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# New Directions in Elementary Particle Physics - $p\bar{p}$ from very low to very high energies*

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Abstract

The recent development of cooling techniques offers the possibility to obtain intense sources of antiprotons, stacking them as they are produced at a multi-GeV accelerator. The wide array of applications presently considered ranging from reactions at extremely low energy in the case of $p\bar{p}$ atoms, to reactions at hundreds of GeV in the case of head on collisions between protons and antiprotons accelerated at the same time in a super synchrotron, is reviewed. Special emphasis is put on the present CERN program, which will reach the data taking stage in 1981. The study of $p\bar{p}$ interactions is meant as an illustration of how new possibilities open new directions in Elementary Particle Physics, whether reaching energies hitherto much beyond accelerator possibilities, or developping new lower energy beams improving tremendously over those presently available.

## Foreword

There are many new promising directions in particle physics. At present, major new machines, projects or design studies are all aimed at extending experimental possibilities to still higher energies. Of particular interest are large storage rings using either protons (the Isabelle machine) or electrons and positrons (the LEP design study). A review of new directions in particle physics has thus to put emphasis on very high energy interactions. Yet, in the spirit of the LAMPF Workshop much attention should also be paid to interesting questions at low energies, where improvement in beams and techniques should offer new interesting possibilities. Rather than attempting listing all promising domains, it is deemed appropriate to merely select one particular type of interaction, namely $p\bar{p}$ physics, for which exciting new developments are within sight over a huge energy range, from very low to very high energies. Our discussion of new directions in $p\bar{p}$ physics is thus meant as that of a particularly interesting example of new directions in particle physics, whether considering an increase in equivalent laboratory energies by two orders of magnitude or an increase in intensity and resolution by three orders of magnitude for low energy beams. The new perspectives thus opened share many common points with perspectives in other domains of particle physics, whether considering hadron or lepton interactions.

## 1. Introduction

The study of $p\bar{p}$ interactions has long been both very interesting and very difficult. Secondary beams obtained from high energy accelerators offer but rather low intensities and often suffer from an overwhelming pion background. The available energy range is much limited, working energies being strongly correlated to that of the primary proton beam. This is illustrated by Figure 1, which gives the momentum spectrum of antiprotons produced in the forward direction with 23 GeV protons on a lead target.[1] At present, the situation is drastically changing with the advent of intense sources of antiprotons. Antiprotons, as those produced at the peak energy of Figure 1, can be stacked in an accumulator ring while the momentum spread of each incoming bunch is "cooled down". With antiprotons as originating from the CERN-PS (Figure 1) stacking of $\sim 10^{12}$ $\bar{p}$ can be achieved over a one day collection. Recent developments with cooling techniques have been very successful[2,3] and both CERN and Fermilab are now developping intense antiproton sources. The CERN Accumulator Ring AA should be an operating source of $\bar{p}$ by 1981.

The key interest in developping an intense source of antiprotons is to reach extremely high energies, accelerating at the same time protons and antiprotons in the CERN SPS (or the Fermilab doubler) and then holding the beams coasting, thus using the synchrotron as a storage ring.[4] This has recently been the object of research and development at CERN and at Fermilab. We shall refer to such a working mode as a collider. The CERN project will mature in 1981. It will be then possible to inject $6 \times 10^{11}$ antiprotons in the CERN SPS, together with the same load of protons. Both beams will be accelerated at the same time while circulating in opposite directions. They will be bunched and held coasting at 270 GeV[5]. Where bunches cross, head-on collisions will take place between protons and antiprotons. The center of mass energy, 540 GeV, will be nearly 9 times larger than the highest machine energy accessible at present, namely 63 GeV at the CERN-ISR. The expected luminosity is $10^{30}$ $cm^{-2}$ $sec^{-1}$ which we shall take as a working hypothesis while assessing physics outlook. A value of $2 \times 10^{29}$ say may however be more realistic at the start. Used in a collider, antiprotons are not expected to be particularily interesting as such. They are of particular interest insofar as they allow to reach very high center of mass energies without having to build a dedicated new machine.[6]

Reaching higher energies has always found much motivation in particle physics. It is however particularily pressing at present. Indeed, particle physics has been recently blessed with a series of important discoveries. In 1973, it was the discovery of weak interactions by neutral currents.[7] In 1974, it was the discovery of the new particles,[8] whose surprisingly narrow width is now known to be associated with their being built from a new kind of basic constituent: the charmed quark. In 1976, it was the discovery of the first charmed particle,[9] and by now all of the 6 expected pseudoscalar and vector mesons, together with some of the lower mass baryons have been found. In 1978, it was the discovery of parity violation in electron scattering,[10] thus confirming the universal character attributed to weak neutral current interactions. This already impressive list does not include many important discoveries made during the same period such as that of the $\tau$ lepton and $\Upsilon$ meson. Actually included are those which did not come as surprises. They all came as expected consequences in a theoretical framework where Weak and Electromagnetic interactions are combined in a unified theory.[11,12] Perfect agreement is indeed obtained with predictions from a particularily simple model of gauge theories, long proposed by S. Weinberg and A. Salam, which has now become the "standard" model[12]. Weak interactions are mediated by vector mesons $W^{\pm}$ (for charged current interactions) and $Z^0$ (for neutral current interactions) whose heavy masses are responsible for the quasi point like aspect, and small effective coupling, of Weak processes as probed so far. The Neutral Current is parametrized in terms of the charged Weak Current and the Electromagnetic current using one adjustable parameter $\sin^2\theta_W$. At present, all phenomenological analysis of neutral current processes agree on a common value of $\sin^2\theta_W \approx 0.22$,[13] from which one concludes that the masses of the W and Z mesons are 80 and 90 GeV, respectively.[12] Searching for these mesons is an extremely topical question. Even though their presence would not yet actually imply that the Standard Model is the correct approach,[14] it would be a key step along a line of research already rich in impressive successes.[8-12]

While the collider may a priori appears as uneconomical for such a search, with center of mass energy 6 times larger than threshold, its excess energy is a necessary asset. It appears that what actually matters for W or Z production is the energy available at the quark level as opposed to the nominal energy of the machine. This implies a reduction by typically a factor of 6. As further discussed later an energy of 500 GeV (or larger) appears therefore as the proper one for W and Z searches in hadron collisions.

We shall see later that $p\bar{p}$ collisions at such energies actually open a wide range of very interesting possibilities. It is however clear that W and Z search appears as of now as the key motivation for the present endeavors.

The Collider use of the $\bar{p}$ source illustrates how new beams can open up a wide new domain and new directions in elementary particle physics. There are however other uses which are also very interesting. At CERN the $\bar{p}$ source will also be used for injection in the ISR. In both cases (SPS and ISR) the $\bar{p}$ stacked at 3.5 GeV in the accumulator ring will be first accelerated in the PS up to 26 GeV and then sent either into the SPS or into the ISR. At ISR energies ($\sqrt{s}$ = 22 to 63 GeV) much information is already available about pp interactions. These interactions now seem well enough understood that predictions can be almost safely advanced about $\bar{p}p$ interactions at the same energy.[15] Nevertheless, checking them is very important and surprises could be met. In this energy range one expects relatively small but yet sizeable differences between pp and $p\bar{p}$ induced reactions. The extensive detectors now available at the ISR can be used just as well for the study of $p\bar{p}$ interactions. While is the case of the SPS the key point is to reach very high energies, in the case of the ISR it is to check in a powerful way present ideas about the proton structure.

The PS, used to accelerate $\bar{p}$ up to 26 GeV can also be used to decelerate them, in practice down to 0.6 GeV/c momentum, at which they could be transferred to a small storage ring with acceleration capability. A design study for this facility (LEAR) is presently under way and it is hoped that it could start operation by the end of 1982.[18] In this case the available momentum range will extend from $\simeq$ 0.1 GeV to $\simeq$ 2 GeV/c. The momentum spread will be reduced with cooling to $\Delta p/p \approx 10^{-4}$. The ring is conceived in order to be very versatile. It will provide an external $\bar{p}$ beam with average intensity at the level of $10^6$ $\bar{p}$/sec, with full purity and excellent duty cycle (this is referred to as the stretcher mode). The internal beam can also be used together with a gas jet target. LEAR can also be used as an "ortho" collider, stacking an $H^-$ beam together with the $\bar{p}$ beam. Both beams coast in the same direction so that one gets very low energy collision. It can finally be used as a standard Collider, stacking p and $\bar{p}$, with a center of mass energy range covering the charmonium region. Depending on the mode, the full $\bar{p}$ stack of the Accumulator ring ($6 \times 10^{11}$) or smaller batches, down to $10^9$ (the lower limit for safe operation of the PS), will be used. With LEAR one will explore low and medium $p\bar{p}$ physics with Gain at a typical level of $10^3$ as compared to what presently possible, beam purity notwithstanding of course since, in that case, the gain is just tremendous.

Low energy $p\bar{p}$ interactions is a domain of physics which is very topical, with a yet frustrating situation with baryonium and an hardly explored protonium physics. At stake in this case are interactions for which the fact that one deals with a particle-antiparticle system is the important feature. A wide and interesting program readily presents itself. The huge gains in intensity and resolution available with LEAR should change experimental conditions.

We shall review in turn the key physics questions in these 3 different energy domains, going from lowest to highest energies. In the latter case of $p\bar{p}$ physics in the SPS used as a collider, we shall then review some of the highly topical issues in particle physics. In the former case of $p\bar{p}$ physics at LEAR, while we shall discuss $p\bar{p}$ physics, which turns out to be particularily rich, it should be understood as a particular example of the type of new directions in particle physics which large improvements in low energy beams may open, whether dealing with $\bar{p}$, Kaon or pion beams.

This review focusses on physics issues and neither discusses the techniques used nor the proposed beam layouts in any detail. However, insofar as the multifacet role of the PS was mentioned on several occasions, it is deemed appropriate to show in Figure 2 how the different rings and beam lines are related to, or connect to, the PS in the present CERN projects.

2. Low energy $p\bar{p}$ physics

Intersecting issues at low energies are as follows:

i. The study of annihilation processes.

ii. The spectroscopy of baryonium states, here defined as $q\bar{q}q\bar{q}$ states.

iii. Quasinuclear states and their relation to baryonium.

iv. The spectroscopy of protonium.

v. Access to the whole Charmonium family.

We shall discuss them in turn, assessing each time new possibilities offered by LEAR which can:[16]

i. Produce a high intensity ($\sim 10^6$ $\bar{p}$/sec), high duty cycle, low energy (0.1 to 2 GeV/c) extracted beam.

ii. Allow storage ring operation with $10^9$ to $5 \times 10^{11}$ $\bar{p}$.

In the first mode of operation one obtains an important improvement over standard beams (Figure 1) which, pion contamination notwithstanding, are wide in dimension while poor in resolution. They require dense targets in order to give large enough stopping rates are hardly extend below 0.1 GeV/c.

Considering annihilation in flight no data exist below 0.2 GeV/c. Considering access to quasi nuclear states (defined here as $p\bar{p}$ system bound by nuclear forces). One cannot make use of the natural feeding process of capture in higher partial wave since stark effect transitions to the S states lead to rapid annihilation in a dense target.

Important gains allowed by LEAR used with an external beam can be summarized as done in Table 2.1.

Table 2.1

| Parameter | Gain |
|---|---|
| Beam purity | huge |
| Beam intensity (<0.5 GeV/c) | $10^3$ |
| Stop rate (gas target) | $10^6$ |
| Stop rate (dense target) | $>10^3$ |

At the same time the spectroscopy of $p\bar{p}$ bound states could be well studied with a gas jet. The energy resolution could be as high as $\Delta p/p \sim 10^{-5}$ using electron cooling in the ring, while standard spectrometer usually give $10^{-3}$. The energy resolution for X ray emission from the bound $p\bar{p}$ systems should be $10^3$ times better than what usually considered, making use of the Doppler shift of the X rays emitted by a system obtained through capture between a $\bar{p}$ and $H^-$ beams circulating in LEAR.

With such improvements in mind, we came back to the list of topic previously drafted.

$p\bar{p}$ Annihilation

The relatively small volume in which one could obtain a large stop rate ($10^6$ stopped $\bar{p}$ per sec in a 30 cm long hydrogen gas target) will allow for a detailed study of annihilation modes. All different modes could be determined. Feeding X rays could be detected in coincidence to determine the annihilation state. Of special interest is also annihilation into an electron-positron pair for which 300 events/hour are expected as compared with a present world statistics of 26. Practically all antiprotons of the extracted beam can be stopped since losses in the moderator due to annihilation in flight is at the 10% level at momentum less than 0.4 GeV/c.

Annihilation at low energy can be studied using degradation in matter and tagging with a spectrometer, or time of flight. The region from 0.2 GeV/c down to annihilation at rest (atomic capture) is unexplored. The relative importance of S Wave annihilation (with even parity modes such as $\pi^0\pi^0$ forbidden) is an issue.

Baryonium and $p\bar{p}$ interactions

$p\bar{p}$ interactions and in particular those of a two body type ($p\bar{p} \rightarrow n\bar{n}$, $\Lambda\bar{\Lambda}$ ....) could be studied with an external beam or with an internal gas jet target. In the latter case the high revolution frequency compensates for the thin target. An external $\bar{n}$ beam of high resolution (at the level of 10/sec) could be obtained.

A very important issue in $p\bar{p}$ interaction is that of Baryonium states: Mesonic states which are strongly coupled to the $N\bar{N}$ channel and relatively weakly to mesons. They should strongly affect $p\bar{p}$ interactions at low energy. Baryonium states are expected to occur extending dual model ideas,highly successful with the meson meson and meson-baryon sectors, to the baryon antibaryon sector. Their quark content is expected to be $q\bar{q}$ $q\bar{q}$. Evidence for their existence is important insofar as they appear in a wide range of theoretical models.[17] Their spectroscopy is of particular interest in view of its close connection with the color degree of freedom. We have somewhat arbitrarily define baryonium states as hadronic states with the spectroscopy of two quark - two antiquark system.[17,18] They can be classified according to the color of the diquark (di antiquark) systems. Configurations of the $3\bar{3}$ and $6\bar{6}$ types are typical of baryonium. They are expected to be weakly coupled to meson channels while the latter one are also expected to be weakly coupled to nucleon-antinucleon channels, the color symmetry or anti-symmetry of the diquark being conserved in the decay process. This could lead to narrow states below and near threshold ($3\bar{3}$) and narrow states even much above threshold ($6\bar{6}$) but which would be also hard to excite.

The experimental signature in $p\bar{p}(\bar{p}n)$ interaction should be clear. In particular annihilation in gas target with detection of feeding X rays can be use to study efficiently baryonium states below threshold. Above threshold important effects are expected analyzing charge exchange reactions and more generally Baryonium states should appear in formation experiments ($p\bar{p} \to X$) or in missing mass experiments ($p\bar{p} \to \Pi + X$) which could both be studied in great detail with an external beam or with a gas jet experiment.

Several narrow resonances coupled to the $N\bar{N}$ channel have been reported. Nevertheless we are at a frustrating time when higher statistics experiments fail to confirm them. The experimental situation which looked interesting is now somewhat negative.[19,20] This is illustrated by Figure 3 which shows as an example the smooth spectrum reported by the

Geneva-Lausanne Collaboration studying diffractive production of exotic mesons $\pi^+p \rightarrow (\pi^+p\bar{p})p$ at 50 GeV/c. It is presented as a particular example of recent negative higher statistics experiments.* Figure 3.a shows the $\pi^+p\bar{p}$ effective mass distribution and Figure 3.b shows the $p\bar{p}$ one. Also shown are the location of previously reported narrow resonances at M = 2.950 ($\Gamma$ < 32) in the former case, and M = 1.932 ($\Gamma \sim 9\pm4$), M = 2.020 ($\Gamma \sim 24\pm12$) and M = 2.204 ($\Gamma \sim 16\pm16$), in the latter one. Production cross sections at the level of $\sigma B \approx 25$nb would give 5 standard deviation effects.[19] This is a serious set back! Nevertheless this should motivate a thorough search, at a basic level, in the $p\bar{p}$ ($\bar{p}n$) reactions.[20,21]

Quasinuclear states

From the known NN potential one is lead to expect short range attraction in $N\bar{N}$ systems and this should result in resonances (quasinuclear Bound States) in the vicinity of threshold. Such states can be thought of as $(qqq)(\bar{q}\bar{q}\bar{q})$ system as opposed to the $(q\bar{q}q\bar{q})$ systems associated with baryonium. Nevertheless, and as previously said, the connection between baryonium states, as defined, and quasinuclear states may not be a sharp one at all. Exploring it should provide valuable clues about hadron interactions and quark structure. The expected spectroscopies of $N\bar{N}$ bound systems and of Baryonium states show different degeneracies and isospin splitting rules.[18]

A combined study of Baryonium states and Quasinuclear states could be done with stopped experiments and gas jet experiments. The latter providing typically $10^6$ interactions/second. Using a secondary $\bar{n}$ beam would provide important additional information. The use of a polarized

*LBL, BNL, Mt. Holyoke, in total cross section
Carnegie-Mellon, BNL, SMU, in baryon exchange reactions
Aachen-Bari-Bonn-CERN-Glasgow-Liverpool-Milan, in diffractive production

gas jet would help in spin-parity determination. The expected luminosity (at 0.5 GeV/c) should be of the order of $10^{27}$ for $10^{9}$ stored $\bar{p}$.

Protonium

Protons and antiprotons can produce Coulomb bound hydrogen-like atoms (protonium). At issue is the exploration of level shifts and widths associated with strong interactions in the low angular momentum states. Precision measurements can become a challenge to theoretical predictions.

Experimentation with stopped $\bar{p}$ in a gas target as possible with LEAR will offer an important advantage. Another promising approach is offered by $\bar{p}H^{-1}$ interactions in flight. Intense beams of protonium could be obtained from the straight sections of LEAR, typically $10^{4}$ atoms from $10^{9}$ $\bar{p}$ and $H^{-}$ stored in the LEAR ring. This seems enough since more important filling would raise some difficulties. The velocity of the produced atoms could be varied, changing the revolution frequency changing correspondingly the Doppler shifts for the X rays. The energy resolution should be at the level of $10^{-3}$. This represents a very significant improvement.*

High statistics experiment could be made with high $Z\bar{p}$ atoms.

Charmonium

The whole Charmonium family can be explored with LEAR used as a collider. Implementation of strong Cooling into LEAR (electron Cooling) could provide a monentum resolution of $\Delta p/p \simeq 10^{-4}$. The present family containing Vector meson and states fed by photon emission is shown in Figure 4. The frustrating situation with respect to the $\eta_c$,[22] which

*The observation of X rays associated with protonium is reported in E. Auld et al, Phys. Letters 77B, 454 (1978).

could be only hardly split from the $J/\psi$ calls for new investigations. The achieved mass resolution could be hopefully brought down to 10 Kev!

Invariant masses up to 4.4 GeV can be reached. Operation would require $10^{11}$ $\bar{p}$ stored for a long time, beam stability being achieved with electron cooling. The good resolution is important since the achieved luminosity will be at the level of $10^{29}$ and rates could be low in view of small branching ratios. This requires important machine development. Excitation of the $J/\psi$ with $e^+e^-$ decay would be at the level of one event/minute. Particular triggering modes (high $p_T$ $\gamma$ rays) could be used for other states.

In conclusion LEAR should be an excellent instrument for precision study of physics topics where many challenging questions can hardly be met otherwise. (The baryonium puzzle, the pseudoscalar puzzle in Charmonium spectroscopy....). This illustrates very well how a new facility can open up new directions even at energies where much activity has already taken place.

## 3. High energy $p\bar{p}$ physics

While $p\bar{p}$ interactions have already been much studied at Fermilab (SPS) energies, available information comes primarily from Track Chamber experiments.[23] They refer to general properties when it would be extremely interesting to have detailed information on low cross sections of high topical interest such as high mass lepton pair production, which probe rather directly the hadron structure. Some will come from new beams at Fermilab and at CERN. Using the source of $\bar{p}$ provided by an accumulator ring and accelerating the corresponding beam to 200-400 GeV would further result in great improvements. Luminosities of the order $10^{32}$ (with heavy target) and $10^{31}$ (with hydrogen target) could be achieved.

At issue are differences between pp and $p\bar{p}$ induced reactions, most of which can be presently predicted from models and do call for tests. They are sizeable, varying from a few mb difference at the total cross section level to an order of magnitude difference for high mass lepton pair production.

Such a use of a $\bar{p}$ source is however not considered at present for a variety of technical reasons. On the other hand, at the building stage at CERN, is a transfer beam line which will allow for the injection of $\bar{p}$ in the ISR. Achieved luminosities will be at the level of $1.5 \times 10^{29}$ for a standard intersection and $10^{30}$ for the superconducting low $\beta$ intersection presently developped. This opens up a new and very interesting program. While luminosities are not as high as those which could be obtained with accelerated beams, the energy range (22 to 63 GeV in Center of Mass energy) is very wide. While it is interesting to test for differences between pp and $p\bar{p}$ induced reactions, the energy behavior of these differences is actually the most important issue. The huge energy "lever arm" offered by the ISR is therefore a great asset.

Main issues are:[24]

i. The eventual common rise of total cross sections. The difference between the $p\bar{p}$ and pp total cross sections is expected to decrease from 2 to 0.6 mb as the $\bar{p}$ total cross section rises by 1.5 mb.

ii. An eventual common shape, the two diffraction peaks merging into each other. The pp differential cross section shows much structure.

iii. The energy behavior of the Real part of the forward amplitude, the value of which would allow for a interesting test of dispersion relations with total cross sections measured up to 500 GeV (section 4). Parameter $\rho$ is expected to rise to $\sim 0.1$ over the ISR energy range.

iv. The dominant features of particle production and of quantum number excitation. Comparison between pp and $\bar{p}p$ induced reactions would add much to present information.

v. High transverse momentum reactions, with their jet structure associated with hard scattering among hadron constituents. The respective role of different mechanisms and in particular that of quark quark scattering is presently under debate and, again, comparing data in pp and $p\bar{p}$ induced reaction should offer interesting clues. No large difference is anticipated according to present models.

vi. High mass lepton pair. In this case one checks hadron structure with the dominant Drell-Yan process being directly related to quark-(antiquark) distributions. Present knowledge about proton structure allows for predictions which can be put to a test. Expected ratios between $\bar{p}p$ and pp induced reactions vary from typically 2 at lower mass (5 GeV) to an order of magnitude at higher mass (10 GeV). While reaching higher masses still would lead in principle to much larger ratios, probing the proton structure is a much finer way, falling rates become prohibitives with an expected luminosity of $10^{30}$.

High mass lepton pair production also show effects which can be related to Quantum Chromodynamics as improving over the proton model.[25] This is in particular the case for their transverse momentum distribution and the rise of the associated multiplicity with transverse momentum. These effects are associated with gluon contributions and comparing pp and $p\bar{p}$ induced reactions would give important information on the respective role of different subprocesses ($q\bar{q} \rightarrow \gamma g$, $qg \rightarrow \gamma q$....). This is very important assessing the role of higher order terms.

At present the prospect of having $\bar{p}$ beams in the ISR by 1981 is prompting an extensive program which should cover all items listed above.[6]

## 4. Physics at Collider energies: Searching for the weak bosons

For reasons discussed in section 1, this is the driving terms in the whole $p\bar{p}$ program, and the main physics prospect according to which beam qualities have to be assessed is the Z and W hunt.

Figure 5 shows the cross sections for $W^{\pm}$ production in $p\bar{p}$ collisions and for $W^{+}$ in pp collision, as calculated as a function of the variable $\tau = M^2/s$, the relevant value (at $\sqrt{s}$ = 540 GeV) being of the order of 0.02. The calculation is based on quark antiquark annihilation, which, to the best of present knowledge, gives the dominant (and calculable) contribution (Figure 6-a). The searched for cross section is estimated to be $2 \times 10^{-33}$ $cm^2$ which, with an expected luminosity of $10^{30}$, corresponds to about 200 events per day. The cross section for $Z^0$ production is expected to be about a factor two lower than for $W^{\pm}$.[26] In this case, there is not such a simple relation between $\sigma$ and $\tau$ insofar as the coupling of the $Z^0$ depends on its mass through their being both dependent upon $\sin^2\theta_W$. Actually the scaling relation between $\sigma$ and $\tau$ is only an approximation, based on the standard quark model. Understanding ist apparent successes in the framework of Quantum Chromodynamics one is lead to expect scaling violation which should represent sizeable deviations when the range over which extrapolation has to be made is huge. (In the present case one has to go from $Q^2 \sim 10^2$ where lepton pair data exist to $Q^2 \sim 10^4$!). Nevertheless it turns out that expected deviations at $\tau \sim 0.01$ to 0.02 are minimal, while production cross sections are expected to be slightly above that of Figure 5 at small $\tau$ and below at larger $\tau$ values.[27] The detailed calculation of two years ago,[25] at a time when Quantum Chromodynamics had not its present currency, thus remain valid while now being far more soundly founded. QCD calculations also give higher order correction terms which may alter the result of a Drell-Yan calculation. As far as the order of magnitude is concern one may however safely use the Drell-Yan process to assess luminosity. The advantage of a high luminosity machine such as ISABELLE ($L \sim 10^{33}$) will have over the Collider ($L \sim 10^{30}$) is clear despite the fact that $p\bar{p}$ induced reactions are slightly more favorable. The relatively small cross-section difference between the $p\bar{p}$ and pp induced reactions is due to the fact that, at such low values of $\tau$, valence quarks no longer have an overwhelming role.

Any detailed theoretical discussion notwithstanding, the important property on which predictions have been based is the validity of scaling in high mass lepton pair production, which should hold to a good approximation. Scaling tests have enormously progressed over the past two years. The quantity $M^3 \frac{d\sigma}{dM}$ , where M is the mass of the produced lepton pair (Figure 6-b), is expected to depend only on $\tau = M^2/s$. This has now been beautifully verified.[28] Figure 7 shows the lepton pair differential cross section (production at rest in the Center of Mass) as measured at Fermilab and at ISR energies.[29] A single curve fits all energies as expected from scaling. At the same time comparison between $\pi^+$ and $\pi^-$ induced reactions at Fermilab and at CERN have clearly demonstrated the role of quarks in such a type of process. This is illustrated by Figure 8, which gives the ratio between the lepton pair yields as a function of mass for $\pi^+$ and $\pi^-$ induced reactions in platinum.* Insofar as the dominant contribution is the annihilation of a $\bar{d}(\bar{u})$ in the $\pi^+(\pi^-)$ with a d(u) quark in the nucleon, one expects the ratio to be 0.25 (0.37 actually when allowance is made for the role of sea quarks). On resonances however (J/ψ at 3.1 GeV and Υ at 9.5 GeV) one expects a ratio 1 since an isospin zero resonance is produced through strong interactions. Data meets expectations in a beautiful way.

Expectations which had to be based on some optimism in 1977[26,30] are now far more firmly founded. If the W and Z exist as expected in unified gauge theories, they should be produced with a reasonable cross section at the $p\bar{p}$ Collider and at Isabelle (Figure 5). At the same time taking one event per day per GeV as an experimental limit, one may say that the lepton pair continuum could be followed up to masses of the order of 20 GeV at $L \sim 10^{30}$, while new narrow resonances (referred to as "onia" in the present vernacular) could be seen through their lepton pair decay mode up to masses of the order of 30 GeV. The latter value is based on present cross section measurements at Fermilab and at the CERN.ISR, assuming a total production cross section decreasing as $M^{-2}$ and a fixed branching ratio into lepton pairs,[30] assumptions which are probably on the optimistic side. The relevant values of τ are small, and pp and $p\bar{p}$ induced reactions should have comparable yields.

Coming back to the production of the weak bosons, one should not belittle difficulties. For reasons discussed later early search may have to be limited to leptonic modes only. With 3 quark colors this

*NA3 Collaboration at CERN, as presented at the EPS Conference on High Energy Physics, Geneva (1979).

corresponds for each leptonic mode to branching ratios of about 8% for W decay and slightly over 3% only for Z decay. In the latter case one has of course a very clear signature, with a pair of large transverse momentum leptons. At the same time, the rapidity distribution of the produced bosons is expected to be rather wide as quarks of much different momenta can be involved. This therefore calls for extensive and highly sophisticated detectors and a luminosity as high as expected. Looking for Z through their $e^+e^-$(or $\mu^+\mu^-$) decay mode, one is at the level of 3 events per day with a luminosity of $10^{30}$. This is certainly difficult! Yet the W and Z hunt remains clearly the main motivation behind the $p\bar{p}$ Collider.

## 5. Hadron physics at Collider energies

Physics at Collider energies has already been reviewed many times and in particular in connection with the Isabelle project.[31] The main topics usually discussed are:

i. The intermediate bosons.

ii. The extension to much higher energies of the study of jet phenomena and lepton pair production.

iii. The extension to much higher rapidity and the possible failure of "lns physics".[32] Cosmic ray results actually hint at something new at $E \gtrsim 100$ TeV[33,34] when 540 GeV in the Center of Mass corresponds to an equivalent laboratory energy of 150 TeV.

iv. Find unexpected things as an entirely new range of energy is opened to experimentation.

In all cases recent data have brought support for great expectations. With respect to point (i), the conclusion was that rates are probably large enough for the $p\bar{p}$ Collider and certainly large enough for Isabelle. The main problems arise from background which may be prohibitive for many decay modes. We shall come back to this after discussing high $p_T$ hadron production.

With respect to point (ii) we already discussed lepton pair production. At the $p\bar{p}$ Collider, limited luminosities will restrict the accessible mass range to a domain which will have been thoroughly covered by PETRA and PEP.* Prospects for finding new narrow states through their $\mu^+\mu^-(e^+e^-)$ decay mode are therefore low. It remains that the study of the production

*Recent results from PETRA exclude a toponium state below 32 GeV.

mechanisms is in any case also very interesting. With its much higher luminosity Isabelle will be able to extend significantly the probed mass range beyond that covered by PETRA and PEP. Insofar as rates are concerned Isabelle compares actually well with LEP. Luminosities and center of mass energies (at the quark level in the case of hadron Collisions) are comparable. Nevertheless one trades high counting rates and versatility for a huge background! This also applies to point (iv). Success is a matter of luck and ingenuity, as usual. We now turn to a discussion of jet phenomena point (ii) and of "ln s physics" point (iii).

Hadronic Jets

Jets are a prominent feature of high energy hadronic interactions. They are associated with the hard scattering of hadron consituents and their study is of high topical interest.[35] The analysis of jet formation and fragmentation, at the CERN.ISR and at Fermilab, has provided a very firm basis for the parton approach. At the same time the development of Quantum Chromodynamics[25] has provided a theoretical framework with which these results can be extrapolated to much higher energies. One is lead to expect rather large cross sections at Collider energies. Figure 9 shows the cross section for jet production in $p\bar{p}$ Collisions at $\sqrt{s}$ = 540 GeV (Collider energy), as calculated in Quantum Chromodynamics.[36] One expects one 20 GeV jet every few seconds! With the luminosity of Isabelle the corresponding rate should be overwhelming. In the parton approach, hadronic jets correspond to the manifestation of quarks once confinement has imposed the production of hadrons. Each hadron takes on the average a fixed faction of the quark momentum (scaling) while having but a limited transverse momentum with respect to the jet axis. These two properties are illustrated by the data presented in Figure 10. Figure 10-a shows a scaling test. The observation of a secondary particle at high $p_T$ (trigger particle) signals a jet. Particles are then also observed on the away side as fragments of the other jet, the two jets originating from the two constituents having experienced a hard collision. Shown is the distribution in a variable usually called $X_e$, the fraction of the trigger particle transverse momentum compensated by any hadron in the away side jet. The distribution does not depend on the trigger momentum. What matters is only the fraction of the trigger particle momentum which is compensated, a quantity proportional to the jet momentum. Figure 10-b shows the mean value of the transverse momentum which particles have with respect to the jet axis. It does not vary as the jet momentum changes. While these data (and many others) leave no doubt about the jet structure,[38] Quantum Chromodynamics leads to very sizeable deviations as very high energies and very high transverse momenta are involved. Jets should initially fragment through the branching of gluons turning into quark antiquark pair.[39] As a result the mean transverse momentum of the observed hadrons with respect to the reconstructed jet axis is expected to grow and sizeable departure from the coplanarity structure of the two wide angle jets should appear. While a two jet configuration is expected to eventually dominate asymptotically, the asymptotic approach is only logarithmic and 3 jet (or more complicated) configuration could occur with appreciable probabilities. Expected rates are such (Figure 9) that $p\bar{p}$ physics or Collider energies opens a wide new testing ground for hadron interactions as predicted in Quantum Chromodynamics. More generally speaking the collider is an ideal instrument studying hadron interactions at the constituent level and for checking specific effects which are presently expected.

Jets of transverse momenta up to 60 - 70 GeV should probably be reached with a luminosity of $10^{30}$. No large differences are expected between pp and $p\bar{p}$ induced reactions. The annihilation term, whereby a quark and an antiquark annihilate into a gluon is stronger in the $p\bar{p}$ case as it involves the valence antiquark in the antiproton. Nevertheless its contribution remains small (at the 1% level) and no strong difference result. This term remains of particular interest though to the extent that it contributes equally to the production of new flavors.

Our discussion of jet physics at Collider energies may look optimistic insofar as no clear test of Quantum Chromodynamics is yet available at ISR energies! Nevertheless the energy dependence of all relevant results hint at the emergence of QCD basic processes as $p_T$ increases.[36] This is particularily clear with the recent ISR data on inclusive $\pi^0$ production at very high $p_T$ shown in Figure 11. The observed distributions neatly departs from above from the extrapolation of the lower $p_T$ behavior (dashed curves). The rate and energy dependence meets what is expected from quark and gluon scattering becoming eventually dominant.

The present analysis of high $p_T$ phenomena leads to very interesting results and to a deeper understanding of hadronic interactions. Simplicity seems to occur at very short distances (or very high $p_T$) which can be reached only a very high energy. The $p\bar{p}$ Collider offers the energy extension how needed beyond the ISR energy range in order to actually test predictions from Quantum Chromodynamics.

The clear drawback, which brings us back to point (i), is that jet cross section is so high that the (dominant) two jet decay mode of the W and Z will probably be below background. In principle the simplest way is to look at the Jacobian peak, the transverse momentum distribution of jets originating from a resonance having a sharp peak at $p_T = M/2$. The peak resulting from the two jet decay of the W and Z is however expected to be over one order of magnitude below the hadronic jet background and could be even lower if a rather wide transverse momentum distribution in W (and Z) production erodes the Jacobian peak in an important way. This is why searches have so much to relly on leptonic modes even though they have relatively low branching ratios. Searches based on Hadronic jets should have to involve momentum and angular correlations or select special jets like charmed jets though the production of high $p_T$ leptons. This will probably be difficult.

While $Z^0$ search is in principle rather simple, with its clear $e^+e^-(\mu^+\mu^-)$ signature, W search is more involved. It will require a high $p_T$ lepton (at $p_T \sim M/2$) with an unbalanced momentum (with evidence for an absence of jet on the away side). Even though specific angular correlations can be used working at the level of a few events a day (at $L \simeq 10^{30}$) will raise problems. W search at low luminosity is difficult.

Dominant Hadronic Interactions

We now turn to point (iii). The discovery of rising cross sections has shaken the idea of a simple asymptotic behavior which would have prevailed for $s/m^2 >> 1$, where m is the proton mass. While the observed rise is amenable to theoretical models, any asymptotic behavior now implies $\ln s/m^2 >> 1$.[40] This becomes then out of reach at the ISR, but reaching 150 TeV will extend significantly the range over which present models can be probed. The total $p\bar{p}$ cross section (which is expected to be very close to the pp total cross section) should be 63 mb at 150 TeV. Figure 12 gives the total pp cross section as measured up to top ISR energies and extrapolated on the basis of the measurement of the real part of the forward amplitude. Through the extrapolation (dashed part of the curve) one cannot practically distinguish between the pp and $p\bar{p}$ cross sections. It is important to verify such a rise. As previously mentioned total cross section results for $p\bar{p}$ could be combined with measurements of the real part at the ISR for a check of dispersion relation (or of consistency). At ISR energies the rise of the cross section does not correspond to a change in the overall shape of the proton. The shape does not change while dimensions are scaled up according to ln s. This is referred to as geometrical scaling. The proton is even not fully black at the center and becomes rather transparent at 1 f. The relative transparency of the proton when so many reaction channels are available is puzzling. The continuation (or not) of such a behavior is an important issue which measurements of elastic scattering at the collider should quickly settle.

The key feature of dominant production processes at ISR energy is the impressive stability of the longitudinal phase space density for particle production. As the energy increases, the available rapidity range increases (logarithmically) but the rapidity density and density fluctuations remain the same.[41] This is illustrated by Figure 13-a, which present a by now classical result at the ISR, namely the rapidity correlation between two charged particles. The important feature is the ridge along the main diagonal which stands for the importance of short range correlations. Observing a particle makes it more likely to observe another one at similar rapidity (as they originate from the same cluster). Changing energy from 22 to 62 GeV hardly change neither the overall pattern nor the value of the correlation.

Such a stability is however only an approximation and a closer look indicates some change. This is shown in Figure 13-b, which shows the behavior of the rapidity density (for slow particles in the center of mass). It slightly rises with energy and amounts to a 30% effect over the ISR energy range.[42]

All these key features: slow rise of the total cross section, slow shrinking of the forward peak, stability of the rapidity distribution of the produced particles.... characterize what is referred to as "ln s physics".

Does it continue? Such a question calls for an important extension of the rapidity range which increases as ln s as opposed to the energy proper. At top Collider energy one reaches $\Delta y \approx 13$ which is a significant improvement over the 8 units available at the ISR. Checking extrapolations based on present models, and discovering departures, should be a relatively easy matter at collider energies. The expected luminosity is more than enough. The behavior of the differential cross section at medium transfer ($|t| \approx 3 - 4$ $(GeV/c)^2$), where it practically does not change over the ISR energy range, could in particular be easily determined.

There are however many hints from Cosmic Ray results that things should change far more than expected from model extrapolation, a very significant change occuring at $E \sim 100$ TeV.[32] This has been known for some time and many new and more precise results have more recently confirm it. Most of the new results come from emulsion chambers and, in particular, from the Brazil-Japan collaboration at M$^t$ Chatalcaya.[33] As a first approximation, it seems that ln s physics, as presently known, continues.* Nevertheless, at $E \sim 100$ TeV, two classes of events seem to appear with roughly equal cross sections. One of them can be considered as the continuation of what presently known. The other one, which gradually gains importance is characterized by a higher mean multiplicity, fewer fast particles (in the Center of Mass system) and larger transverse momenta. While the production of low mass hadronic clusters ($M \lesssim 2$ GeV) is also typical of present ln s physics, higher mass leading clusters with $M \sim 20$ GeV seem to appear in the second case. Such a set of properties

*Important new results should also soon come from the Tien-Shan experiment.

should be easily amenable to thorough tests at Collider energies. The expected correlations are such that triggering on each type of configuration should be possible.[43] Figure 14 gives the inclusive distributions associated with each class of events, thus showing their apparently clear difference. The emergence of a new set of configuration could be associated with a change in the proton shape. There are serious indications that present models do not include the proper asymptotic property. More dramatic however in cosmic ray results is the occurrence of very peculiar types of events, the frequency of which calls for sizeable cross sections. We shall discuss here only one of them, namely the very spectacular "Centauro" events, 4 of which have been analyzed so far.[33] A Centauro event is characterized by a large multiplicity (of the order of 100) with no $\pi^0$. The mean transverse momentum is rather high, namely 1.7 ± 0.7 GeV/c, as compared with the value of 0.35 GeV/c typical of hadronic interactions. The most obvious interpretation is terms of fragmenting heavy nuclei, is ruled out by the atmospheric depth at which they are still found. One may entertain the idea that they correspond to an hitherto unknown type of hadronic interaction. They could then be search for with great expectation at Collider energies. It may however seem fustrating that the estimated energy for all of the Centauro events is of the order of 1000 TeV,[44] thus much above the accessible range, even at Isabelle. Nevertheless, about 10 "mini" centauro have recently been reported.[33] They have a lower multiplicity ($\sim$ 15) and also show a surprising absence of $\pi^0$. They have been found in the 50-500 TeV range and should then be seen at Collider energy. However the absence of

$\pi^0$ is so surprising that rather than considering Centauros as corresponding to a new kind of hadronic interactions, one may look at them as suggesting a new kind of nuclear matter. As discussed by Björken and Mclerran,[45] nuclear matter could become[37] tightly bound together in the colour field of a free quark. This "quark-matter" could explode into nuclear constituents in a Centauro event. This would meet the reported properties but at the expense of bold hypotheses. In this case Centauro events should not occur at collider energies but the prospect of seeing free quark should be high. Quarks originating from very high energy interactions should not have time to agglomerate nucleons as they cross the beam pipe and detector material. They should be searched for directly as fractionally charged particles.

## 6. The $p\bar{p}$ Collider program

Experimentation with $\bar{p}$ in the SPS should start in 1981. Each beam ($p$ and $\bar{p}$) will consist of 6 bunches of $\sim 10^{11}$ particles. The beam energy will go up to 270 GeV with an expected luminosity in excess of $2 \times 10^{29}$ and aimed at $10^{30}$ $cm^{-2}$ $sec^{-1}$. There are already 5 approved experiments.[46] Two are involved with major detectors looking at Z, W and almost anything. They will each occupy an interaction area. One of them (C. Rubbia et al) will be in LSS5 (UA1). The other one (P. Darrivlat et al) will be in LSS4 (UA2).[47] Beside these two major experiments there are 3 smaller ones. One is a measurement of elastic scattering (and total cross section). This experiment (G. Mathiae et al), UA4,will be installed together with UA2. Another one is a monopole search experiment (P. Musset et al) UA3. This experiment will be installed together with UA1. The last one is a streamer chamber experiment (J. Rushbrook et al) aimed at quickly looking at possible peculiar configurations while testing how key features of ln s physics continue or not to higher energy. This experiment, UA5, will be installed either with UA1 or UA2, preceeding the completion of either one of these detectors.

Experiment UA1 uses a practically $4\pi$ detector with capability for everything. The Z and W will be searched for in $e^+e^-$ pairs and $e^\pm$ missing energy. The detector sonsists of drift chamber surrounded by a Calorimeter (EM energy) surrounded by a magnet (Dipole). Experiment UA2 has no magnetic field but uses precise calorimetry for $e^+e^-$ detection. Its aims are similar to these of UA1.

With no special triggering, the number of events should be $\sim 60{,}000$ per second. Half of the energy should go inside the vacuum pipe.

## 7. Conclusions

The unification of Weak and Electromagnetic interactions, as possible in the framework of gauge theories, and the quark structure of hadrons with the theoretical framework provided by Quantum Chromodynamics are clearly the most topical questions in particle physics. While a tremendous amount of progress was possible during the past few years, many challenging questions still exist. We saw that in both cases $p\bar{p}$ interactions as now considered following the development of intense sources of antiprotons should provide many of the looked for answers. The existence of the weak bosons should be tested. Jet dynamics very relevant to quark and gluon interaction should be probed. While topical questions in hadron physics call for experimentation at much higher energies, we also saw how very important ones also present themselves at low energy. The detailed study of $p\bar{p}$ annihilation, of baryonium states, if they exist as expected, and of Charmonium states, is also very important to the understanding of hadronic interactions. The new directions in particle physics opened by $p\bar{p}$ interaction are particularily rich and extend over a tremendous energy range. They illustrate very well the progress which one can anticipate with new beams, whether at very high or low energies.

Acknowledgement

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2. Ingenious techniques have been developped to reduce the momentum spread of stored particle beams. This is referred to as cooling. Two techniques are followed: Electron cooling, with pioneering work developped in Novosibirsk, and stochastic cooling, with pioneering work developped at the CERN-ISR. For a discussion of the implementation of these techniques constructing an intense antiproton source see F. Bonandi ISR 2-12 and J. Cronin ISR 2-13, CERN reports (1977).

3. Following successful developments with ICE (intermediate cooling experiment) at CERN, stochastic cooling has been chosen for the development of the CERN source. It has the advantage to operate at collection momentum namely 3.5 GeV/c, whereas electron cooling which has the advantage of being more rapid requires deceleration to a few hundreds of MeV so that the $\bar{p}$ and electron velocities match. For a discussion of the theory of stochastic cooling and a presentation of the ICE results see G. Petrucci, S. Van der Meer *et al.*, Physics Reports, to be published (1979).

4. The use of proton synchrotrons as Colliders has been much discussed at CERN and at Fermilab since 1976. Several specialized workshops have been held, Aspen (1977), CERN (1977) . The role of C. Rubbia in pushing the idea ahead has been of key importance.

5. While the CERN machine usually operates at 400 GeV as an accelerator, holding the beams coasting implies a sustained magnetic field which cannot be increased beyond that corresponding to 270 GeV/c beam momentum. At Fermilab, the main ring probably does not meet the extra qualities required for operation as a collider with a luminosity close to $10^{30}$ (see Ref. 2). The Dobbler, when completed, should meet them successfully. In this case operation as a collider could readily be extended to ~ 2 TeV Center of Mass energy.
6. The $p\bar{p}$ program may appear as a serious contender to Isabelle, a proton-proton colliding beam machine with 400 GeV beam energy (BNL 50698 (1977)). Big surprises notwithstanding, one does not expect prominent differences between $p\bar{p}$ and pp interactions at 500 GeV. However if ingenuity (and some money!) buys the energy, money (for a dedicated machine) buys the luminosity. Indeed the expected luminosity at Isabelle is 3 orders of magnitude larger than that expected for the $p\bar{p}$ Collider. Insofar as $Z^0$ production (first on the hunting list) correspond to a cross section of the order of $10^{-33}$ $cm^2$, and that some of its decay modes only could be used for detection, luminosity is of a key importance.
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12. For a review of unified gauge theories see: S. Abers and B. W. Lee, Physics Reports 9C, 1 (1973); Gauge Theories and Neutrino Physics, Physics Reports reprint Volume 2 (1978).

13. F. Dydak, Rapporteur talk, EPS Conference, Geneva (1979).

14. Testing gauge theories of weak electromagnetic interactions also implies the analysis of the direct coupling among W's and Z's and that of the interactions of Higgs mesons. This requires a dedicated $e^+e^-$ colliding beam machine with $\sim$100 GeV beam energy such as LEP. For detailed discussion of the corresponding physics, see CERN 79-01.

15. For a discussion of $p\bar{p}$ physics at ISR energies see ISR 2-9 and ISR 2-16, CERN reports (1977); G. Giacomelli et al., Physics at the CERN-ISR, Physics Reports, to be published (1979).

16. U. Gastaldi, K. Kilian and G. Plass "A low energy antiproton facility at CERN" CERN/PSCC/79-17.

Our discussion of low energy $p\bar{p}$ physics is actually based on this review which should be consulted for a more detailed discussion and references to original works.

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Phys. Rev. D17, 1444 (1978); H. M. Chan, Tokyo Conference
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19. L. Montanet, Proc. 5th International Conference on
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20. G. Kienzle, Rapporteur talk, EPS Conference, Geneva

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22. M. Davier Rapporteur talk, EPS Conference, Geneva

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29. Fermilab data are from J. K. Yoh et al., Phys. Rev. Lett. 41, 684 (1978); ISR data are from experiment 806 (28 GeV) and 209 (62 GeV).

30. This is domain where the much higher luminosity of Isabelle becomes a prominent asset. Lepton pairs up to 100 GeV should probably be reached and "onia" well above 100 GeV could be detected.

31. BNL 50648 (1977). Big surprises notwithstanding, one does not expect prominent differences between pp and $p\bar{p}$ interactions at 500 GeV.

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## Figure Captions

Fig. 1. Momentum spectrum of antiprotons produced in the forward direction with 23 GeV/c protons on a lead target. The number of $\bar{p}$ per interacting proton is normalized to 1 msr and $\Delta p/p = 1\%$. The distribution peaks at 3.5 GeV/c which corresponds to production at rest in the CM system. The higher energy part of the curve is measured. The lower energy part is obtained by kinematic reflection.

Fig. 2. The PS as a $\bar{p}$ generator and a proton and antiproton accelerator (or decelerator) Beam lines feeding the ISR and the SPS are shown. The locations of the Accumular ring (AA), LEAR and the ICE ring are indicated. AA stands for antiproton accumulator.

Fig. 3. Invariant mass distributions for $\pi^{+}p\bar{p}$ and $p\bar{p}$ system produced in the reaction $\pi p \rightarrow (\pi p\bar{p})p$ at 50 GeV. Data from the Geneva-Lausanne Collaboration. Previously reported narrow peaks at 1932, 2020, 2204 and 2950 MeV do not appear in such a diffractive production experiment.

Fig. 4. Total cross section for $W^{\pm}$ production in $p\bar{p}$ (solid line) and pp (dashed line) collisions, as calculated in the standard parton model. At $\tau = 0.02$, one does not expect much change when taking scaling violation into account.

Fig. 5. The spectroscopy of Charmonium. Solid lines indicate well established states. Dashed lines indicate states which are still in doubt, not yet found while expected, or found but with conflicting pieces of evidence.

Fig. 6. 6 - a Drell-Yan process for W(Z) production

6 - b Drell-Yan process for high mass lepton pair production

Fig. 7. Lepton pair production cross section as a function of the scaling variable $\tau = M^2/S$. Data from Experiment 288 at Fermilab, 209 and 806 at the CERN-ISR.

Fig. 8. Ratio of $\pi^+$ to $\pi^-$ induced reactions for lepton pair production off a heavy nucleus, as a function of the mass of the lepton pair. Data from experiment NA3 at CERN.

Fig. 9. Expected Jet cross sections at high $p_T$ as calculated according to Quantum Chromodynamics. The solid and dashed lines correspond to top collider and top ISR energies, respectively. Yields in pp and $\bar{p}p$ induced reactions are expected to be similar.

Fig. 10. Jet fragmentation

10-a Scaling in jet fragmentation. The number of away side particles for fixed values of $X_e$ - The fraction of the transverse momentum of the trigger particle $p_T$ compensated by each secondary - is shown as a function of $p_T$. The data are normalized to $X_e < 0.3$. Data from the Athens-Brookhaven-CERN-Syracuse Collaboration at the ISR.

10-b Mean transverse momentum of jet fragments with respect to the reconstructed jet axis, for different trigger momenta. Data from the CERN-Columbia-Oxford-Rockefeller Collaboration at the ISR.

Fig. 11. Inclusive $\pi^0$ yields at very high $p_T$ at 3 different ISR energies.

The dashed curve correspond to a precise ( and theoretically motivated) fit at lower $p_T$. Data from the CERN-Columbia-Oxford-Rockefeller Collaboration at the ISR.

Fig. 12. The actual and extrapolated value (practically common to pp and $p\bar{p}$) up to 150 TeV, together with some Cosmic Ray data. The extrapolation is based on the results of the CERN-Rome experiment. The Cosmic Ray points are from the Maryland and Tien-Shan experiments.

Fig. 13. The stability of distributions in longitudinal phase space

13-a. Two particle correlations among changed particles. The short range correlation can be translated into the production of clusters with on the average 2 charged particles. Data from the Pisa-Stony Brook Collaboration. L. Foa, Ref. 41.

13-b. The rise of the particle density in the central region. Data from the British-Scandinavian-MIT Collaboration.

Fig. 14. Inclusive distribution for the two classes of events appearing above 100 TeV. Data from the Brazil-Japan Collaboration. See Ref. 34.

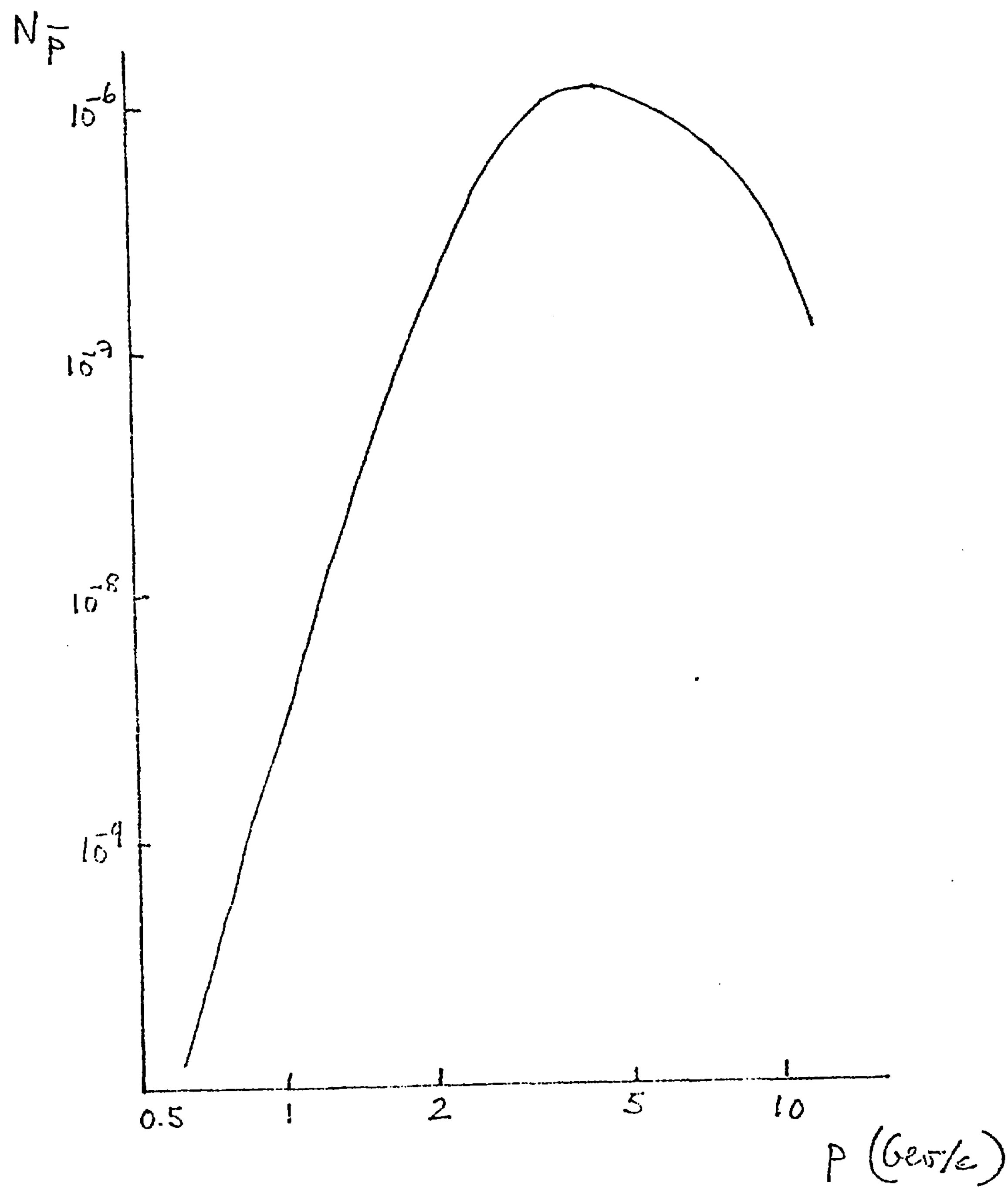
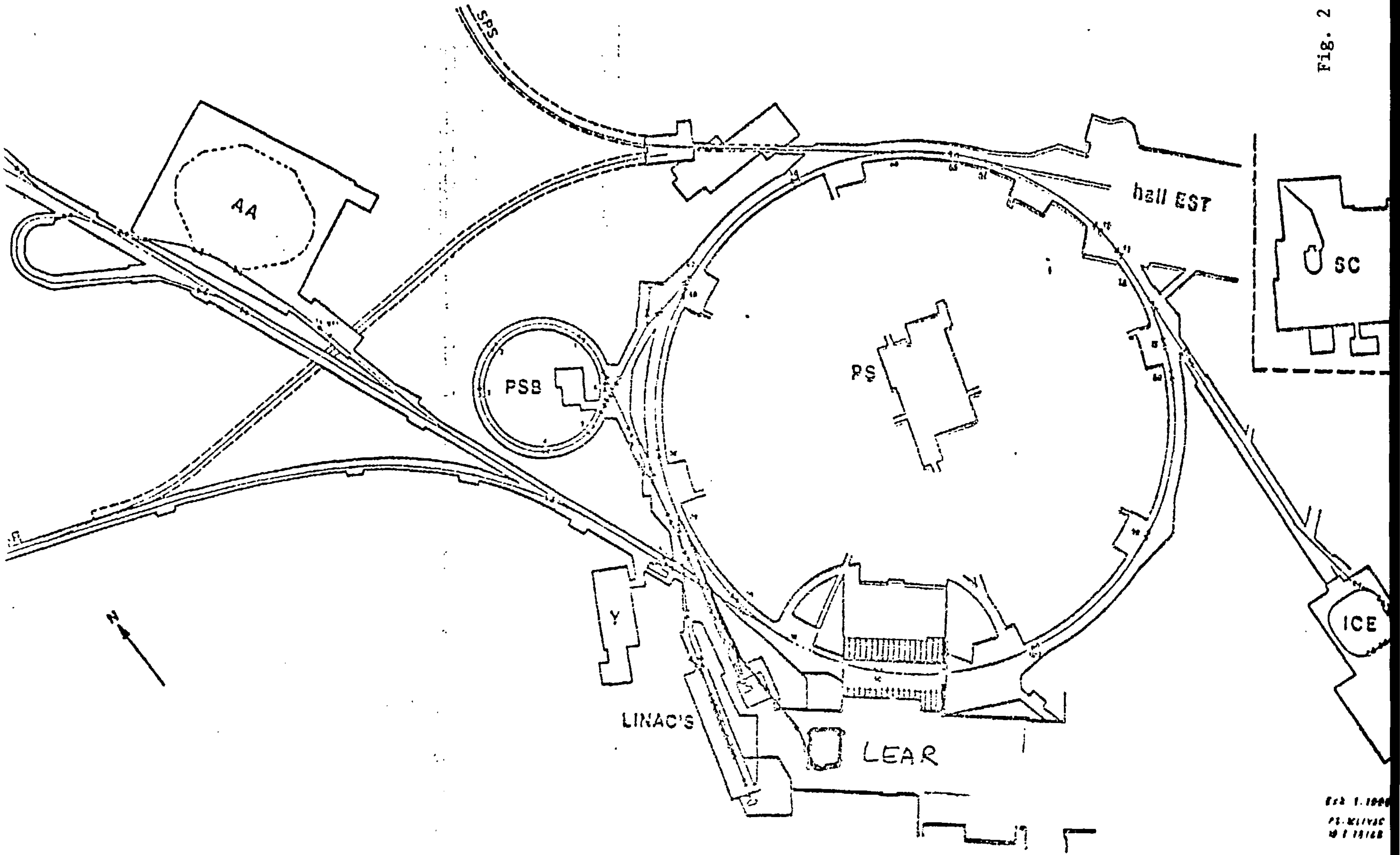



Fig. 1

Fig. 2




PS ACCELERATOR COMPLEX

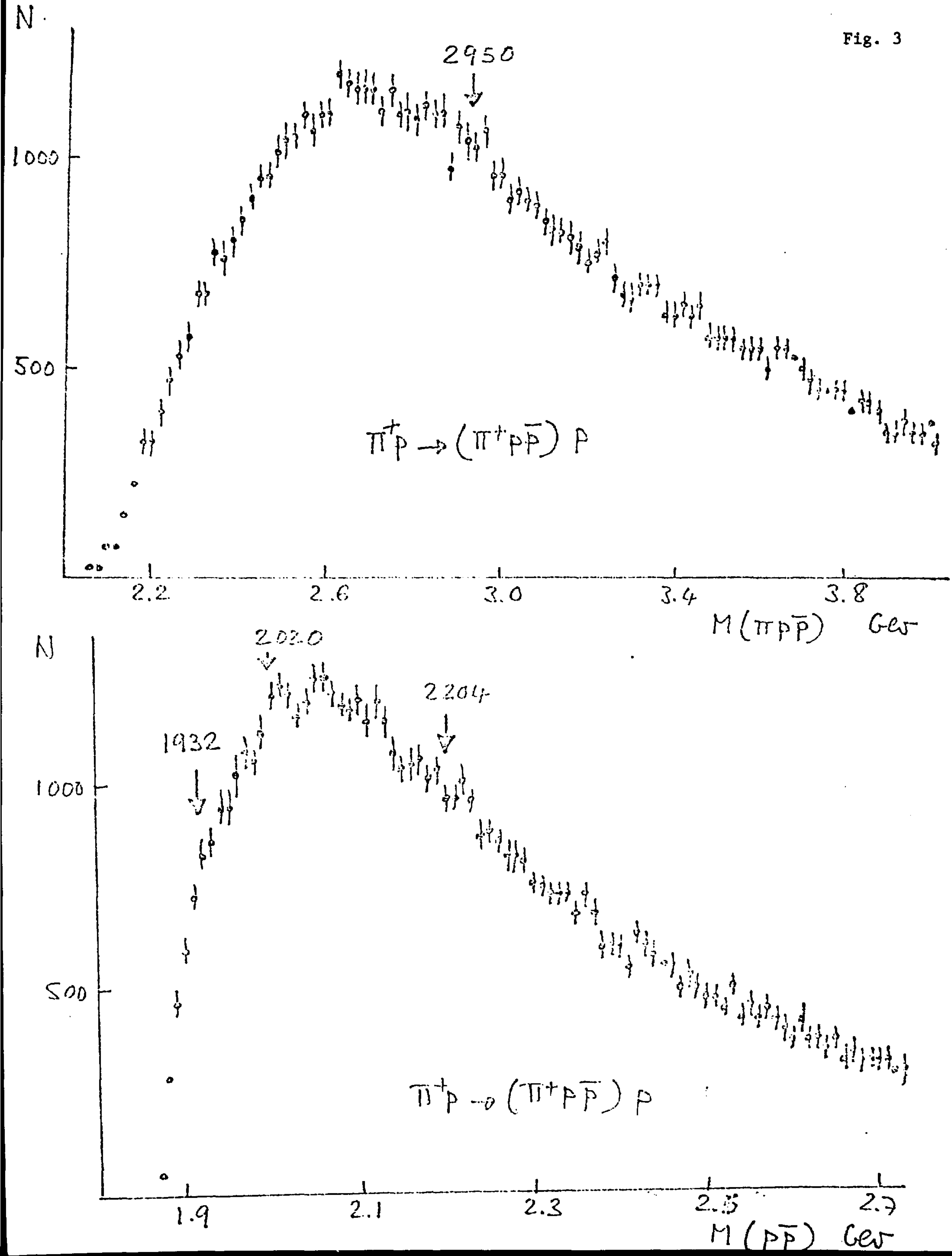


Fig. 3
N
2950
1000
500
π⁺p → (π⁺pp̄) p
2.2
2.6
3.0
3.4
3.8
M(πpp̄) Gev
N
2020
2204
1932
1000
500
π⁺p → (π⁺pp̄) p
1.9
2.1
2.3
2.5
2.7
M(pp̄) Gev

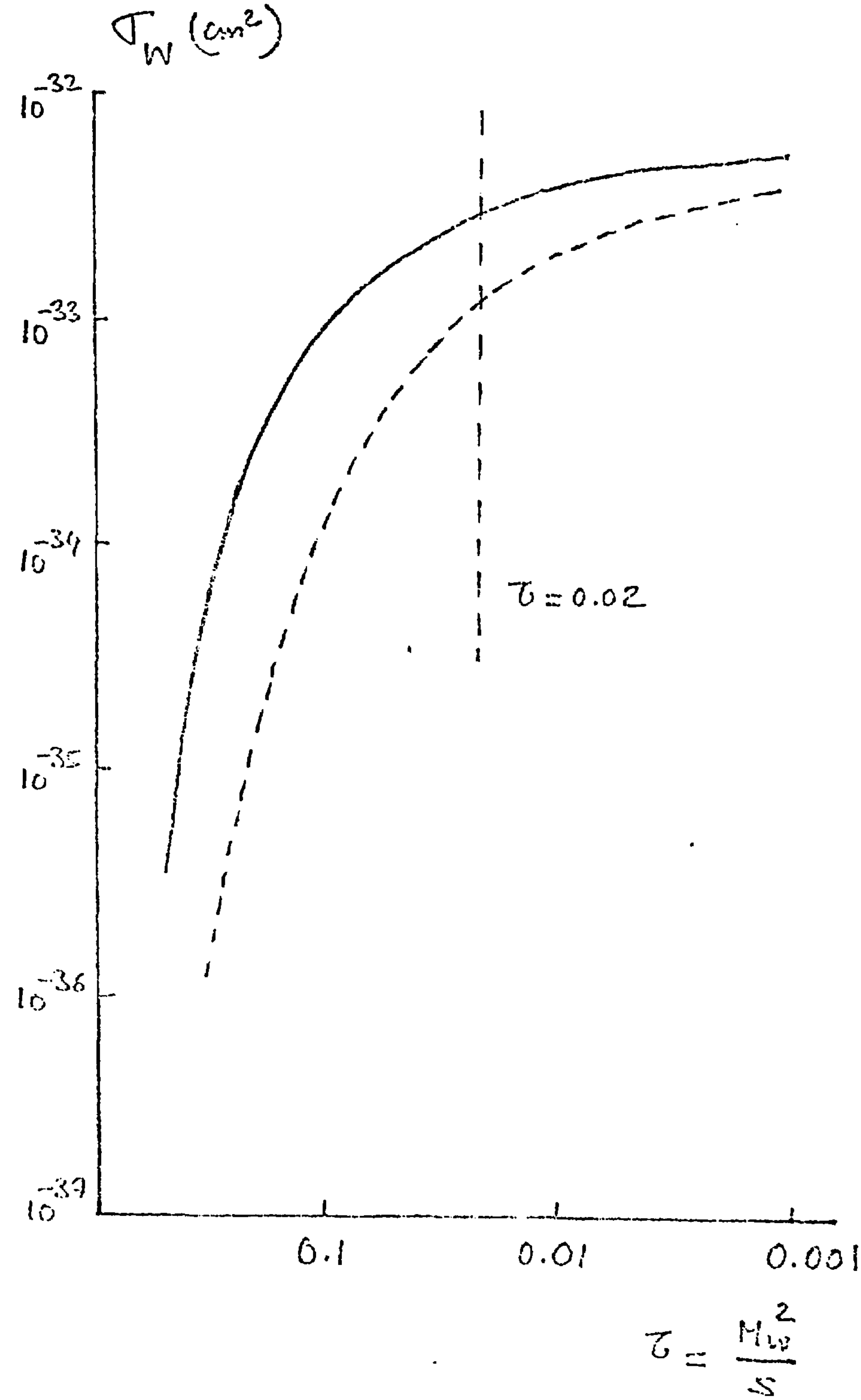
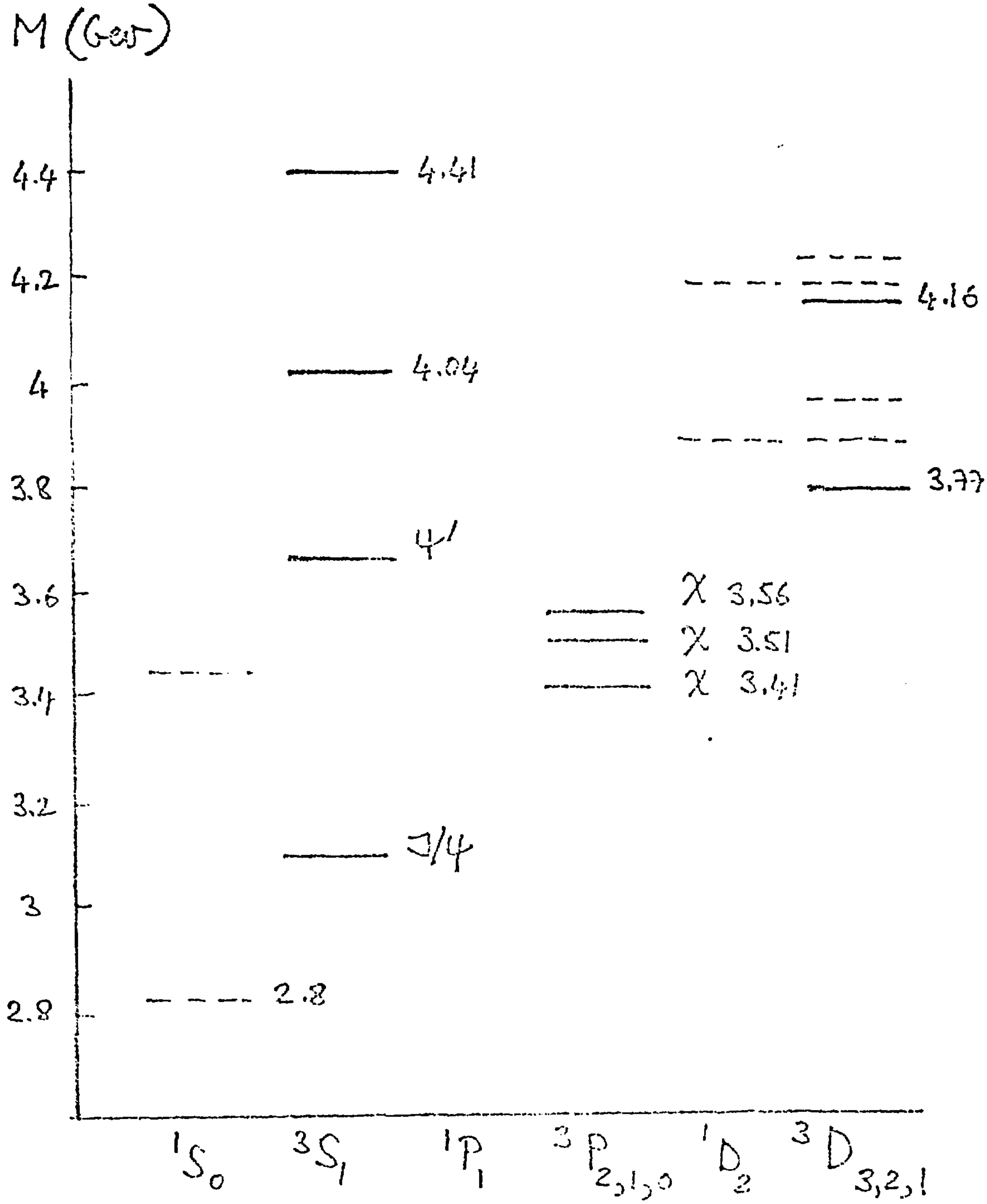



Fig. 4



M (Gev)
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
4.41
4.04
ψ'
J/ψ
2.8
χ 3.56
χ 3.51
χ 3.41
4.16
3.77
$^1S_0$
$^3S_1$
$^1P_1$
$^3P_{2,1,0}$
$^1D_2$
$^3D_{3,2,1}$


Fig. 5

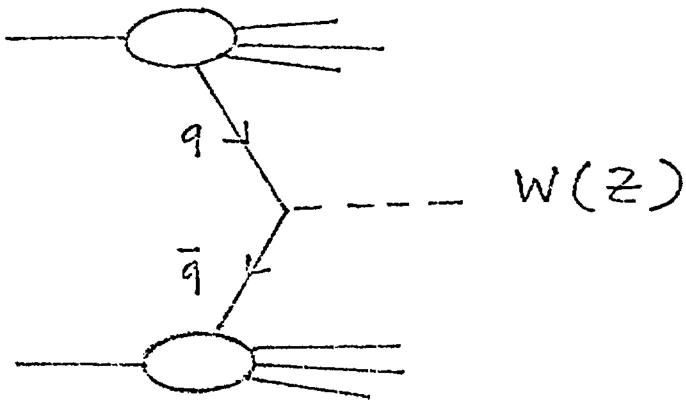



Fig. 6-a

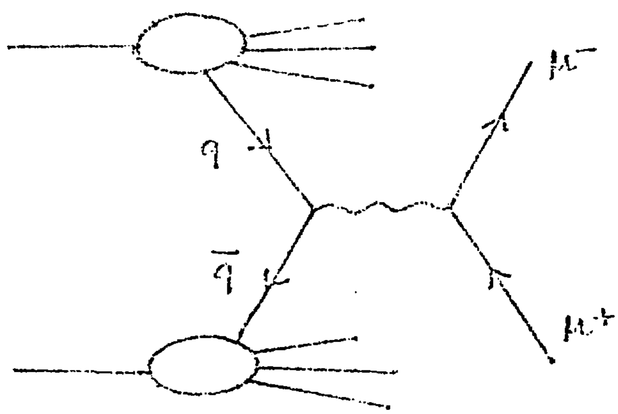
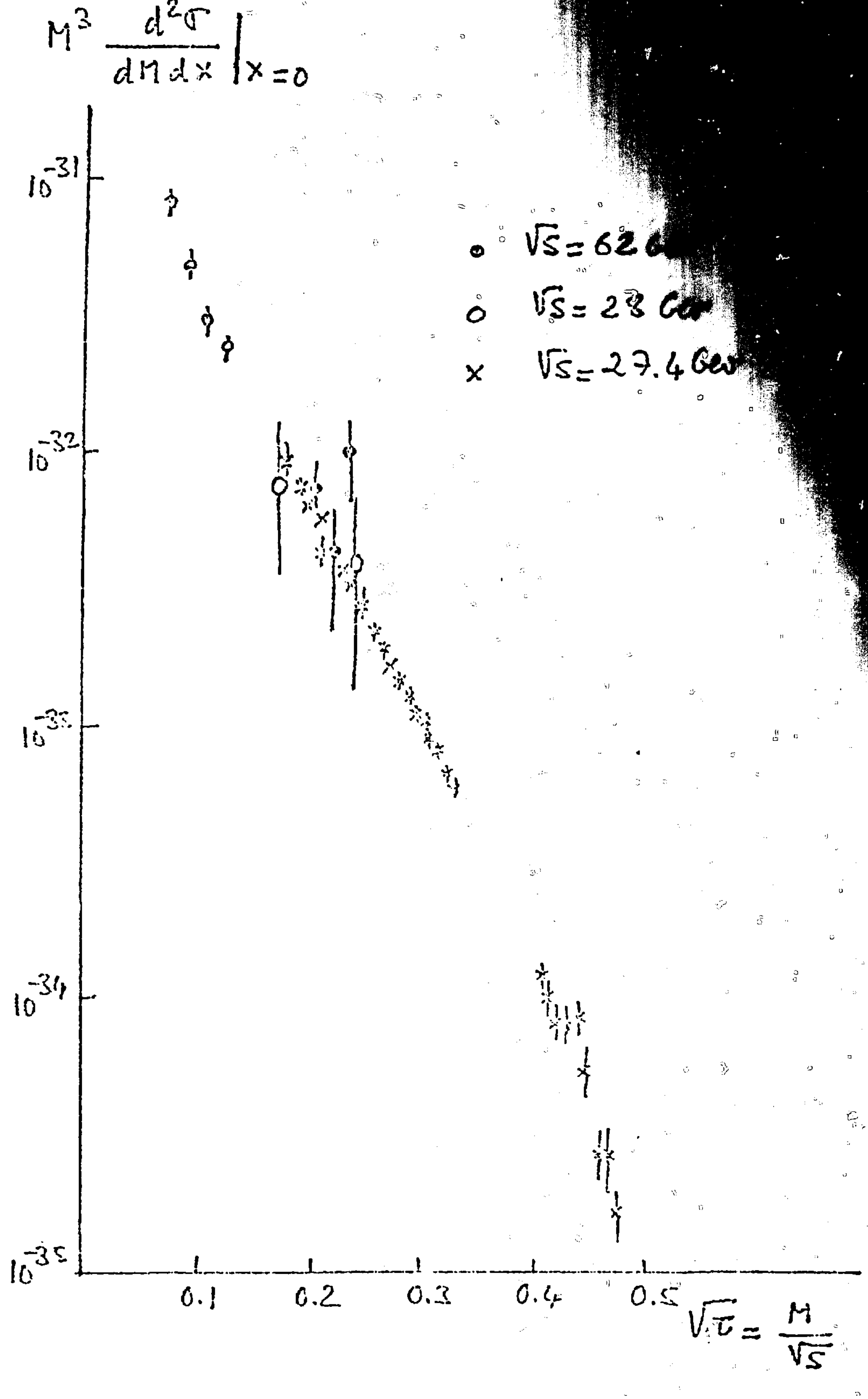



Fig. 6-b



$M^3 \frac{d^2\sigma}{dM\,dx}\Big|_{x=0}$
$10^{-31}$
$10^{-32}$
$10^{-33}$
$10^{-34}$
$10^{-35}$
$\sqrt{s} = 62$ Gev
$\sqrt{s} = 28$ Gev
$\sqrt{s} = 27.4$ Gev
0.1
0.2
0.3
0.4
0.5
$\sqrt{\tau} = \frac{M}{\sqrt{s}}$

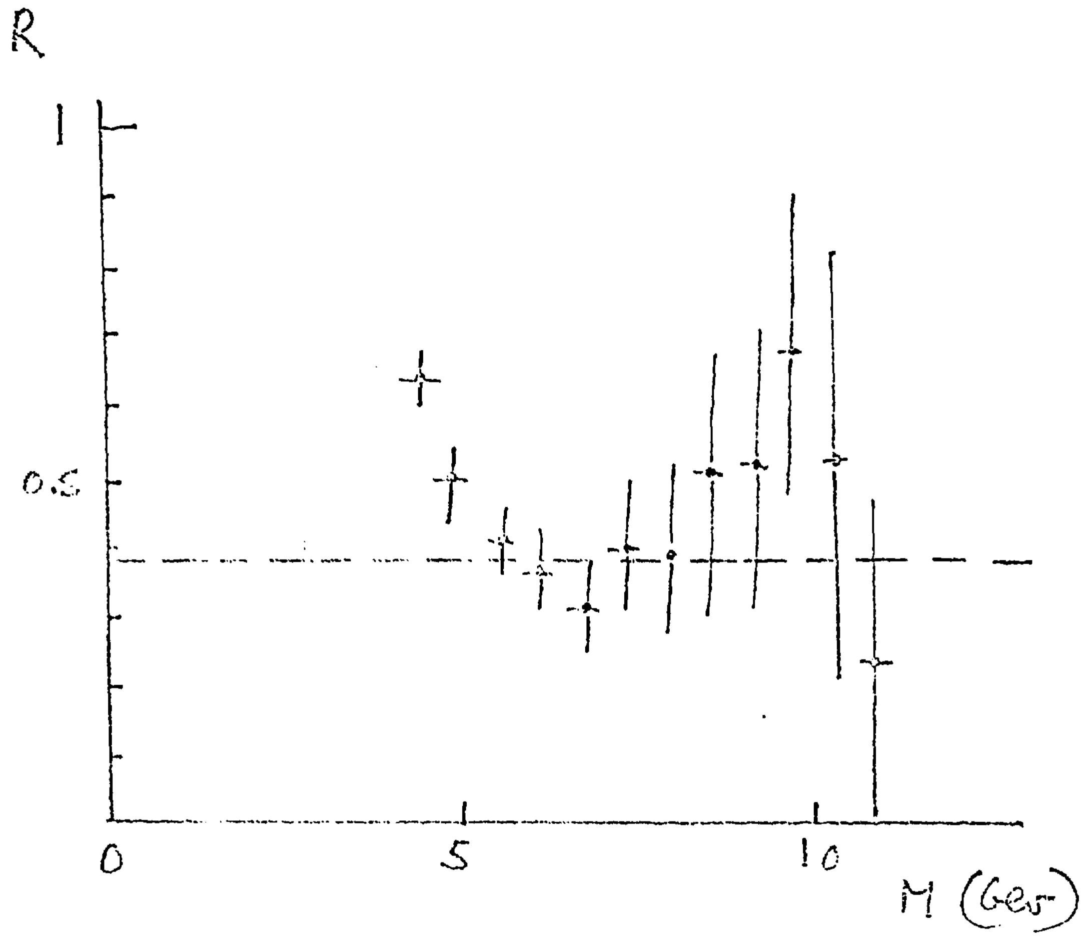
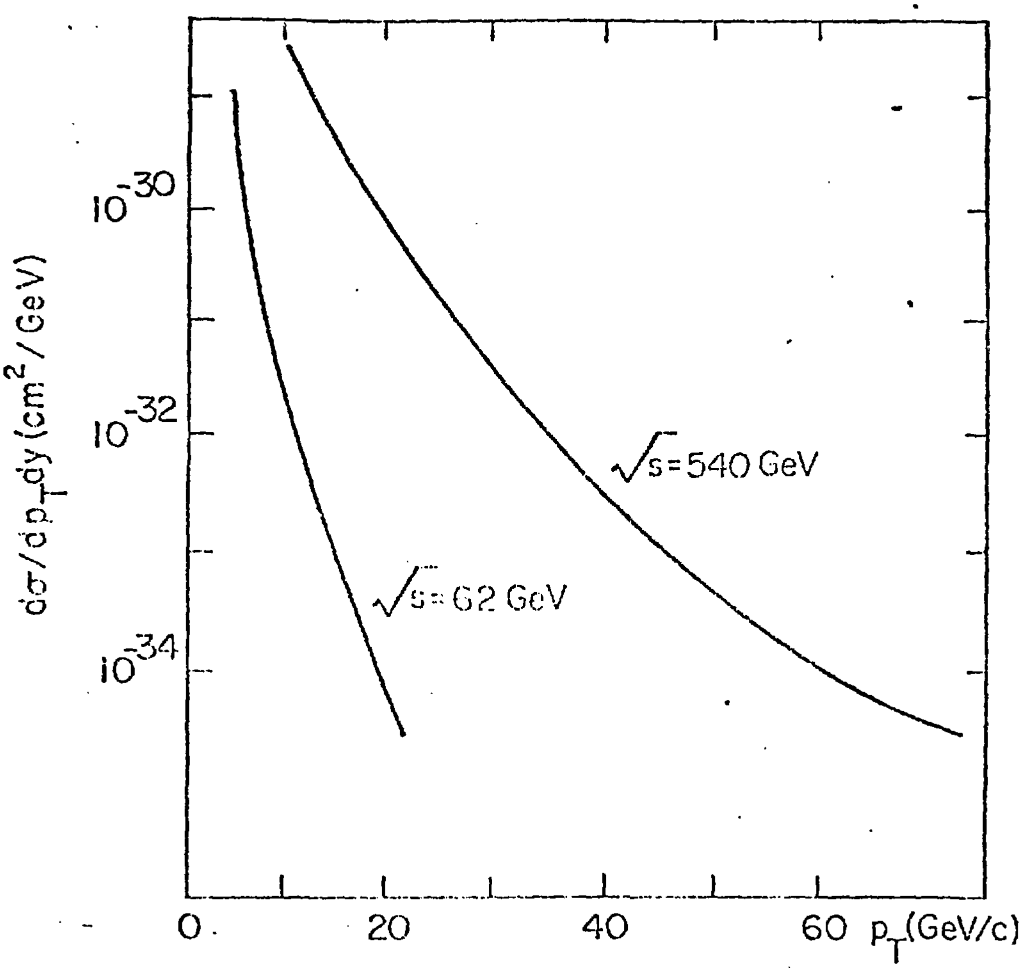



Fig. 8

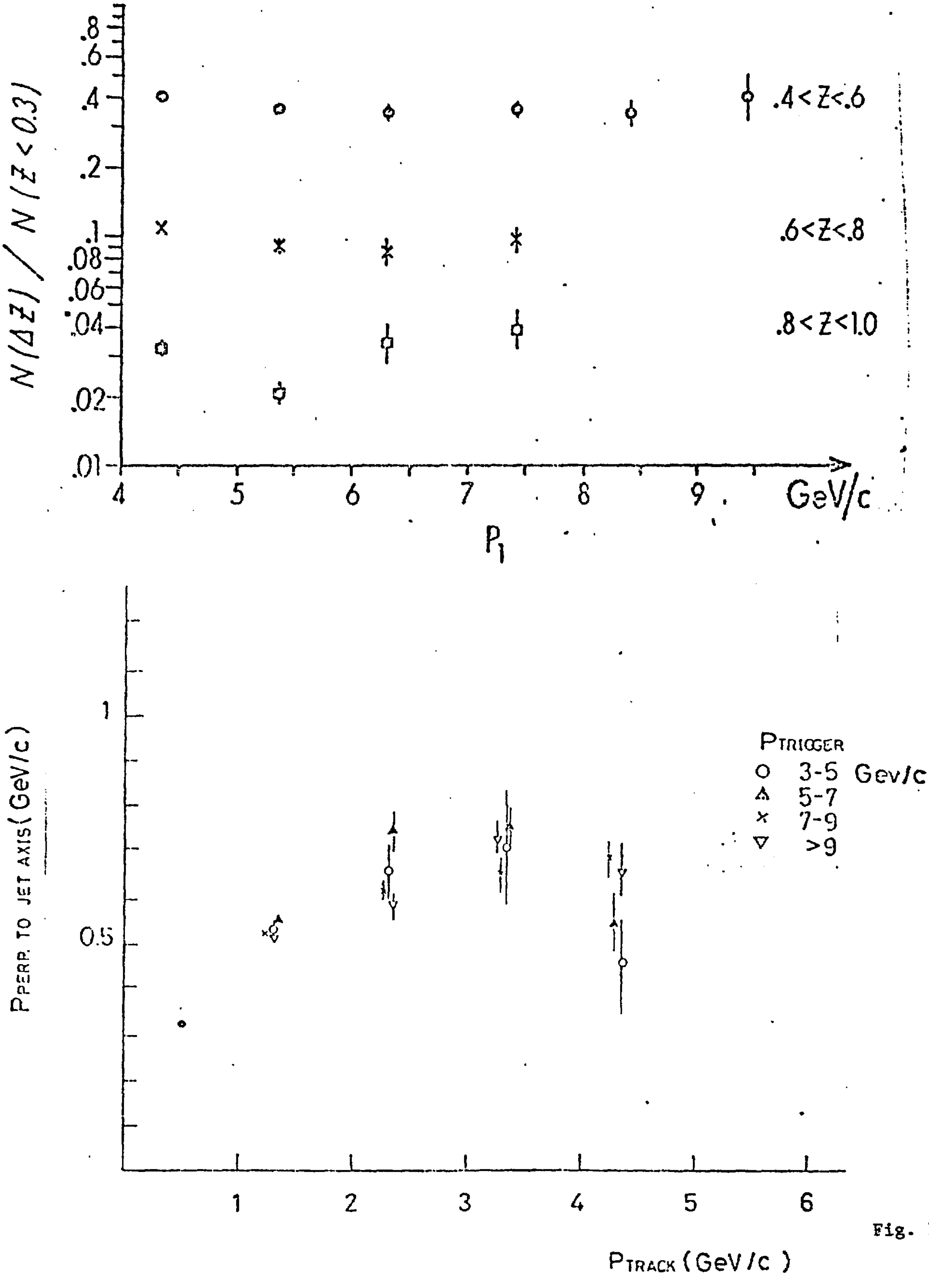


$d\sigma/dp_T dy$ (cm$^2$/GeV)
$10^{-30}$
$10^{-32}$
$10^{-34}$
$\sqrt{s}$ = 540 GeV
$\sqrt{s}$ = 62 GeV
0
20
40
60
$p_T$ (GeV/c)


Fig. 9

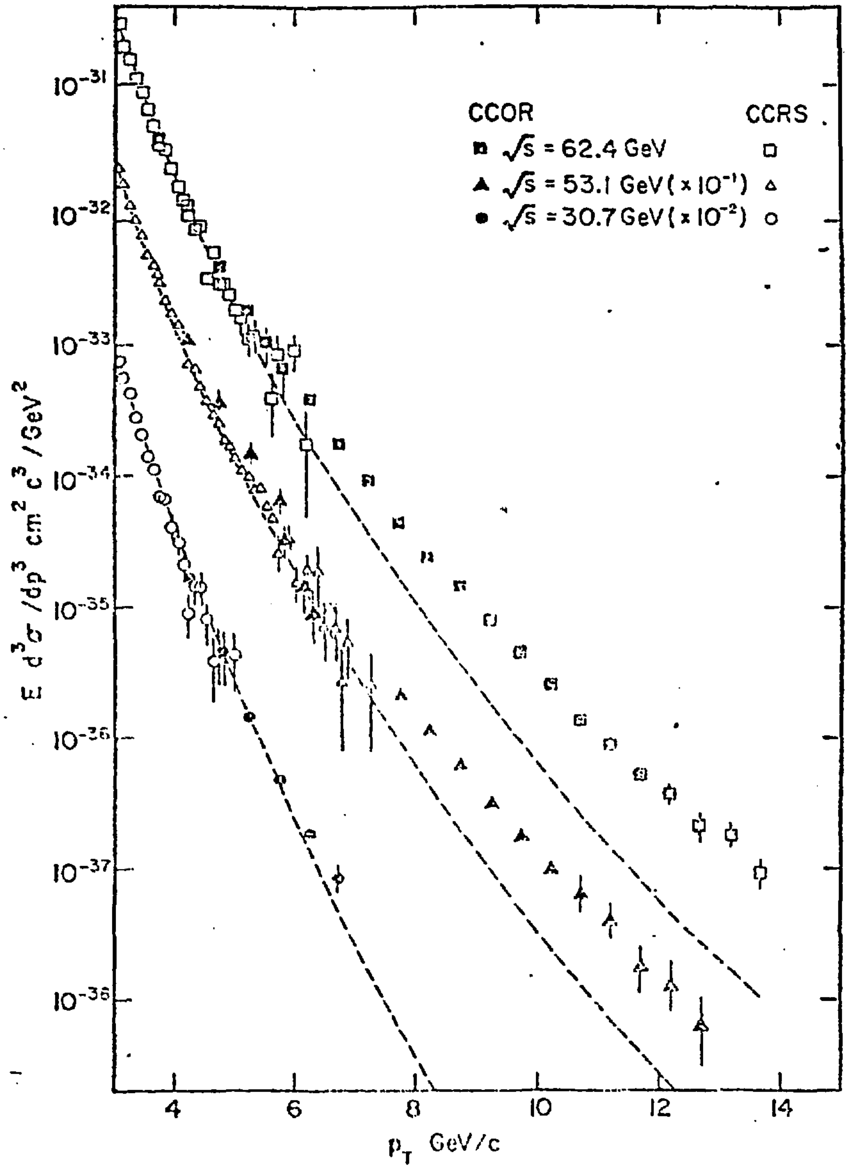
(a)

(b)



N(ΔZ) / N(Z < 0.3)
.8
.6
.4
.2
.1
.08
.06
.04
.02
.01
4
5
6
7
8
9
GeV/c
$P_\perp$
.4 < Z < .6
.6 < Z < .8
.8 < Z < 1.0
PPERP. TO JET AXIS (GeV/c)
1
0.5
PTRIGGER
3-5 Gev/c
5-7
7-9
>9
1
2
3
4
5
6
PTRACK (GeV/c)


Fig. 10



CCOR
CCRS
$\sqrt{s}$ = 62.4 GeV
$\sqrt{s}$ = 53.1 GeV (× 10⁻¹)
$\sqrt{s}$ = 30.7 GeV (× 10⁻²)
E d³σ /dp³ cm² c³ /GeV²
10⁻³¹
10⁻³²
10⁻³³
10⁻³⁴
10⁻³⁵
10⁻³⁶
10⁻³⁷
10⁻³⁸
4
6
8
10
12
14
p_T GeV/c


Fig. 11

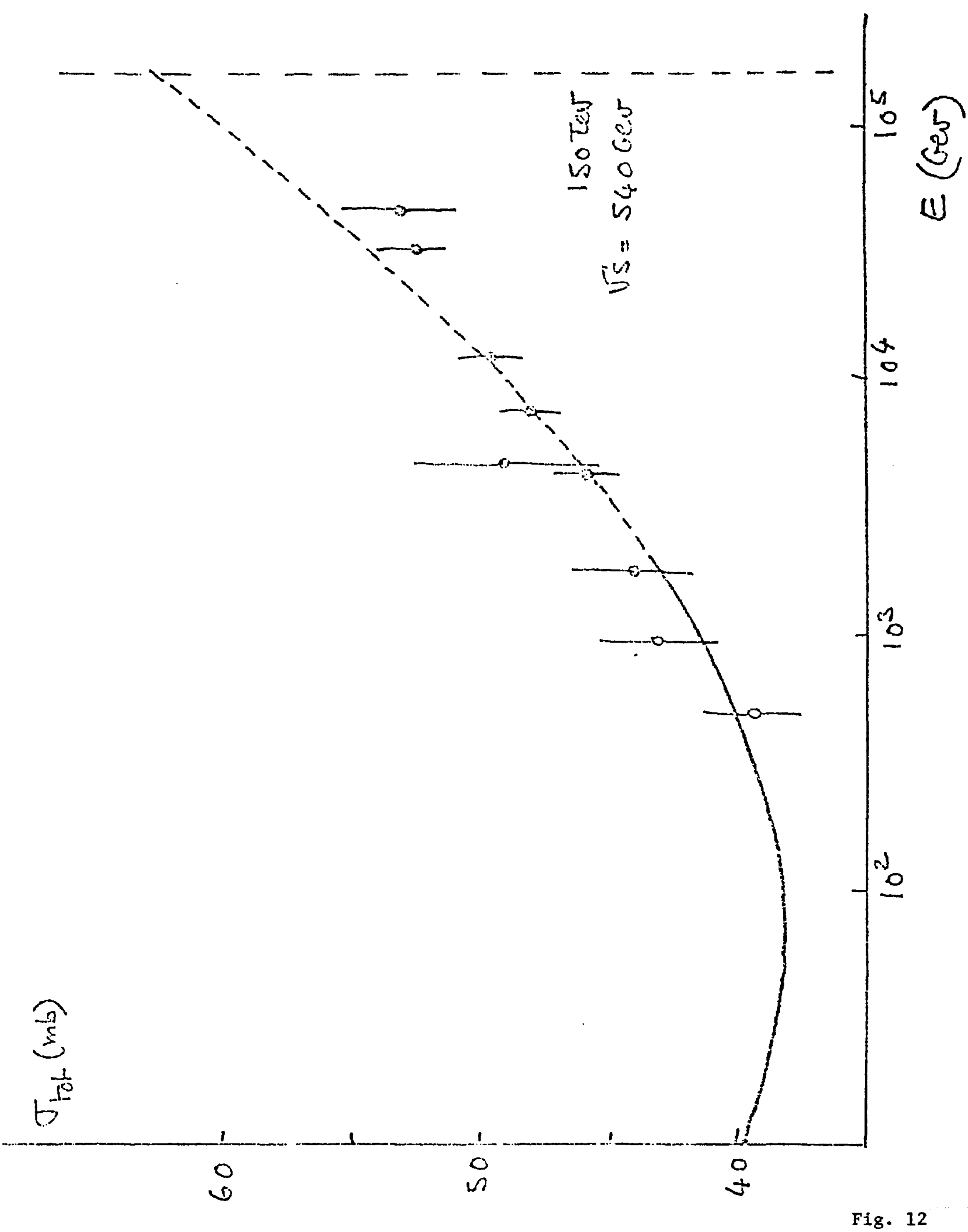
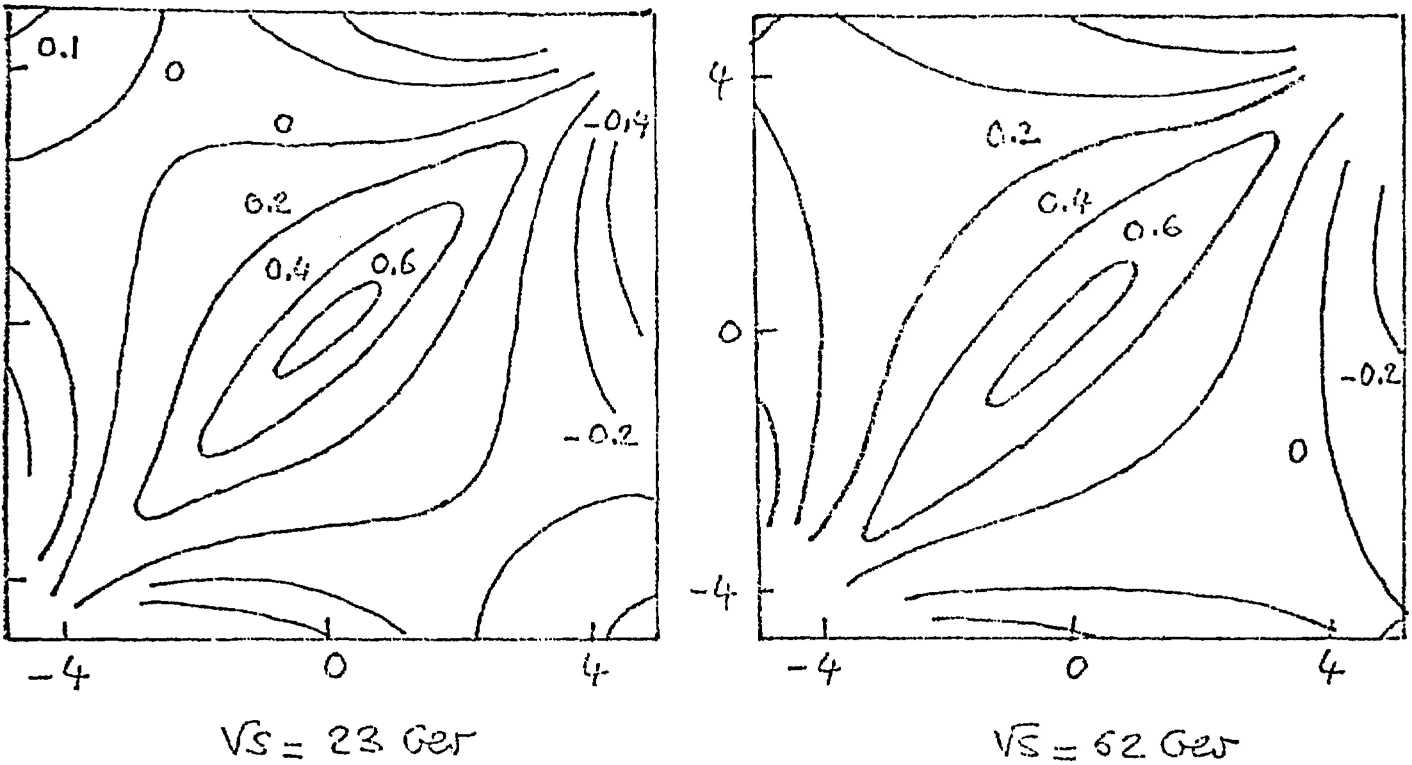



Fig. 12

(a)


0.1
0
0
-0.4
0.2
0.4
0.6
-0.2
-4
0
4
√s = 23 GeV
4
0.2
0.4
0.6
0
-0.2
0
-4
-4
0
4
√s = 62 GeV

(b)

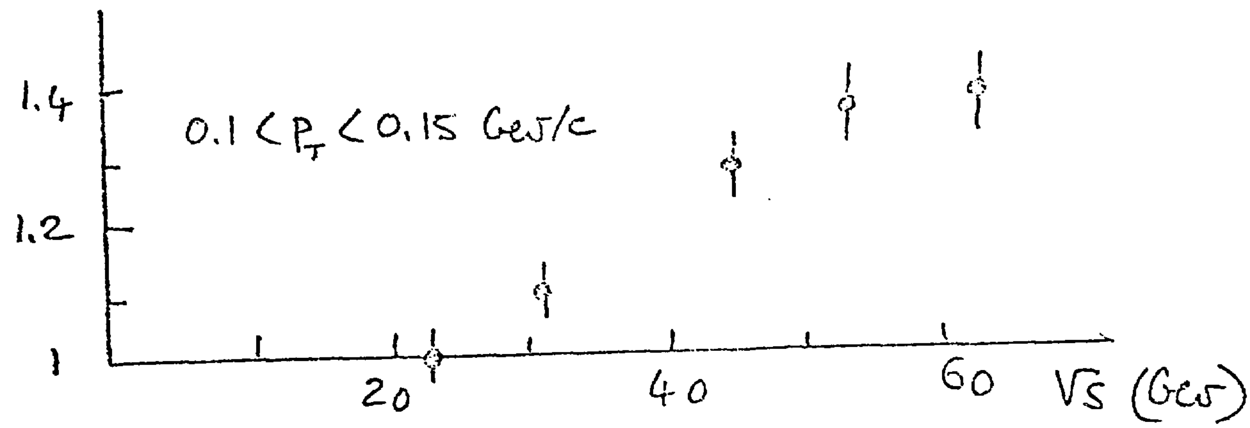

1.4
1.2
1
0.1 < $P_T$ < 0.15 GeV/c
20
40
60
√s (GeV)

Fig. 13

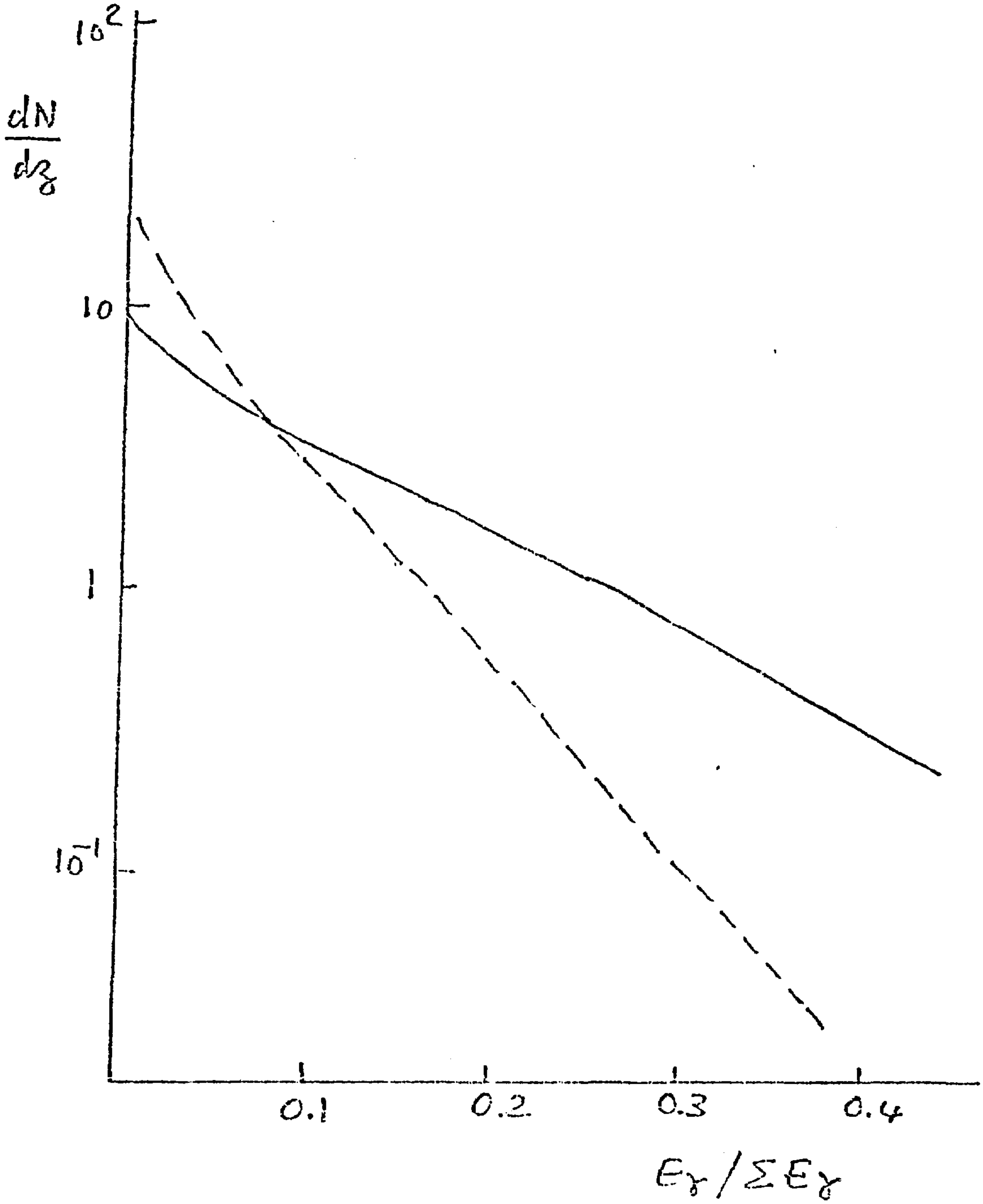



Fig. 14