DETECTORS; RELATION OF DETECTORS TO PROTON-ANTIPROTON MACHINES

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We started our discussions on detectors for Proton-Antiproton interactions at high energy with some general considerations, but we soon turned to more practical aspects.

I. Philosophical Considerations and General Aspects.

We assume the following working hypothesis:

- There has been until now and there will be in future a continuity of heavier masses and higher energy levels at any c. m. energy we shall reach, at least in this century.
- Energy resolution of the apparatus will always be an important and a limiting factor at all energies ($\Delta M/M$; $\Delta E/E$; $\Delta P/P$ etc.); present-day resolutions are far from being satisfactory.
- High luminosity (L) will always be important; adequate detectors for high L have still to be invented.
- The quality of the machines is today perhaps better than that of the detectors for them. The ratio (cost of detector)/(cost of machine) should increase, in order to get detectors adequate to the progress of the accelerators.
- Proton-Proton and Proton - Antiproton interactions will be very different on the important points at all energies. The comparison between the two will always be essential to our understanding.

The following question has been considered in our working group: is it conceivable to build a Super Detector, looking at all 4π solid angle, capable of recognizing all particles, and "socially relevant" in the sense that it can supply many groups of physicists with pictures, as the bubble chambers did in the past? Or we must rather admit that in this case that the dream of a 4π universal detector is impossible, and specialized different detectors in a variety of configurations will be more important? We went back to this point after a concrete discussion on existing projects.

II. Relation of Detectors to Proton - Antiproton Machines.

It is important to discuss and plan colliders and detectors in strict collaboration. Among the reasons for this, we recall:

- The Luminosity per bunch is today limited by the detector capacity to support the huge number of hadronic interactions. At CERN, with 6 $p\text{-}\bar{p}$ bunches and a total luminosity $L = 10^{30}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, we can have double interactions in the same crossing in approximately 20 per cent of the cases. This is very close to a maximum acceptable limit, when one wishes to measure all particles and energies (total calorimetry). Total calorimetry will be of great importance, for instance, for the evaluation of the charged masses decaying with the emission of one neutrino.
- The time interval between the $p\text{-}\bar{p}$ bunches is also relevant. If it is less than one microsecond, it can seriously trouble observation by drift-chamber techniques (for instance in an experiment like proposal P92[1]).
- The measurement of the total energy in a detailed balance (total calorimetry) may require either long straight sections (for instance $\geq 2 \times 50$ meters at 1000 + 1000 GeV) or "calorimetrization" of low-beta quadrupoles by inserting layers of scintillators between the iron plates. The shape of the donut and the level of the vacuum inside will obviously be important. We must keep in mind that $p\text{-}\bar{p}$ interactions approximately 40% of the energy will flow through angles of $\lesssim 10$ milliradians. In fact, typical values of the angle of emission of the particles in the forward jets will be:

$\theta_i \sim$ (0.3 GeV/p_i(GeV) (Average angle of emission of a particle in the forward jet);

$\theta_0 \sim M_{\pi^0} / E_\pi$, (minimum angle of emission of the photons in π^0 decay);

$\theta_{Bi} = \ell / R = 0.3\, \ell\, B/p_i$ (angle of emission of a charged particle of momentum p_i when leaving magnetic field of the apparatus, if it is a dipole). In the case of P92 [1] it is $\sim 0.6/p_i$.

Typical resulting angles for the most energetic particles in the forward cones are of order 5 milliradians. For a donut diameter of 10 cm, this corresponds to a straight section length of 10 m or more.

Note that the idea of pursuing the forward particles along and between low-beta quadrupoles is justified when considering the value of the angles θ_p, $\theta_{\bar{p}}$ of protons and antiprotons in the beam:

$$\theta_p \sim \frac{0.15}{\sqrt{\beta}}\ ; \quad \beta = 0.5\ \mathrm{m}; \quad \theta_p \sim 0.2 \text{ milliradian.}$$

Our conclusions have been summarized in the sketch of Fig. 1.

III. Some Specific Apparatuses for Proton - Anitproton Experiments.

The CERN P92 proposal,[1] already described in this workshop, is (see Figs. 2 and 3) an example of a 4π detector to measure momentum, energy and ionization of each produced particle. Complete calorimetry and analysis at very small angles are planned, by extending the central apparatus with smaller calorimeters and wire chambers.

Another experiment [2] has been proposed at CERN for the SPS $p\bar{p}$ facility. The main purpose is to study production and decay of the $W^{\pm}$ and Z^{o} bosons. It must be remarked that a small azimuthal wedge in the central region is instrumented to cover other aspects of $p\bar{p}$ collisions, like free-quark production and structure of large transverse-momentum jets.

A number of detectors being proposed at Fermi Lab have been discussed in our working group. The program at Fermi Lab is to reach an optimum design for a modest-cost detector suitable for studies of either $p\bar{p}$ or pp collisions up to 2 TeV in the center of mass, at luminosities in the range $10^{28} - 10^{31} cm^{-2} s^{-1}$. The time schedule for assembling the detector is about three years, so that it will be available for physics in 1980-81. This roughly parallels the scenario for construction of the Energy Doubler. The search for the $W^{\pm}$ and Z^{o} intermediate bosons, although by no means the only experiment of interest, has served as a test case for the evaluation of the performance of the detector.

The study made by the Hitlin group at the 1977 Fermilab Summer Study serves as one of the points of departure. Of course the design at CERN and PETRA are also very useful. Four proposals are being pursued in competition, and one of them or one combination among them, will be selected for the task. These proposals are as follows:

a. A calorimetric detector (see Fig. 4a) without a magnetic field, emphasizing hadronic-energy measurements in a heavy-concrete and scintillator segmented calorimeter, and electron gamma-ray energy measurements in lead-scintillator shower counters. Lithium-foil transition-radiation detectors will be used for additional π-e discrimination. Total weight is about 1200 tons, with very good solid-angle coverage.

b. A toroidal magnetic detector. It will have a 1.5-m diameter field-free region around the pipe, followed by a superconducting toroid 5m long, with inner radius 0.75 and outer radius 1.5 m. The inner field is 1.8 T. The opaque space, because of the shadows of the coils and support will be about 10% in azimuth. Calorimeters will be outside the magnet. Total weight with end caps is about 2500 tons (see Fig. 4b).

c. A small solenoidal detector with a magnetic field of 1 T over a 1 m radius, 5 m long. Field uniformity will be insured by iron pole tips. The iron return can be used as hadron calorimeter.

d. A large solenoidal detector with a magnetic field of 2 T, and a radius of 2 m and total length of at least 5 m. The iron return will be again used as part of the large hadron calorimeter. This large device can be rotated around a vertical axis to allow its use as a dipole for small-angle physics. Its weight will be about 4000 tons. (Fig. 5)

The main claim in favor of option a. is cost and simpler analysis. In favor of option b. is the large field-free region surrounding the beam pipe. Options c. and d. are similar, apart from scale and resolution, and hence cost. Decreasing the product Bl^2, where l is a typical chord of the charged-particle arc, decreases the momentum p_0 at which the resolution reaches its largest (worst) value, and where the resolution from the magnet trajectory equals that from the calorimetry. (See Fig. 6.)

IV. Use of a Magnetic Field in the Detectors.

We think that a low magnetic field may be much better than having no field at all, because of the physics advantage of recognizing the sign of the particle up to 50-100 GeV, to measure charge asymmetries, which can be clear and strong in $p\bar{p}$ collisions, [1] when for instance charged $W^{\pm}$ bosons are produced.

Some of us gave a brief look at a magnetized-iron calorimeter, and suggest that a system capable of determining muon momenta to 20% is possible, together with tracking and otherwise good calorimetric energy determination of hadrons, photons and electrons. That concept is illustrated in Fig. 7. It is a simple rectangular box of 1 in. iron plates spaced at 0.5 in. intervals, with a minimum path length in the iron of 1 m. The region around the interaction point would contain tracking chambers and lead scintillator shower detectors. Both the box and the end caps will be magnetized by 10^4 ampere-turns wound at the corners of the box to B=2 T. Large external drift chambers will observe the deflection of muon candidates.

V. Resolution in Energy and Masses.

As we said, we assume that a better resolution will always be extremely useful, independently of today's theoretical speculations. It is important to recall that beyond 200 GeV c. m., only the proton-proton and proton-antiproton colliders will remain to give us the farthest information of our universe of energy and momentum. The miracle of 1 - MeV resolution obtained at SPEAR, Frascati, Doris with the J-ψ particle will not be possible again, for it was due to the precision in energy of the $e^+ e^-$ beams at 2 GeV. Up to 200 GeV c. m. the future $e^+ e^-$ rings will allow a total resolution (for neutral vector bosons) of 200 MeV, due to the precision of the $e^+ e^-$ beams. Beyond that energy, we shall depend on detection of the produced particles. The best resolution today with 4π detectors is $\Delta M/M$ ($\Delta E/E$) $\simeq$ 1 GeV for completely identifiable particles. A sketch of the situation is given in Table I.

We express the opinion, perhaps rather obvious, that the best efforts of the physicists must be devoted in the coming years toward the goal of reaching a resolution of approximately 0.2 GeV with a detector even at the highest energies and masses of the produced particles.

VI. Back to the Universal 4π Detector.

a. Some of us firmly believe that one, full 4π detector (that is, an instrument which allows in each interaction the measurement of the energy or momentum of each particle, the charge, identification of the neutral particles, the ionization of each particle) will be necessary, although expensive. An instrument like this means a large effort in cost and some hope of having many physicists divided into different groups to explore millions of detailed interactions, as in bubble chambers. There are of course, advantages over bubble chambers of trigger, statistics, precision in momenta and ionization.

These beautiful hopes still need some "caveat". In fact we must temper consideration of this large ambitious detector with the recollection that similar projects in the past have on occasion proven more difficult than anticipated. Moreover, we must admit that there are specific requests which cannot be easily extended to the full solid angle, like polarization, structure of jets, refined masses of stable and unstable particles. All this demands some kind of arm spectrometer. But before developing this point, we make a comment connected to the hopes which arose in the work shop, regarding the future luminosities of a p-$\bar{p}$ ring.

A large increase of the luminosity, for instance to the level $L = 10^{31-32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ as indicated by Carlo Rubbia in his talk of March 29, could mean that even at 90° and p_t values of $\gtrsim$ 30 GeV, we can get

$$10^{-(33-34)} \times 10^{(31-32)} \times 10^{5} = 10^{(2-4)} \text{events/day,}$$

particles or jets, entering a small-angle well-prepared detector.

We could in this way in a reasonable time have at our disposal some 10^5 particles coming from the deep core (if there is one) of the proton-antiproton interactions. If we stick to the hypothesis made in point 1 above, that in the most important aspects pp and $p\bar{p}$ interactions shall be very different, then the high luminosity of $p\bar{p}$ colliders will be very welcome, even necessary, independent of any record luminosity of pp.

b. In this optimistic view of a high luminosity, a spectrometer external to a 4π detector can study secondaries with much more sophisticated particle identification than possible with a 4π detector. Questions which such a detector could study would include:

- search for massive, stable particles; search for quarks;

- a quantitative study of K, π, p, $\bar{p}$, n differential production spectra;

- unambiguous identification of muons through momentum and velocity as well as range.

This dector should incorporate:

- Magnetic deflection
- Cerenkov counter
- Good dE/dx measurements
- A good calorimeter
- Time of flight
- Perhaps transition-radiation analysis

The experiments at CERN already reported have proposed an azimuthal wedge [2] or central opposite windows [1] in order to make a refined analysis of the particles emitted. Another CERN proposal [3] is particularly studying the instrumentation of the 90° holes in the P92 proposal [1], in order to separate the particles of a jet and to observe individual quarks, even if associated with high multiplicity.

An example of a fine small-angle detector is given in the Aspen 1977 Summer study [4]. Their spectrometer is 7 m overall in length, and would for instance extend 7 + 3 = 10 m from the interaction point if attached to large-angle CERN experiments.

VII. An Optimistic Touch.

Before closing, let us give a glance toward the future, with the optimism inspired from the discussions and findings of these last three days. Let us assume that future detectors will succeed, that it will become possible with a luminosity $L = 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ to separate and recognize an interesting object (like the heavy boson) in a jungle of hadrons and photons, which are more abundant by a factor 10^{10} or more. Let us assume also that in the 1980's we shall be able to get masses in the 100 - 1000 GeV/c^2 range with resolutions $\Delta M \lesssim 0.2$ GeV/c^2, and that new masses and objects will come out (our working hypothesis in section 1).

Then, after a few years of operation with the Fermi Energy Doubler or Isabelle, perhaps in 1990, the physicists could have at disposal a series of masses, as given f. i. in Fig. 8. Particles like Z^0 and $W^{\pm}$ and Higgs particles will have been studied in detail by the powerful $e^+ e^-$ colliders. But we insist again that beyond the limit of 200 GeV in the center of mass the pp and $p\bar{p}$ will be the only colliders capable of detecting a possible new spectroscopy of very high masses, as far from us today and perhaps as intriguing as Quasars are for the astronomers. Notice in Fig. 8 that the yields per day become comparable with what expected for neutral bodies from $e^+ e^-$ rings.

These perspectives bring us again to the main point of this summary: the pp and $p\bar{p}$ machines will soon be alone in exploring new domains, and an improvement in resolution and scope of the particle detectors around them will be of fundamental importance.

References

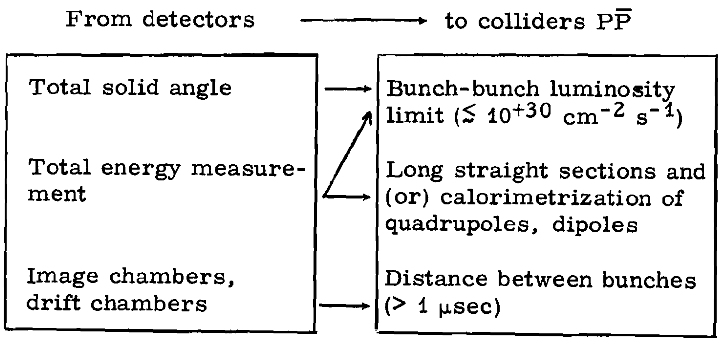
1. A 4π solid angle detector for the SPS used as a Proton Antiproton collider. CERN / SPSC/78-06 (SPSC/P92) Jan. 30/78.
2. Proposal to study Antiproton Proton interactions at 540 GeV c. m. CERN/SPSC/78-08 (SPSC/P93) Jan. 31/78.
3. Search for Quarks at the Proton Antiproton collider CERN/SPSC/78-16 (SPSC/P97.) Feb. 6/78.
4. Fermilab 1977 Summer Study; page 179 and Foll. Volume 2.

Table I. Resolution ΔM In The Measurement Of Masses and Widths.

Particle	ΔM_e, Resolution in Mass From e^+e^- Colliders	ΔM_H, Resolution From $p\bar{p}$ Colliders	$\Delta M_H/\Delta M_e$
$J\psi$	1 MeV	30 MeV	~ 30
$W^{\pm}$	60 MeV	~ 1000 MeV	~ 15
W^{o}	150 MeV	~ 1000 MeV	~ 6
M (>200)	No e^+e^- collider available	1 - 2 GeV ?	

Notice that for possible masses $M \geq 200$ GeV / c^2 the pp and $p\bar{p}$ colliders will be the only machines available. It will be of paramount importance to get $\Delta M \sim 200$ MeV in future detectors.

REQUESTS



From detectors → to colliders $P\bar{P}$

Total solid angle → Bunch-bunch luminosity limit ($\lesssim 10^{+30}$ cm^{-2} s^{-1})

Total energy measurement → Bunch-bunch luminosity limit ($\lesssim 10^{+30}$ cm^{-2} s^{-1}); Long straight sections and (or) calorimetrization of quadrupoles, dipoles

Image chambers, drift chambers → Distance between bunches (> 1 μsec)

Fig. 1. The requests of the detectors to the parameters of the $P\bar{P}$ collider, in case a very large or total solid angle is requested.

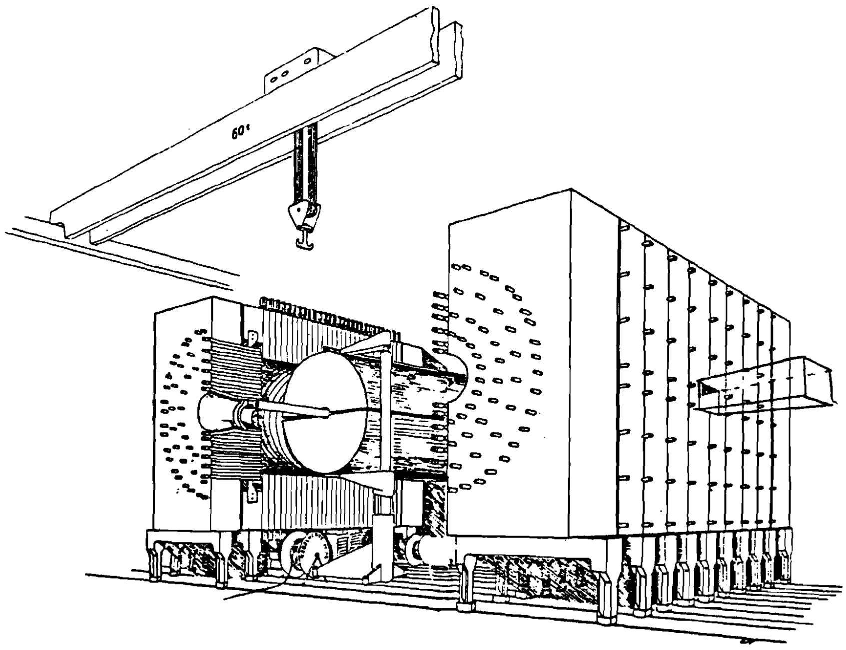


Fig. 2. The 4π detector proposed at CERN (Ref. 1): artist's view.

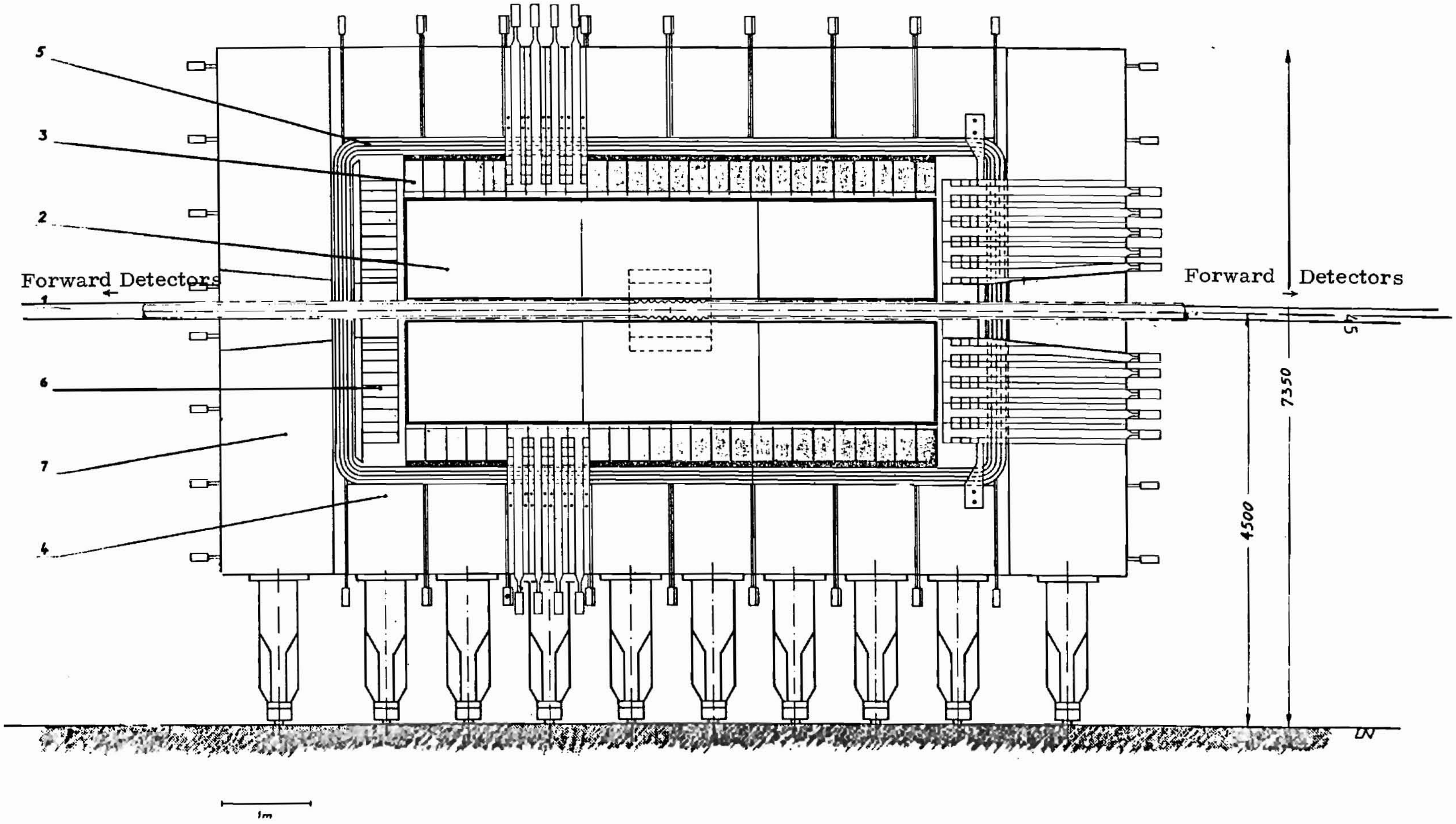
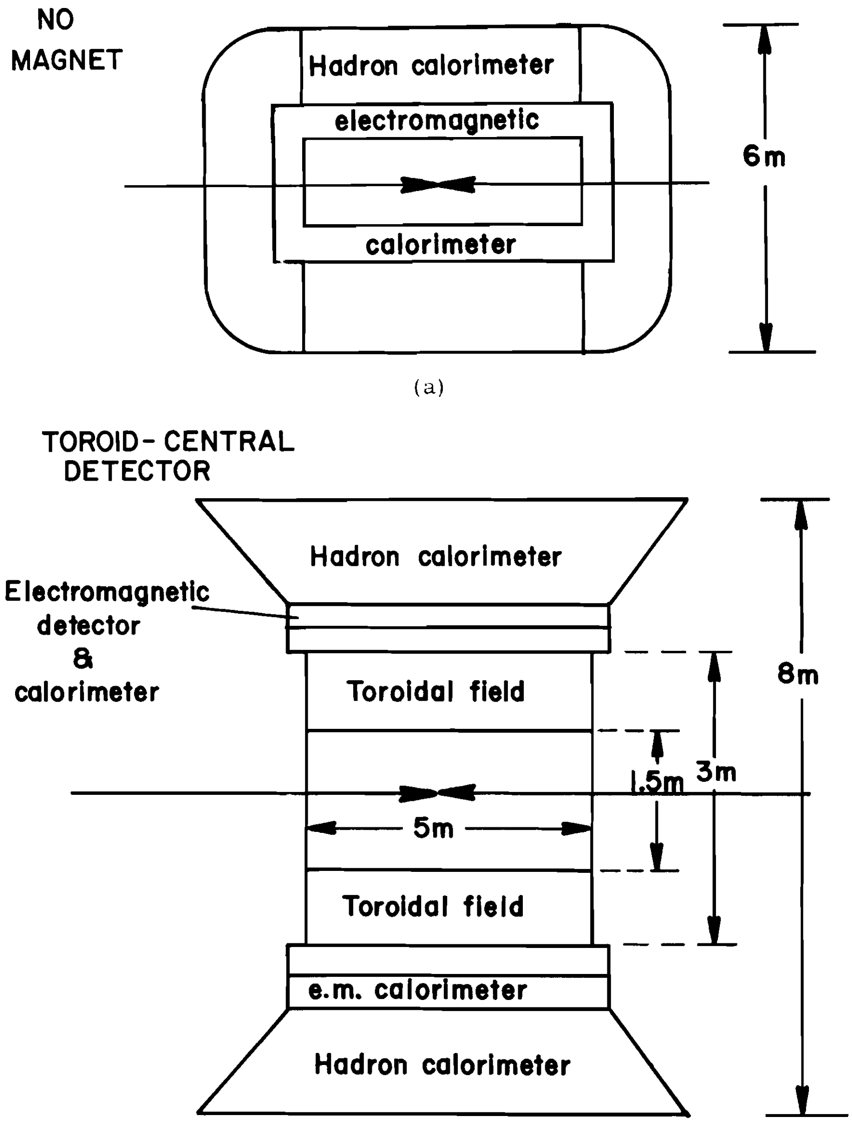


Fig. 3. The proposed 4π detector at CERN, side view. Legend: 1) vacuum chamber; 2) vertex chambers; 3) electromagnetic (e. m.) detectors; 4) hadron calorimeters and return yoke; 5) Al coil; 6) forward e. m. detectors; 7) end caps.



(a)

(b)

Fig. 4(a). A calorimetric solution, without magnetic field (Fermilab). (b) A solution with magnetic field produced by toroidal coils (Fermilab).

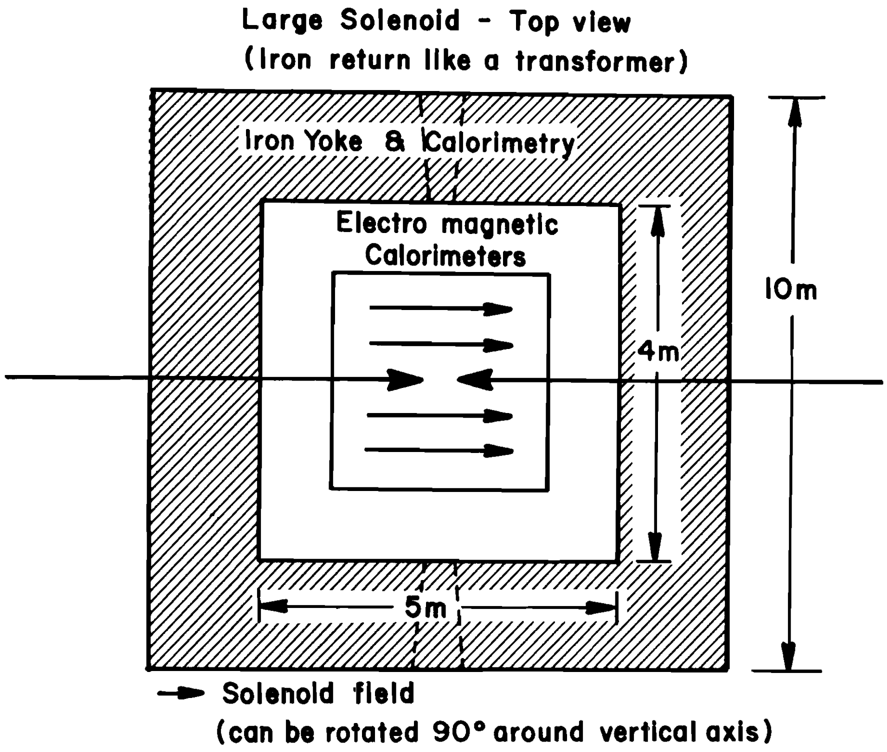


Fig. 5. The proposal at Fermilab with an high field solenoid.

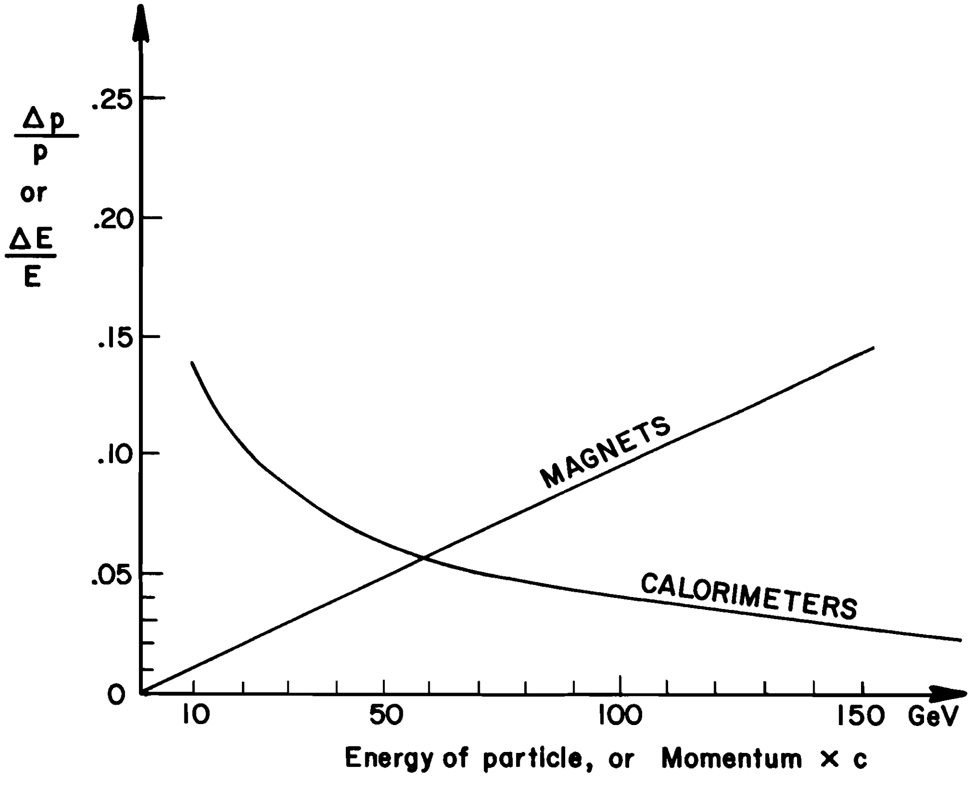


Fig. 6. The energy resolution with calorimeters compared with the resolution obtained with a magnet. Most expensive solutions will have the crossing point at higher energies. In the case of Ref. 1, the crossing is around 50 GeV.

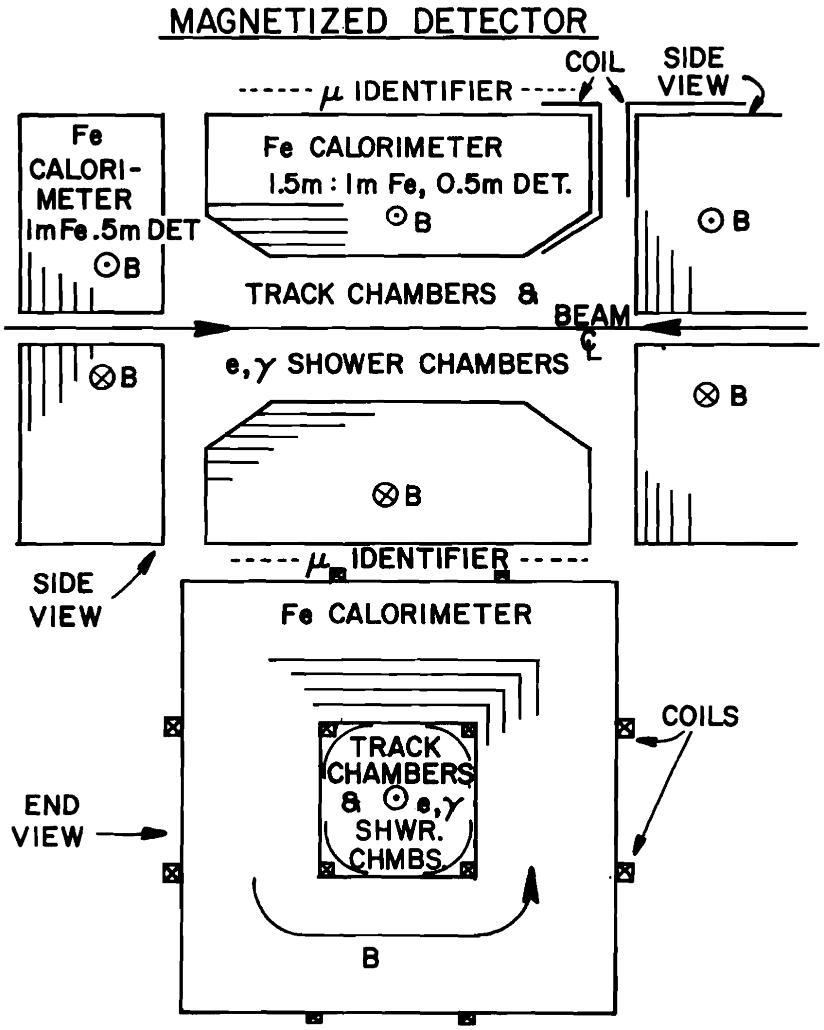


Fig. 7. Calorimetrization and magnetization of the iron, in order to measure the momentum of nonhadronic charged particles (like the muons) emitted in $P\overline{P}$ interactions.

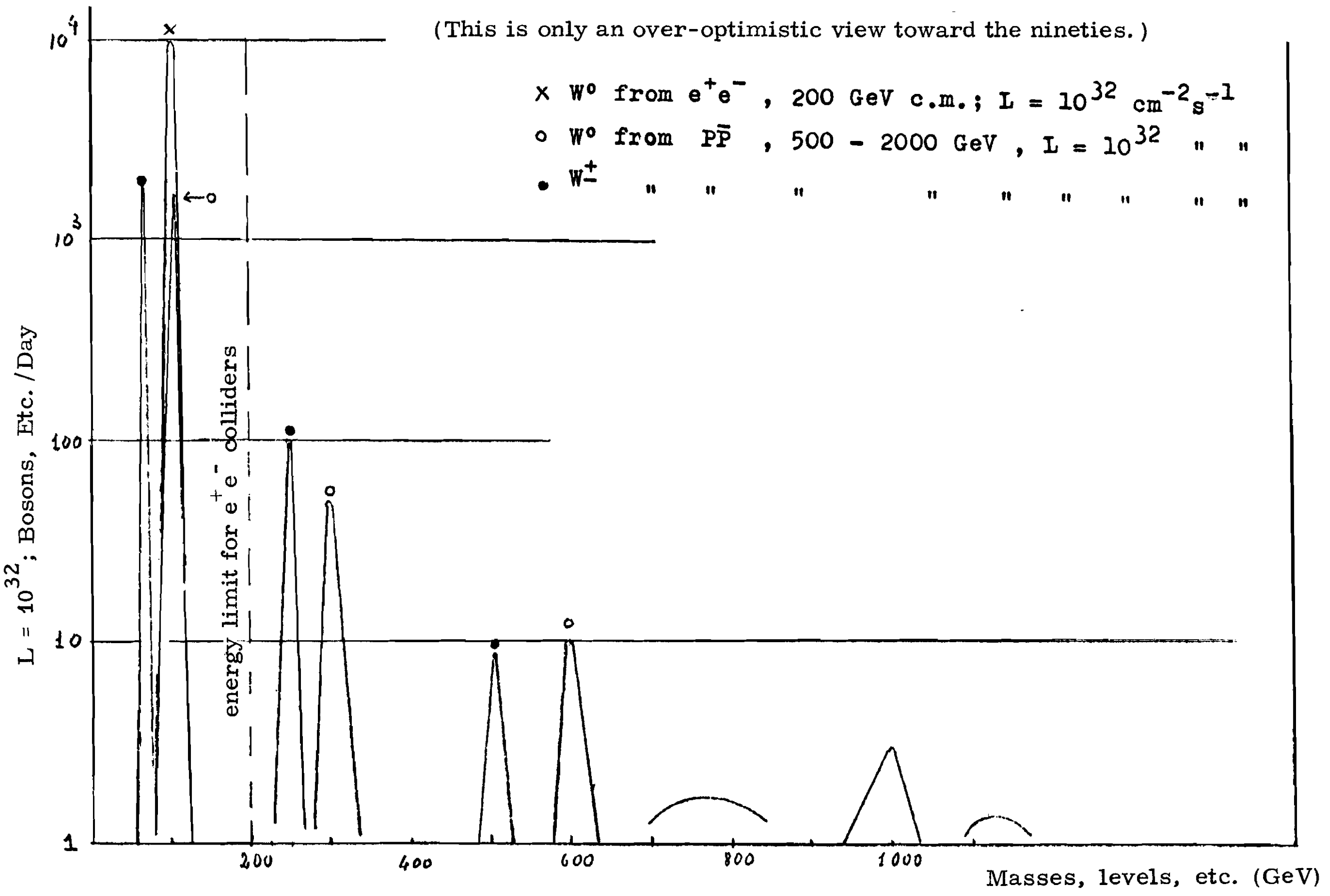


Fig. 8. An over-optimistic view of possible masses discovered in the eighties by e^+-e^- colliders, CERN SPS, Energy Doubler, Isabelle.

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