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ERRATUM

GRADUATE EDUCATION AND RESEARCH IN THE ERA OF LARGE ACCELERATORS*

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Because of an error, Table 2 should be replaced by the following table:

Table 2. Federal funding for elementary particle physics in fiscal year 1987 in millions of dollars. The numbers are rounded off to the nearest million dollars.

Agency	Institutions	Operating and Equipment	Construction
NSF	Universities	23	
NSF	CESR	8	11
DOE	Universities	80	
DOE	BNL	62	10
DOE	FNAL	156	16
DOE	SLAC	106	5
DOE	LBL and ANL	27	
DOE	SSC R&D	20	
DOE	Other	18	
Total		500	42

Invited talk presented at the Third Topical Conference of Departmental Chairs, American Association of Physics Teachers, Arlington, Virginia, February 19–20, 1988

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*Work supported by the Department of Energy, contract DE–AC03–76SF00515.

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I. ISSUES AND QUESTIONS

In the past three decades, the great progress in elementary particle physics[1,2,3] and its associated technologies — accelerators and detectors — has brought changes in research methods and research style. Most experimental work in particle physics[3,4,5] involves: huge accelerators; large and complex particle detectors, Fig. 1; collaborations of many physicists; and long times for equipment building, data acquisition, and data analysis.

These aspects of experimental particle physics have raised questions[6,7,8] in the physics community as to how to evaluate the quality and contributions of the research of individual experimenters: graduate students, staff, and faculty.

⋆ This work was supported by the Department of Energy, contract DE–AC03–76SF00515.

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The questions and concerns of the community fall into five categories:

Quality: Is the quality of experimental particle research per individual as high as other areas of physics?

Independence: How much independence is there in this research?

Creativity: Can most physicists be creative in this research work?

Evaluation and Recognition: How can the contributions of individual students, staff, and faculty be evaluated and recognized?

Value in Graduate Education: What is the educational value of having experimental particle research in a physics graduate program?

My discussion is based on three kinds of information. First I consider a case history: the present Mark II collaboration at the SLAC Linear Collider (SLC), of which I am a member. Second I rely on my observations during thirty years of particle research at the University of Michigan and at the Stanford Linear Accelerator Center. Third I use the literature in the references.

There are several major limitations to my discussion. It is restricted to the physics community in the United States. The discussion does not include research in particle physics theory or in accelerator physics and technology. The increasing importance of the latter field deserves a separate discussion. I will not discuss the basic question of the proper balance between large scale and small scale physics research with the concomitant issues of funding, priorities, and visibility.

Another basic question which I will not discuss is the philosophical one raised particularly by Pickering.[8,9] Is the study of leptons and quarks the only possible form of elementary particle physics, or is there a different direction which would not be so demanding of large accelerators and equipment? I take experimental elementary particle physics as it is practiced today, worldwide. I examine the effects of that practice on the education, careers, and research of the individual physicist.

II. THE UNITED STATES PARTICLE PHYSICS COMMUNITY

As a framework for this discussion I give an overview of the numbers of physicists, of the number of groups, and of federal funding. Table 1 gives the number of U.S. physicists in a 1981–1982 survey,[10] the numbers have not changed much since then.

At present the U.S. National Science Foundation (NSF) supports[11] about 60 grants in experimental particle physics at about 40 universities. The Foundation also supports the CESR electron-positron collider facility at Cornell University.

The U.S. Department of Energy (DOE) supports[12] about 110 tasks in experimental particle physics at about 60 universities and at the Lawrence Berkeley Laboratory (LBL) and the Argonne National Laboratory (ANL). The Department of Energy also supports the three large high-energy accelerator facilities at the Brookhaven National Laboratory (BNL), the Fermi National Accelerator Laboratory (FNAL), and the Stanford Linear Accelerator Center (SLAC).

The federal funding in fiscal year 1987 for elementary particle physics is given in Table 2. Operating and equipment funds tend to change slowly from year to year, but construction funds vary depending on what is being built that year.

The four accelerator facilities provide particle accelerators and colliders for the use of physicists funded by NSF and DOE as well as physicists from outside the United States. Conversely some physicists funded by NSF and DOE use accelerators and colliders in Western Europe and Japan. A few have used accelerators in the Soviet Union.

At present extensive information on the United States particle physics community is being gathered by a subpanel of the High Energy Physics Advisory Panel (HEPAP) to the Department of Energy. The subpanel is chaired by S. Treiman of Princeton University.

III. THE MARK II COLLABORATION AT THE SLAC LINEAR COLLIDER

A. The Collaboration

The present Mark II collaboration is typical of associations of experimenters who gather together to build and carry out large experiments at high-energy particle colliders. With 133 physicists it is of average size for such a collaboration: some present and projected collaborations are larger with 200 to 400 physicists, other collaborations are smaller.

The collaboration began to form in 1983 to carry out three intimately connected physics studies:

(i) The production physics of the Z^0 elementary particle through electron-positron annihilation,

$$e^- + e^+ \rightarrow Z^0$$

will be studied. The Z^0 which along with the $W^\pm$ carries the weak interaction, is the heaviest known elementary particle – 92 GeV/c^2.

(ii) The properties of the Z^0 will be measured.

(iii) The decay processes of the Z^0 into many different kinds of particles will be studied to measure the properties of known particles, to search for new particles, and to search for new interactions.

Table 3 gives the composition of the collaboration: 7 groups from universities and 5 groups from the LBL and SLAC national laboratories. This collaboration has a larger-than-average fraction of national laboratory members because of its history. The category Ph.D. staff excludes faculty but includes postdoctoral research associates and visitors. To see what these 133 physicists have done and are doing, I turn to the apparatus, Fig. 2.

B. The Apparatus

A modern, multipurpose, experimental apparatus at an accelerator or collider has three components:

(i) Particle Detectors: The part of the apparatus one sees directly, Figs. 1, 2, consists of interconnected particle detectors: drift chambers, magnets, electromagnetic shower detectors, muon detectors, and so forth. This part is huge[4] by ordinary physics apparatus standards, occupying 100 to 1000 m^3 of space and weighing thousands of tons.

(ii) Electronics: Not so obvious is the electronics which includes signal manipulation, data acquisition, data storage on tape or disc, and on-line monitoring of the apparatus performance. The number of channels of initial signals may number 100,000 or more.

(iii) Computer Codes: Large and complex computer codes are necessary for on-line and off-line use. These codes are needed to analyze the data and to monitor the performance of the particle detectors and electronics.

Those such as myself who did our doctoral research thirty years ago may tend to include only (i) particle detectors in our mental picture of the experiment, and we may be careless about (ii) electronics and (iii) computer codes. That is a very wrong picture. The electronics and computer codes associated with a modern particle experiment involve as much inventiveness, ingenuity, technical skill, and effort as is involved in the particle detectors; all three components are necessary.

In the Mark II collaboration as in most collaborations, individual parts of the apparatus are designed, built, maintained, and improved by a few physicists working together, usually less than ten, sometimes just one. I call this a working group to distinguish it from the institutional groups. As you will see next, a working group may or may not coincide with an institutional group.

The Mark II apparatus is a major rebuilding of an older detector. I list next the individual parts of the apparatus and the institutional groups from where the working group members came. Usually the working group began with the initial design involving new ideas which had to be laboratory-tested, prototypes, and learning new skills. The working group is now responsible for maintaining the apparatus and improving it if time and funds allow. An approximate list of most of the individual parts follows with the associated institutional groups listed in alphabetical order. There is no order of importance in this list. Only the principal involvements of each institutional group are given.

Main drift chamber: U. C. Santa Cruz, SLAC Group E, SLAC Group H.

Inner drift chamber: U. of Colorado, LBL, SLAC Group E.

Silicon strip vertex detector: U. of Hawaii, Johns Hopkins, LBL, U. C. Santa Cruz, SLAC Group C.

Collider background control systems: Johns Hopkins, SLAC Group A, SLAC Group C, SLAC Group E.

Scintillation counters: Cal. Tech.

Data Acquisition electronics: SLAC Group C, SLAC Group E, SLAC Group H.

On-line computers: SLAC Group C, SLAC Group E, SLAC Group H.

Data format computer codes: SLAC Group C.

Apparatus simulation codes: SLAC Group C, SLAC Group E.

Small angle particle detectors: Johns Hopkins, U. of Michigan.

End electromagnetic shower detectors: LBL.

Refurbished cylindrical electromagnetic shower detectors: Cal. Tech.

Refurbished muon detectors: Cal. Tech., Indiana U., U. of Michigan.

Magnet: SLAC Group C.

The working groups are voluntary associations. Individuals gather around a part because the technology interests them or because the part is important to their physics interest. For example, the working groups associated with the inner drift chamber and the silicon strip vertex detector are interested in particle decays at small distances. Sometimes a graduate student is in the same working group as her or his advisor, sometimes she or he go off on their own to a different group. The latter is an example of the freedom which can be provided in a large collaboration.

At the beginning of this section I listed the three components of an apparatus: particle detectors, electronics, and computer codes. Each individual in a working group is usually involved in at least two of these components. Sometimes the involvement is sequential, particle detector and electronics construction coming first, then computer code writing and testing. There is danger in this sequence; several large experiments have had poor initial performance because the computer codes were rudimentary or incomplete. In the MARK II collaboration a special effort is made to insure that graduate students and postdoctoral research associates are involved in at least two components.

Up to twenty years ago, most particle physics experiments except large bubble chamber collaborators, involved five or ten, sometimes up to fifteen physicists. These are the number of physicists involved in a working group in the Mark II. And the amount of innovation, prototype work, design, and construction carried out by a working group is of the same magnitude as that required for a single particle physics experiment of twenty or thirty years.

C. Physics Results

The SLAC Linear Collider is scheduled to begin producing Z^0 particles through electron-positron interactions in 1988. The Mark II apparatus is in place around the interaction point and the computer codes are ready. There are twenty or more different types of physics results being sought: the Z^0 mass, the shape of the Z^0 resonance, the dynamics of the Z^0 decay into the five different known quarks, the dynamics of the Z^0 decay into the three different known charged leptons, counting of the number of types of neutrinos, searches for new quarks, searches for new leptons, searches for supersymmetric particles, searches for the proposed Higgs particles, searches for new forces, and so forth.

Graduate students and Ph.D. level researchers are completely free to choose the physics that interests them. Important or fashionable topics will have several physicists, sometimes as much as five or ten. Unfashionable topics, obscure topics, long shots may occupy only a few physicists or just one. For example, I want to examine Z^0 decays into very few particles, looking for new phenomenon. No one else in the collaboration is interested in the methods I use, so I developed them by myself and will apply them to the data by myself. A graduate student is similarly free to work alone analyzing data, but she or he must have the right combination of confidence and foolhardiness.

When a number of physicists are interested in the same topic they may work together or separately. Most physicists like to work with a few others. But there are some who believe that the one who travels alone travels fastest. As in the physics community, inside the Mark II collaboration just about all the credit goes to the one who gets there first — if they are right!

If the experiment works as planned, it will produce more results and more important results than its equivalent of ten or twenty single purpose experiments. The combined analysis power in the particle detectors, electrons, and computer codes of the Mark II allow one to make discoveries of phenomenon which were not conceived when the apparatus was designed.

This is what happened when my colleague Gary Feldman and I discovered the tau lepton (τ) thirteen years ago with the Mark I apparatus at the SPEAR electron-positron collider. We found the unexpected reaction

$$e^- + e^+ \rightarrow e^\pm + \mu^\mp + \text{ missing energy}$$

with no other particles or photons produced. This reaction turned out to come from the intermediate step

$$e^- + e^+ \to \tau^- + \tau^+$$

The Mark I was the first multipurpose apparatus at a particle collider. With it we could identify e's and μ's, we could show no other particles or photons were produced, and we could show energy was missing. Although the Mark I apparatus was not designed to find the tau lepton, we found it.

IV. AN ASIDE ON SMALL PARTICLE PHYSICS EXPERIMENTS

This talk is about large particle physics experiments and large collaborations of physicists. I point out that not all particle physics experiments are large. Some accelerator experiments are carried out by half a dozen to half a hundred physicists. These are usually fixed target experiments. The smallest are often neutrino oscillation searches, particle decay studies, or beam dump experiments with relatively simple apparatus and a few parameters to measure.

Non-accelerator, non-reactor particle physics experiments are increasing in number. Examples are searches for dark matter, searches for magnetic monopoles, measurements of very high energy cosmic rays. Sometimes the entire experiment is carried out by a few physicists. On the other hand, some new underground experiments are approaching the large collider experiments in apparatus and collaboration size.

Information on the distribution of experimenters among various kinds and sizes of experiments is being gathered by the HEPAP subpanel mentioned at the end of Sec. II.

V. SOME ANSWERS AND SOME REMAINING PROBLEMS

At the beginning of the talk I listed five categories of questions and concerns about experimental particle physics: quality of research, independence in research, creativity in research, evaluation and recognition, and value in graduate education. Most of the questions have answers, many positive but some negative; and there are problems remaining. I discuss these answers and problems as they come to mind.

A. Quality of Research

Particle physics uses the full range of experimental physics skills. There are many opportunities for invention and development of new devices, new data analysis methods, and new computational methods. The quality of research will be good if the physicist is good. As in the rest of science, experiments can be wise or foolish, clever or dull, lucky or unlucky. The problem is how to decide what physicists in a large collaboration did fine research resulting in a wise or clever or lucky experiment, Sec. V.D.

B. Independence in Research

There are opportunities for independence in a wisely organized collaboration, even a very large one. Physicists can follow their interests in apparatus development and in particle physics within the scope of the experiment.

But the physicist's independence is limited when she or he wants to change the apparatus or change the experiment's parameters — change the energy for example. Then the collaboration has to be convinced, and if there are several experiments using the same particle collider, other collaborations may have to be convinced. Unfortunately the ability to convince may depend upon one's status in a collaboration and one's political skills. Of course this is true in all joint research work, but it is less important if an experiment is small and easily changed.

C. Creativity in Research

Paradoxically, large particle physics experiments support and encourage creativity in some people while repressing creativity in other people. Creativity is stimulated in people who like to invent and develop new kinds of apparatus. Here apparatus as defined in Sec. III.B means particle detectors, electronics, and computer codes. There is a large payoff for better apparatus performance at less cost in large experiments. Creativity is also stimulated in people who like to range over all the data acquired by a multipurpose experiment, who like to look for new phenomena, who like to test new ideas.

Creativity is repressed in some people partly by the rigidity of a large experiment, by the need to construct on a schedule, by the need to carry out long and tedious data handling and analysis. But more of the problem comes from the pressure to do what is conventional and fashionable. Some topics are in, some topics are out. Some null results will be quoted by every particle theorist,some beautiful measurement will be ignored by every particle theorist.

The question of where creativity, and also where independence, can thrive comes down to a question of personality. Some people don't mind the pressures of a large collaboration, some are even stimulated by going against the fashionable, by going against the conventional ideas of other collaboration members. Other people need quiet and gentle support for creativity and independence. Good physics and great physics comes from both kinds of people, but the first kind has an easier time doing physics in large collaborations.

D. Evaluation and Recognition for Research Staff and Faculty

The question is how to evaluate the work of a physicist in a collaboration of a hundred or more physicists. The answer has two parts. First, a department has to find out what she or he did and how well they did it. Second, a department has to judge the worth of what was done.

Finding out what was done and how well it was done requires phone calls to, and letters from, collaborators in the same working group or who are knowledgeable about the working group. If a physicist worked on the on-line data acquisition system, what do the other physicists in the collaboration who know about data acquisition say? Did the system work well, did it use modern technology, were there innovations? Is the physicist competent in both electronics and programming? Remember that such a system is as complicated or more complicated than an entire particle physics experiment of twenty or thirty years ago. Thus the same care has to be applied to evaluating a physicist's contribution to a part of a large particle physics experiment as is used to evaluate a non-particle physicist's contribution to an entire small experiment.

The second part of the answer is concerned with judging the worth of what was done. Here I have a quarrel with the standard of worth often used in experimental particle physics. As I discussed in Ref. 13, there is too much emphasis on the contributions of a physicist to the data analysis, to the final numbers coming out of the experiment, to the Physical Review Letter. But most of the heart and much of the soul of a large particle physics experiment lies elsewhere. They lie in the conceiving and design of the apparatus, in the construction of the apparatus, in the careful collection of data, in efficient use of the accelerator.

Ask the senior members of a collaboration, when they are relaxed and not writing letters of recommendation, about the post-doctoral research associates in the collaboration. They'll talk about a research associate who helped build a drift chamber and has the design ability of a mechanical engineer and the steady hands of a watchmaker. They'll talk about another who devised a new fast method for finding particle tracks. Those research associates are the treasures. Oh, they'll talk about wizards in data analysis, but only about the wizards.

The long time from the conception of a large particle physics experiment to its completion is becoming a problem in the evaluation of physicists beginning their postdoctoral careers. Some particle experiments from conception to first publication of results may require only three or four years, but others will require eight or ten years. In the latter situation how can research associates or nontenure faculty be evaluated in three or so years? Departments can evaluate what the physicist contributed to the design and construction of the apparatus if the physicist joins the collaboration early. But physicists who join after the completion of construction may not be able to exercise or demonstrate a range of experimental skills. There is no general solution to this time problem, and it is occurring in other fields: space physics and gravitational radiation detection physics are examples.

E. Value in Graduate Education

I left this concern for last because it encompasses many of the other concerns: independence, creativity, evaluation. Beasley and Jones[7] have described and discussed the issues. Under proper conditions a graduate student can carry out independent research within a large particle physics collaboration. The student can develop a variety of experimental skills and learn much in a fundamental field of physics. The student can have the opportunity to demonstrate ingenuity and creativity.

The proper conditions which must be provided by the faculty advisor and the collaboration are: freedom for a student to choose the apparatus work and physics; latitude for a student to make mistakes; time to explore new ideas and come to one's own conclusions. But one proper condition cannot always be provided: that the student can get all this done in three or four or five years. Construction lags, accelerators shut down, equipment breaks, and some experiments take eight or ten years even if nothing goes wrong.

At SLAC we sometimes solve the time problem by a graduate student working out physics results from a concluding large experiment, then helping with the initial construction of a new large experiment. Another solution is provided when a student joins an ongoing experiment as some of its equipment is being replaced and improved. But sometimes there is no solution to the time problem. There will be stages of very large and long particle physics experiments when the conditions for proper graduate research do not exist. Some students will turn to the small particle physics experiments described in Sec. IV. But the majority will want to do research at the highest energies, and that requires huge accelerators and large experiments.

VI. FINAL REMARKS

High energy and high intensity particle accelerators and particle colliders continue to be the main tools for studying elementary particle physics. The efficient and creative use of these huge facilities requires large experiments and large collaborations of experimenters. Graduate education and research in particle physics are immersed in that world for the foreseeable future. The main goal is to understand more about the physics of elementary particles and basic forces. But another goal is stimulating new ideas and inventions in particle accelerators and experiments, ideas and inventions which may reduce the size and complexity of our present particle physics tools.

Table 1. Number of U.S. particle physicists in 1981–1982 survey from Ref. 10. The numbers are rounded off to nearest 10.

Type of physicist	Experimenters	Theorists	Total
Graduate students with 3 or more years of completed graduate study	450	310	760
Ph.D. level physicists in universities	800	630	1430
Ph.D. level physicists in laboratories	530	110	640
Total	1780	1050	2830

Table 2. Federal funding for elementary particle physics in fiscal year 1987 in millions of dollars. The numbers are rounded off to the nearest million dollars.

Agency	Institutions	Operating and Equipment	Construction
NSF	Universities	31	
NSF	CESR	19	
DOE	Universities	80	
DOE	BNL	62	10
DOE	FNAL	156	16
DOE	SLAC	106	5
DOE	LBL and ANL	27	
DOE	SSC R&D	20	
DOE	Other	18	
Total		519	31

Table 3. The Mark II Collaboration as of February, 1988

Institution	Graduate	Ph.D. Staff students	Faculty	Total
Cal. Tech.	3	5	3	11
U. of Colorado	2	1	2	5
U. of Hawaii	1	2	2	5
Indiana U.	3	2	3	8
Johns Hopkins	2	3	2	7
LBL	2	10	2	14
U. of Michigan	3	3	2	8
U.C. Santa Cruz	5	9	4	18
SLAC Group A	0	1	2	3
SLAC Group C	8	12	2	22
SLAC Group E	4	9	3	16
SLAC Group H	3	10	3	16
Total	36	67	30	133

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FIGURE CAPTIONS

1. The UA1 detector at CERN used for the Nobel Prize discovery of the Z^0 and W particles that carry the weak force. Note the large size of the detector compared to the person standing at its lower right side.
2. The rebuilt Mark II detector at the SLAC Linear Collider.

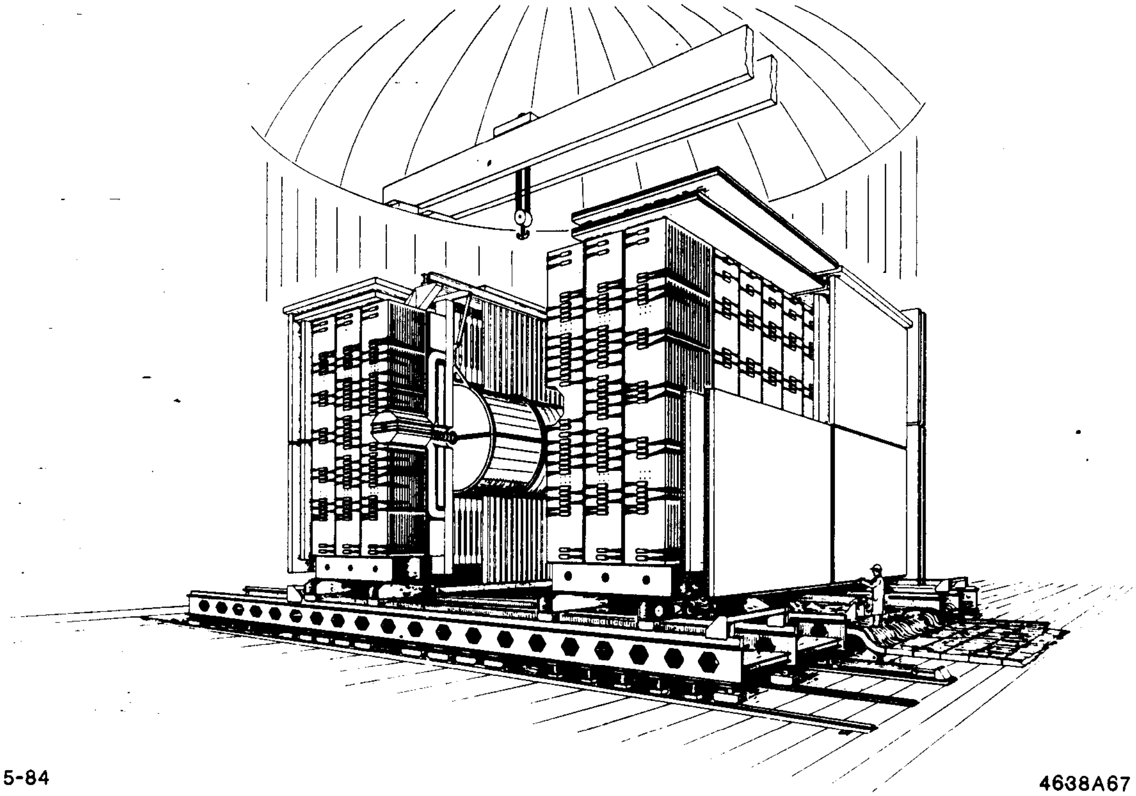

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Fig. 1

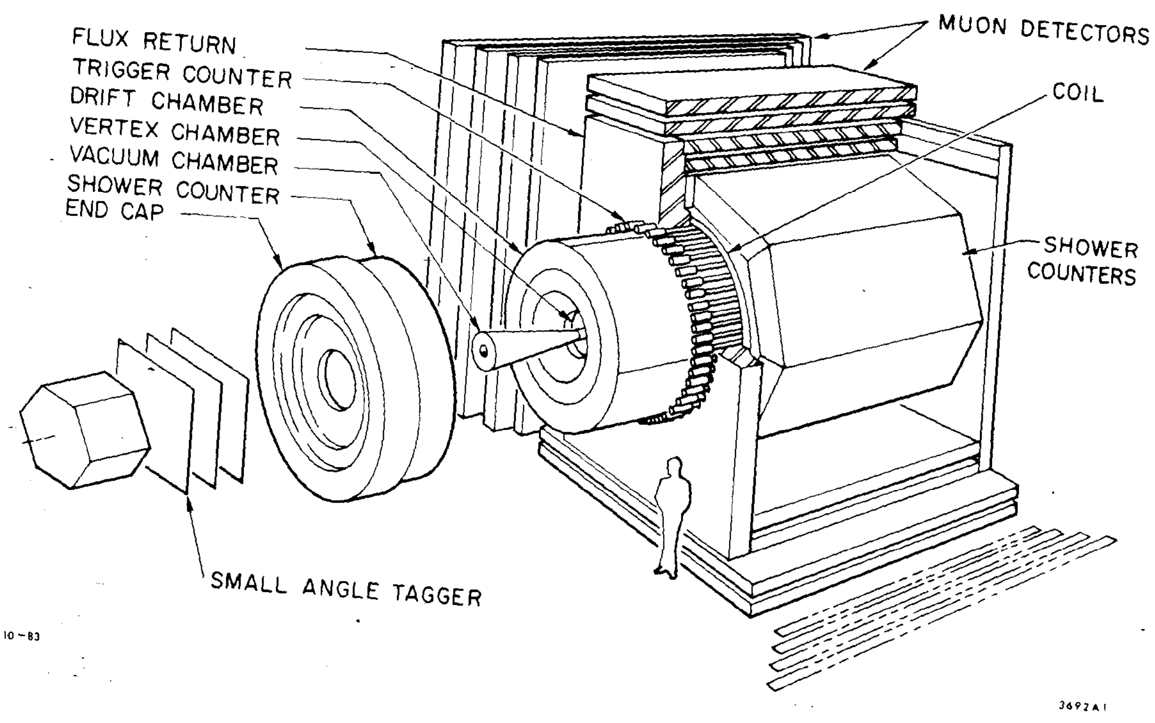
FLUX RETURN
TRIGGER COUNTER
DRIFT CHAMBER
VERTEX CHAMBER
VACUUM CHAMBER
SHOWER COUNTER
END CAP
MUON DETECTORS
COIL
SHOWER
COUNTERS
SMALL ANGLE TAGGER
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Fig. 2