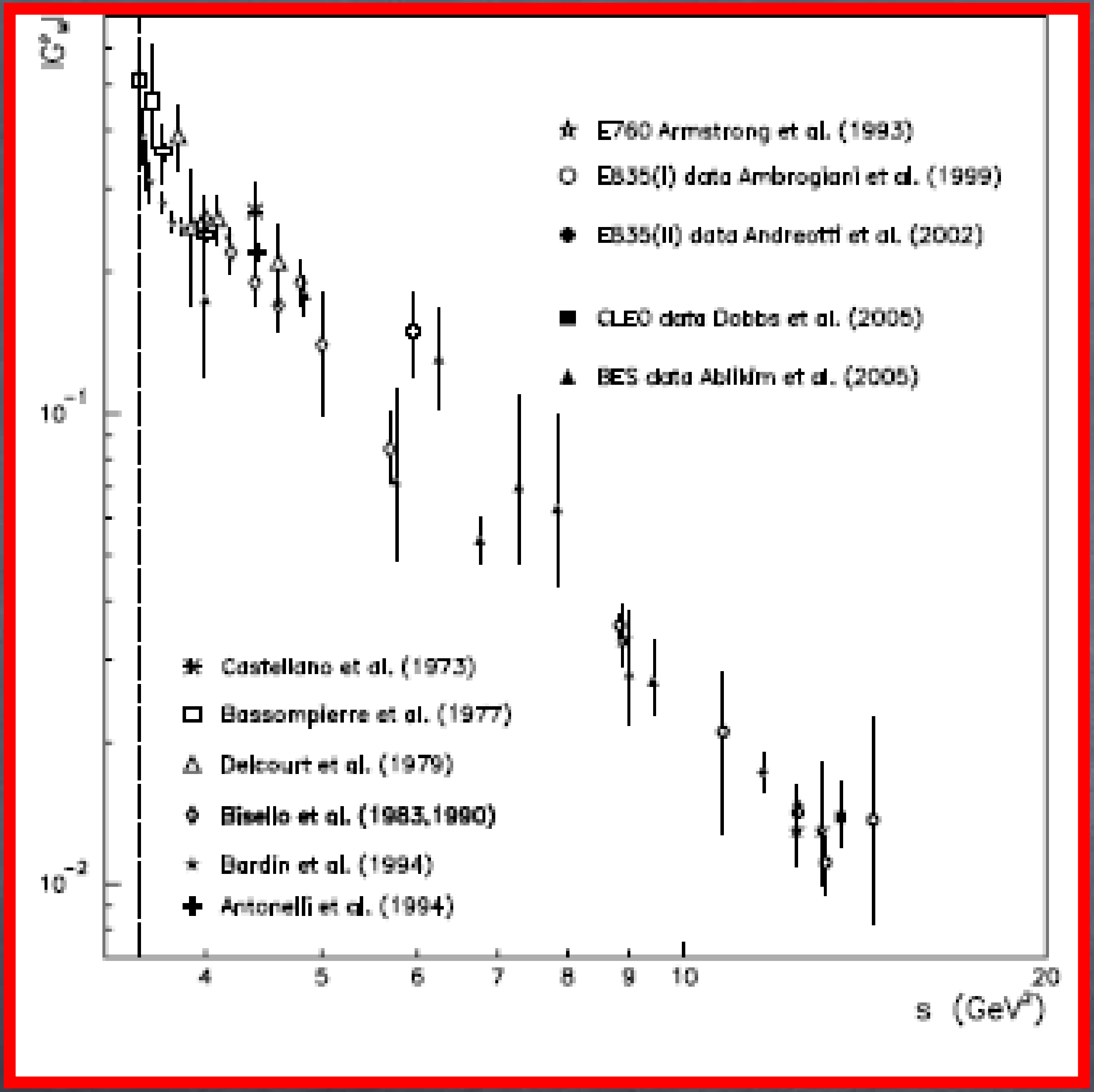
The FENICE experiment at ADONE, primarily devoted to the measurement of the neutron form factor, produced also a measurement of the proton magnetic form factor with 69 events in 4 points.



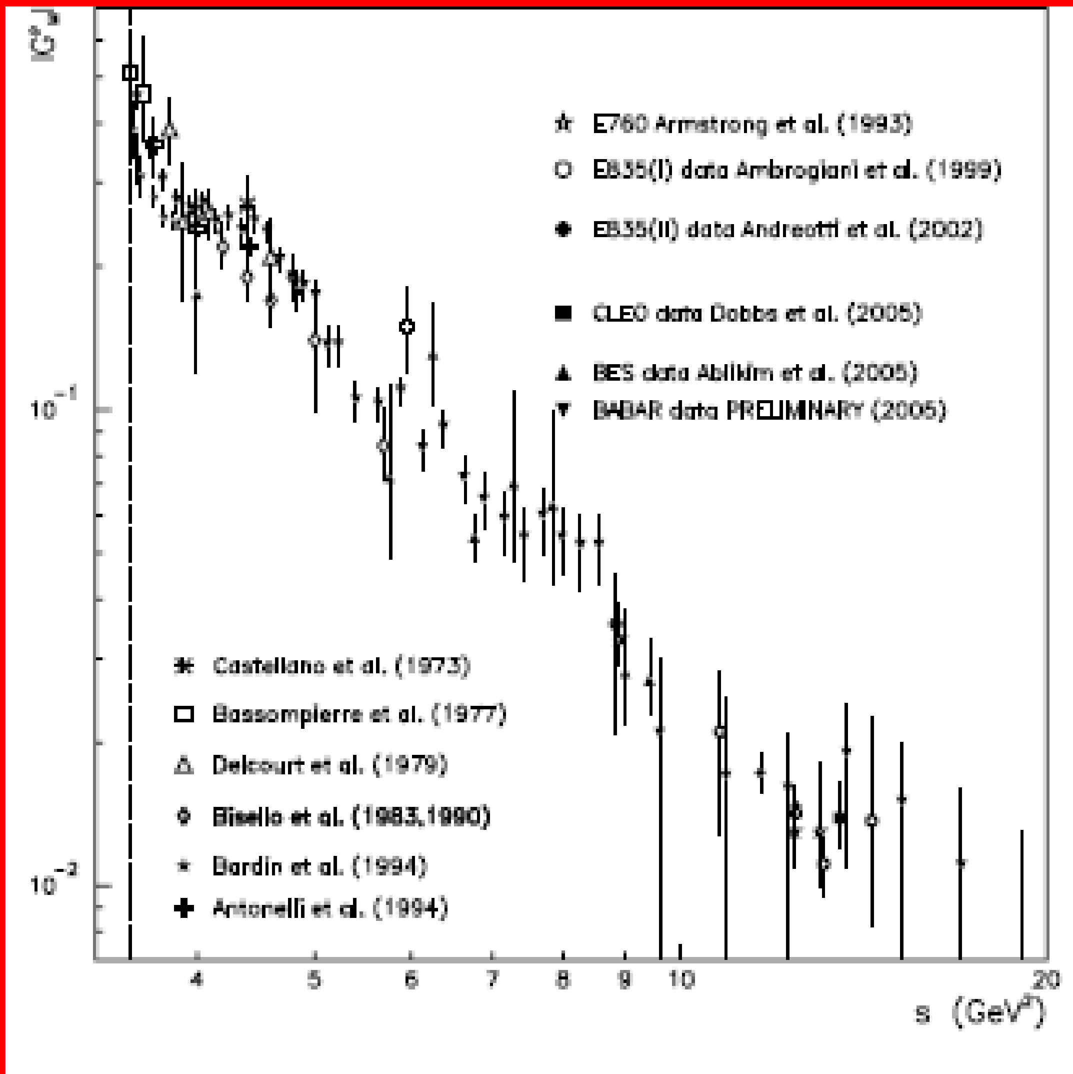
E835 at FNAL, continuation of E760, made further measurements at high Q2 with a total of 206 events in 2 data taking runs. Proton



A new measurement at high q^2 was recently made by the CLEO at CESR in e+e-→pbar p. It assumes |GE|=|GM|. The measurement is based on 14 events.

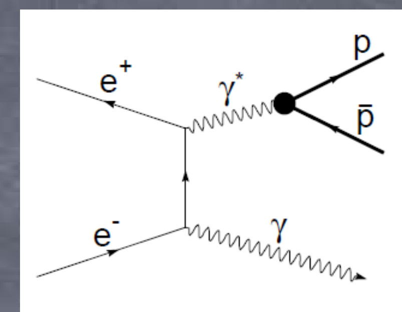


Another measurement of the proton timelike form factors has been reported by BES.
The measurement covers 9 data points from (2.0 GeV)2 to (3.07 GeV)2 using the hypothesis |GE|=|GM|.



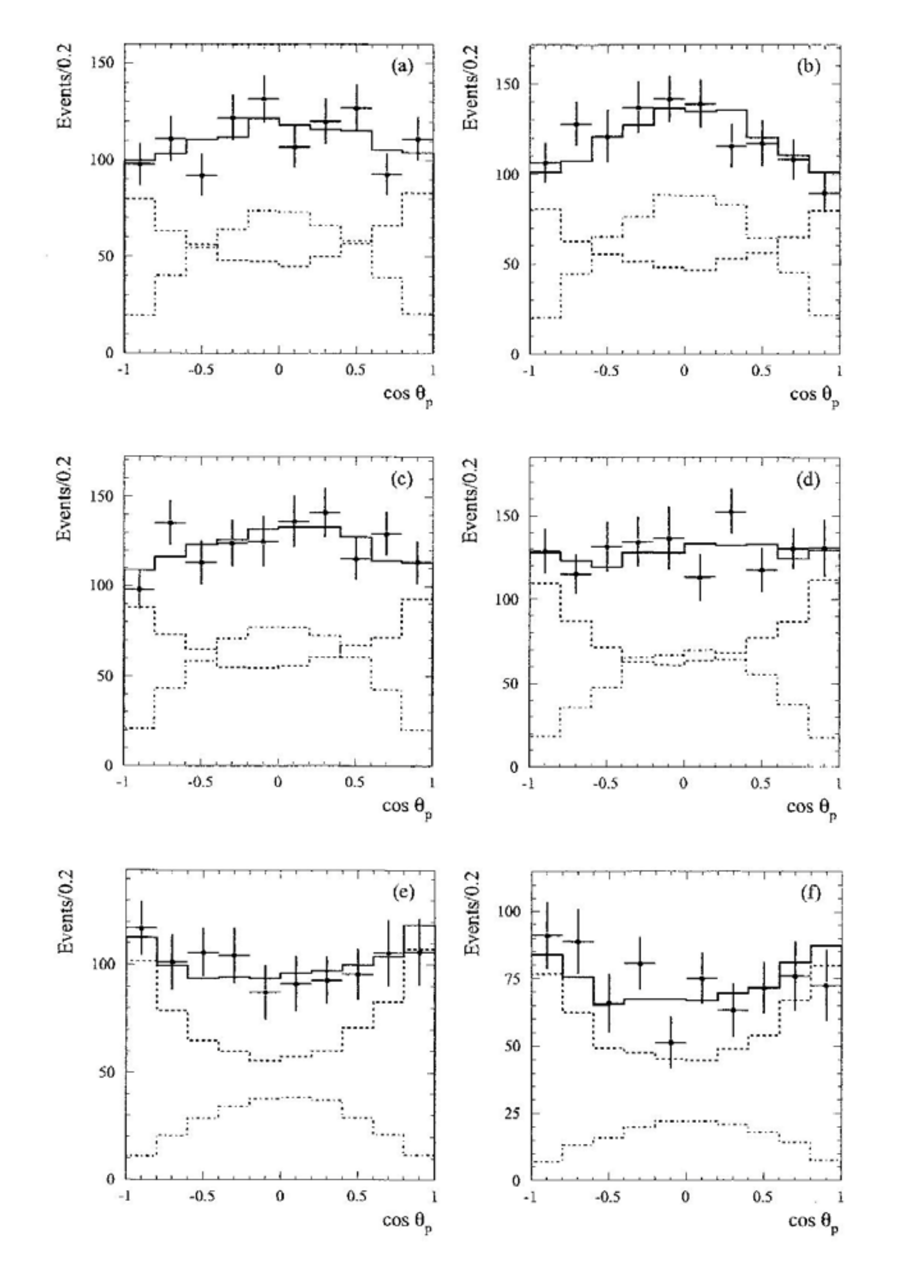
BaBar measurement using Initial State Radiation (ISR) e+e- $\rightarrow$pbar pγ.

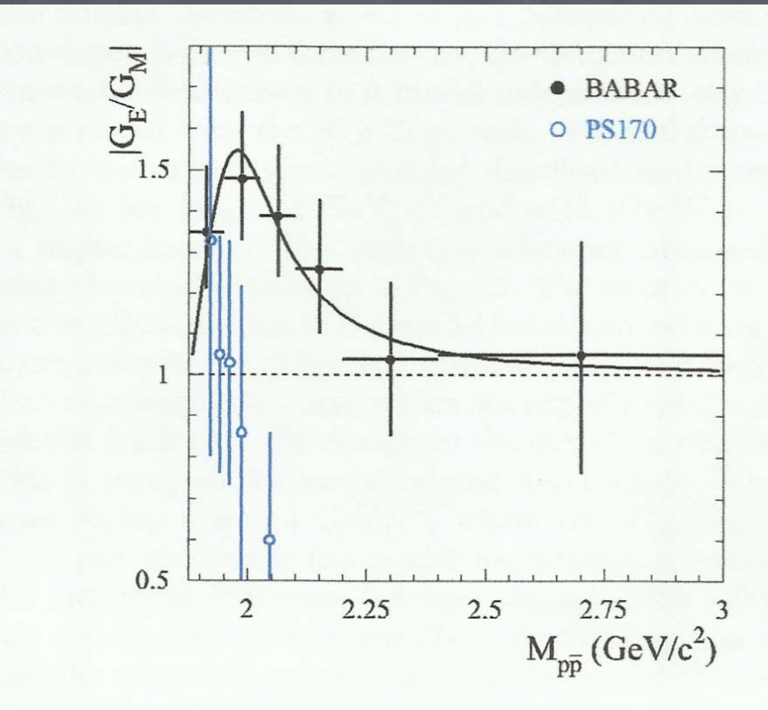
background



BABAR

Angular distribution "after background subtraction"

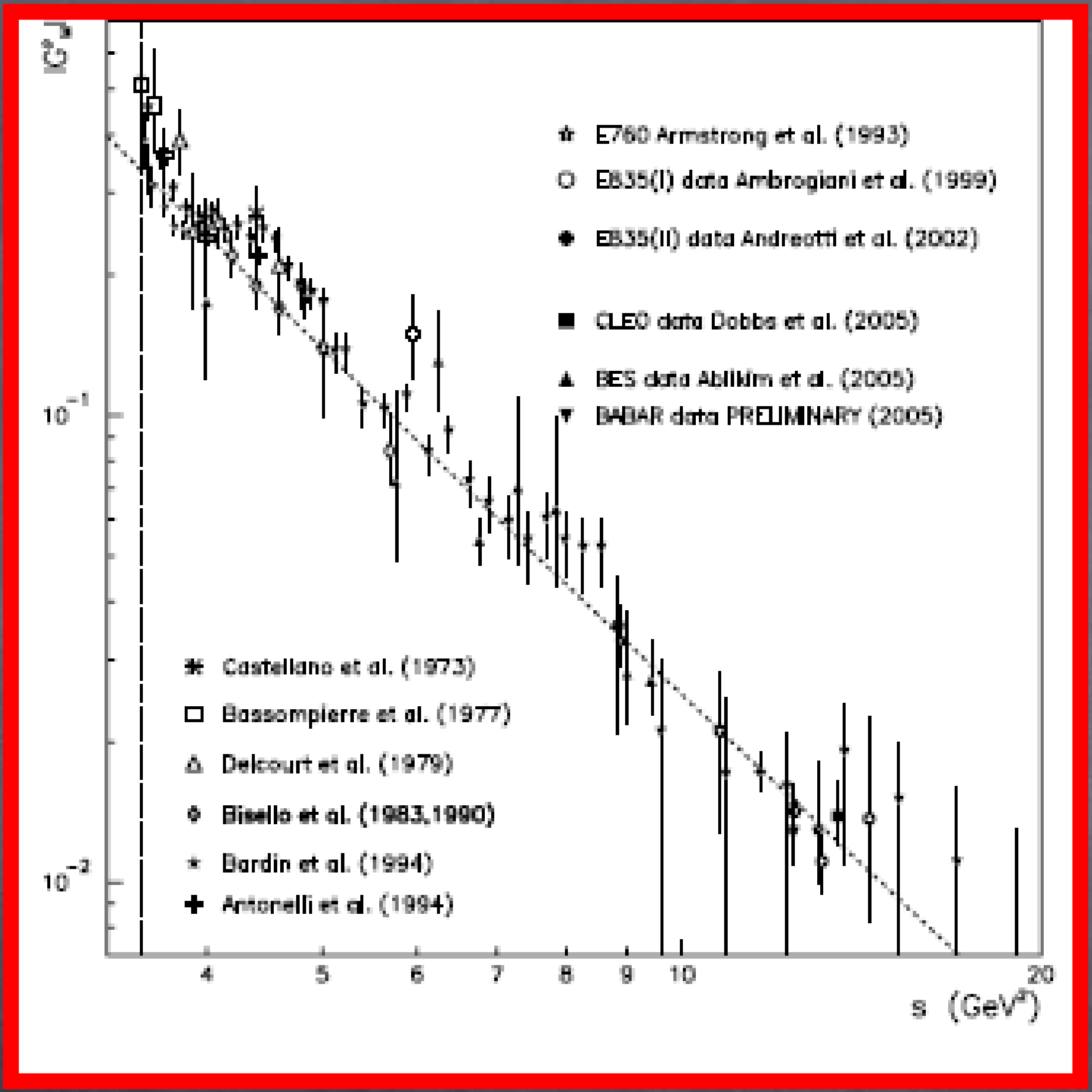




gh energy results with differential method

	1 parameter fit		2 parameter fit		
(MeV/c)	$\|G\|$	χ^2/N^a	$\|G_E\|/\|G_M\|$	$\|G_M\|$	χ^2/N^a
470	0.277 ± 0.014	10.1/10	1.33 ± 0.53	0.244 ± 0.045	9.2/10
540	0.252 ± 0.013	9.6/10	1.05 ± 0.29	0.247 ± 0.027	9.6/10
600	0.248 ± 0.010	6.0/10	1.03 ± 0.30	0.245 ± 0.029	6.0/10
700	0.241 ± 0.011	6.4/10	0.86 ± 0.36	0.253 ± 0.033	6.2/10
900	0.239 ± 0.009	9.6/10	0.60 ± 0.26	0.272 ± 0.020	6.8/10

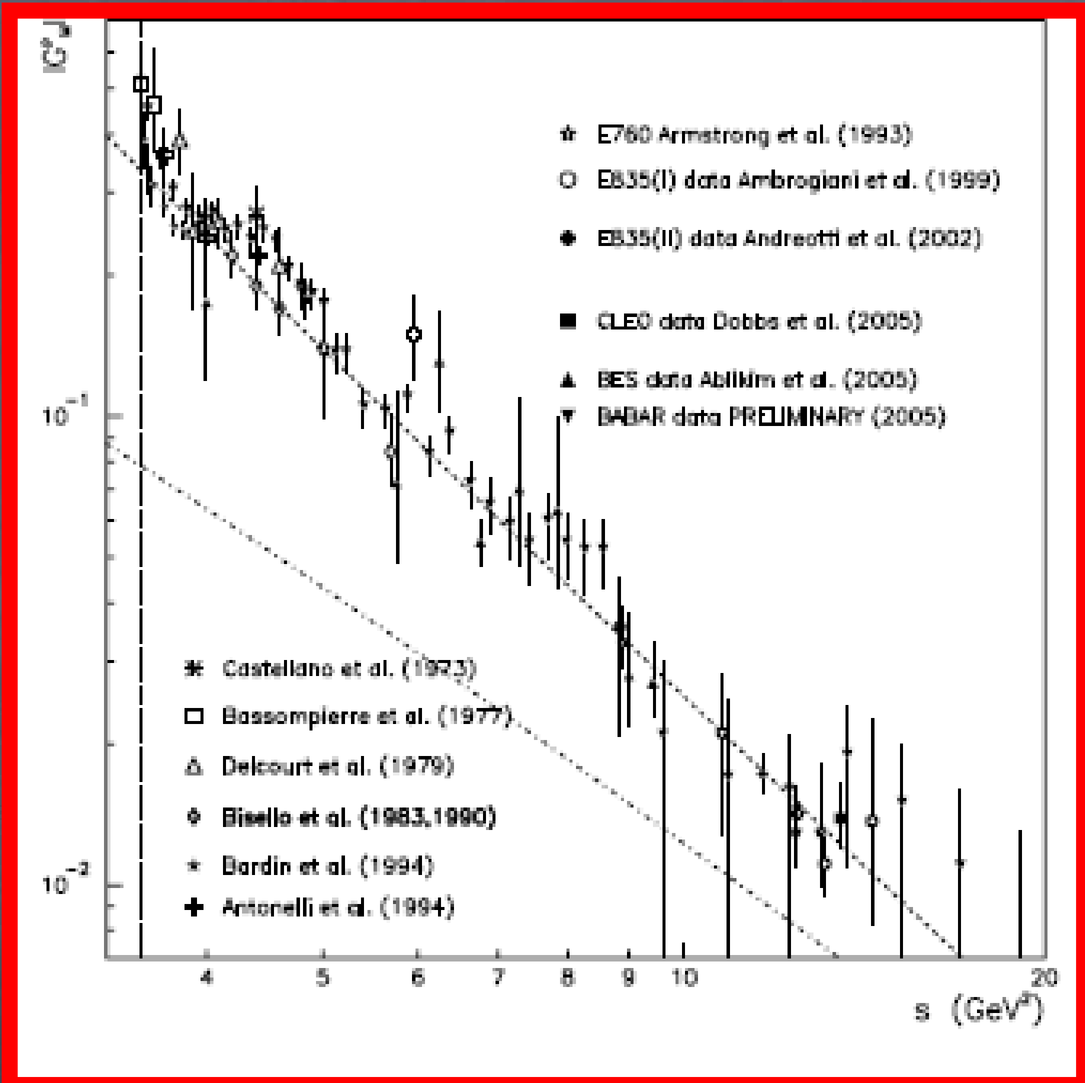
[a]N= number of points fitted



The dashed line is a fit to the PQCD prediction

$$\frac{|G_M|}{\mu_p} = \frac{C}{s^2 \ln^2\left(\frac{s}{\Lambda^2}\right)}$$

The expected Q2 behaviour
is reached quite early,
however …



The dashed line is a fit to the PQCD prediction

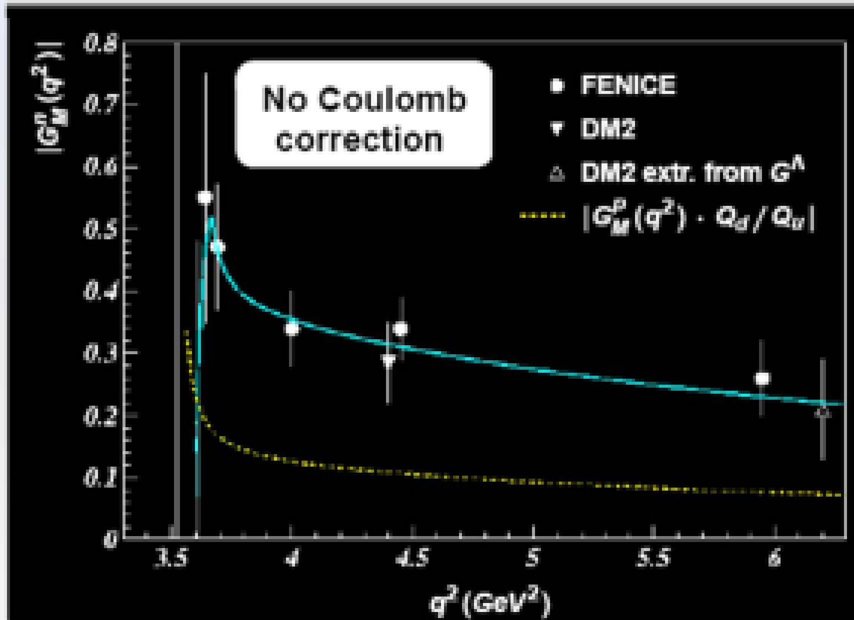
$$\frac{|G_M|}{\mu_p} = \frac{C}{s^2 \ln^2\left(\frac{s}{\Lambda^2}\right)}$$

The expected Q2 behaviour
is reached quite early,
however ...

... there is still a factor of 2 between timelike and spacelike.

Neutron Timelike Form Factor

Only two measurements by FENICE and DM2



	$\|G_M^n / G_M^p\|$
Data	~ 1.5
Naively	$\sim \|Q_d/Q_u\|$
pQCD	< 1
Soliton models	~ 1
VMD	$\gg 1$

$1.9 < \sqrt{s} < 2.55 \quad GeV$ $\int Ldt = 0.4\ pb^{-1}$ 80 events

The neutron form factor is bigger than that of the proton !!!

The end