Fermi National Accelerator Laboratory

FERMILAB-Pub-91/65

A Trigger For Beauty*

George Charpak
CERN
Geneva, Switzerland

Ioanis Giomataris
World Lab
Lausanne, Switzerland

Leon M. Lederman
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510
and
University of Chicago
5640 Ellis Avenue
Chicago, Illinois 60637

March 1990

* Submitted to *Nucl. Instrum. Methods.*

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

A TRIGGER FOR BEAUTY

G. Charpak,[1] Y. Giomataris[2] and L. Lederman[3]

Abstract

The possibility of B-meson experiments in a fixed-target high-energy proton machine (Tevatron) is discussed. Compared to a B-meson factory experiment, it can produce $10^5 B\overline{B}$'s per hour, using 10^8 proton interactions per second, but it suffers from high background and needs high selectivity to cope with the million times higher interaction rate. To overcome these difficulties a technique called the 'optical trigger for beauty' is proposed, based on the detection of Cherenkov photons produced in a 2 mm thick LiF crystal, through a fast photodetector. Its virtue is that it is opaque to minimum bias events originating in a small target but sensitive to the high impact parameter B-meson decay charged particles from a secondary vertex. Calculations and first simulations results give a good efficiency for B-meson detection. A multistep trigger, combining the 'optical trigger' and a tracking detector, allows significant selection and a consequent enrichment of the data sample. Taking into account its fast response (≈ 10 ns), the above considerations can be extended to other hadronic machines, especially high rate environments such as those of the LHC or SSC.

Submitted to Nucl. Instrum. Methods

1) CERN, Geneva, Switzerland
2) World Lab, Lausanne, Switzerland
3) Fermilab, Batavia, IL and University of Chicago, IL, USA

1 INTRODUCTION

A major challenge to experimental high-energy physics as carried out with proton accelerators has to do with the fact that protons are complex objects. The standard image of protons, especially as characterized with some justice by advocates of electron machines, resembles a "garbage can", where the banana peels, coffee grounds and egg shells are replaced by quarks and gluons. Gluons themselves are capable of virtual dissociation into pairs of quarks, further increasing the messiness of our picture of the proton as a probe of subnuclear physics.

The collision of two complex objects then has two major disadvantages over the collision of the elegantly simple and point like (i.e. structureless) electrons. One is the fact that the energy per constituent is decreased over the laboratory energy of the proton; a rule of thumb suggests that this factor is about 5, for an average collision in which the interest is in the quark-quark or the quark-gluon interaction. The other is the presence of a multitude of spectator objects, many of which will acquire some of the energy of the collision and assist in cluttering the detector. The saving grace for protons is again twofold in this simplified debate. For one, protons are easier and cheaper to accelerate, and this more than compensates the factor of 5 Also, the cross sections for a quark-quark hard collision to produce a particular interesting object, say W or B particles, is much larger than the equivalent electron-positron cross section. It is not inhibited, as is the e^+e^- collision, by the necessity of exciting only the quantum numbers of the intermediate photon or Z°.

The key problem then is most dramatically illustrated by (but by no means restricted to) the hadronic production of heavy quarks, i.e. charmed mesons and beauty mesons. Here, the production rates can be a factor of 100 higher than the ones at the equivalent e^+e^- total energy sitting on a resonance like the J/Ψ or the Ψ', etc. The equivalent hadronic production is, however, about 10^{-3} of σ_T, with Fermilab's 800 GeV protons hitting a target.

The production and study of charmed mesons was the exclusive province of e^+e^- colliders from 1975 until the Fermilab experiment E-691, using two new technologies, successfully beat down the backgrounds, actually in a photoproduction experiment. In order to distinguish between an event originating in the target from a decay of a charmed meson near the target, E-691 used the then new silicon microvertex technology [1]. The laboratory lifetimes were such that impact parameters of the order of 50 μm had to be detected. E-691 and its follow-up hadroproduction experiments used a very loose trigger and a then-new parallel processing technology (ACP) developed with the specific objective of handling huge amounts of data and doing the event reconstruction rapidly. E-761 wrote over 10,000 high density magnetic tapes in their 1988 run on hadroproduction of charm. The data are being processed with an ACP system.

Whereas it is true that data-recording technology is improving it seems that a more selective trigger, which provides an enrichment in charm events by a factor of 100 or more, would encourage a more sophisticated on-line analysis, a relatively refined data storage, and perhaps quicker off-line analysis.

When all these problems are applied to beauty particles, the motivation for trigger development becomes far more forceful. Whereas lifetimes in the laboratory system are far more favourable in the B-meson case, the fraction of the total cross-section is now only 10^{-6}. This minuscule cross-section (20 nb) is still large compared with the one in e^+e^- colliders, which have again dominated the subject since the discovery of b quarks at Fermilab in 1977. For example, in a beam producing 10^8 interactions per second of 800 GeV protons, some 10^2 $B^0\overline{B}^0$ are produced. Fermilab's duty cycle is such that 2 x 10^3 $B\overline{B}$'s can be produced per minute or 10^7 per 100 hour week. It is clear that with reasonable attention to acceptances and efficiencies, huge yields can in principle be expected. As of late 1990, not a single B° event has been seen in the Fixed-Target program. The challenge is in the huge rates (10^8 per second is equivalent to a luminosity of 10^{33} cm^{-2} s^{-1} in a collider) and the huge backgrounds.

The motivation for solving these problems is very great. The production and decay of B mesons contains some of the least-known parameters of the Standard Model. More than that, it is another approach to one of the most crucial problems of our times, the famous CP-symmetry breakdown heretofore only observed in the neutral-K system. This process is generally considered to be the origin of matter-antimatter asymmetry in the Universe and is known as the 'origin of matter' problem. This has been widely appreciated and has resulted in many proposals throughout the world for the construction of 'beauty factories' at a cost of many hundreds of millions of dollars. Thus, the drive to find a way to use the intense fixed-target source is very amply motivated.

2 THE VIRTUES OF A TRIGGER FOR b-QUARKS

Much of the specific examples are derived from a current Fermilab experiment, E-789 which hopes to see B mesons via their presumed two-body decay modes $(\pi^+\pi^-, K^+\pi^-, K^-K^+, ...)$. The prevalence of silicon microvertex hardware and possible improvements (e.g. diamond detector [5]) is essential. Suppose one developed a 'zero level' trigger which could select events generated in space near the target and which would thereby enrich the data in B-meson events by a factor of say, 50. The Fermilab duty cycle has 10^7 buckets per second; with 10 interactions per bucket the event train following this trigger would have an average of 1 event per 500 ns. In this time, level-1 on-line event analysis could further filter the events to gain another factor of 50. This in turn permits a very sophisticated on-line analysis (level-2), which can lead to a comfortable $\approx$ 1000 events per minute for recording on tape. If the various levels of filtering did not unacceptably reduce the efficiency, some 10 $B\overline{B}$ decays are recorded per minute with a typical 1% acceptance. The very selective E-789 spectrometer adds another 10^{-5} in branching ratio for each two-body channel, but even here, some few hundred events would be recorded and fully reconstructed. Thus, the challenge to the instrumentalist is to distinguish between events arising from a target of 200 μm diameter, 1 mm thick, and decays of B's whose laboratory mean path length averages about 1 cm, with a mean impact parameter of 800 μm. If this is to serve as a zero-level trigger, the decision time must be comparable with or less than 20 ns, the radio frequency bucket spacing

3 THE PROPOSAL

In the next sections we describe a new detector, based on the Cherenkov photon detection, satisfying the main requirements for a zero-level trigger of a Tevatron fixed-target experiment. This detector, named 'Optical Trigger', is sensitive to the main characteristics of a B meson event, a high decay-particle impact parameter, high multiplicity, large azimuthal angle with respect to the beam axis. Moreover, its 1ns (or less) response makes it a candidate for even higher rate environments, as with the LHC or SSC machines.

3.1 Review of the Cherenkov effect

The emission angle of Cherenkov photons by an ultra relativistic particle traversing a medium of refractive index n, is give by the relation: $\cos\theta_{Ch} = 1/n$, and the number of emitted photons in an interval of energy ΔE is

$$N = (\alpha/\hbar c)L\Delta E\sin^2\theta_{Ch} \qquad (1)$$

where α is the fine structure constant, $\hbar$ Plank's constant, c the velocity of light, and L the thickness of the radiating medium. The limiting angle for total reflection by a plane, for a photon travelling in a medium of index n is given by the relation: $\sin\theta_{tr} = 1/n$. As a consequence, for particles orthogonal to the limiting surface, if $n = \sqrt{2}$ the emitted Cherenkov photons are exactly at the limit for total reflection, if $n \geq \sqrt{2}$ the photons are trapped, if $n \leq \sqrt{2}$ they escape. If the particles are within a narrow cone around the line perpendicular to the surface, the Cherenkov photons can all be transmitted or reflected. depending on the value and sign of $(n - \sqrt{2})$. [11]

A detector based only on this configuration is sensitive to relatively large azimuthal particle angles which is the case of the decays of B mesons, but its rejection of minimum-bias events is certainly poor. Another way to control the angular spread of the beam so as to favor total trapping or transmission of the photons is to adjust the curvature of the exit surface limiting the medium.

3.2 The principle of the optical trigger

The beam target is at the centre of the spherical boundary of the medium of index n. A hole follows the target in such a way that non-interacting primaries as well ss a substantial fraction of the secondary particles traverse the medium without any interaction.

The refractive index n close to $\sqrt{2}$, and the curvature are chosen in such a way that Cherenkov photons, produced in the medium by charged particles from the target, escape through the surface. However, a small fraction of the photons is reflected. Since there are over 10^6 times as many tracks from the target as B's, even a small fraction is unacceptable. It is possible to coat the surface in such a way that a substantial part of these photons is transmitted. The principle of anti-reflecting coating is very efficient for a given wave-length band and for a given angle of incidence Fortunately all the photons cross the surface at the same angle within a narrow band determined by the width of the beam and the target. Although this technique is not excluded, a better one, based on the multi-reflection suppression of background photons, seems possible. It is discussed below.

The B mesons are produced at some distance from the target and their decays are emitted at angles slightly larger than the average angle of the secondary, particles from minimum-bias events, giving rise to a relatively large impact parameter. These particles generate Cherenkov photons, some of which are sufficiently inclined to the exit surface to be totally reflected. They are focused by the surface into a ring or a fraction of a ring whose position depends on the direction of the particle.

An example of the process is illustrated in Fig. 1, where a B meson decays at point A, giving a charged particle ABE. An exact calculation has to take into account three-dimensional geometry, since the Cherenkov light can be emitted out of the plane defined by the trajectories of the particle and the B meson. If the Cherenkov photon is emitted in this plane, if ρ is the impact parameter of the particle ABE and if $n = \sqrt{2}$, it is straight forward to find the condition for internal total reflection. From triangles OAB and OCB respectively, we get:

$$\sin\alpha = \frac{p}{r} \tag{2}$$

$$\frac{\sin\theta_i}{r} = \frac{\sin\Omega}{R} \tag{3}$$

From relation (3) we find the angle at which the photon is incident upon the exit surface:

$$\sin\theta_i = \frac{r}{R}\sin\left(\theta_{ch} + \alpha\right) \tag{4}$$

The condition for total internal reflection is then

$$\frac{r}{R}\sin\left(\theta_{ch} + \alpha\right) \geq \sin\theta_{crit} = \frac{1}{n} \cong \frac{1}{\sqrt{2}} \tag{5}$$

Since $\theta_{crit} \cong \theta_{ch} \cong 45°$, where θ_{crit} is the critical angle:

$$\sin\alpha + \cos\alpha \geq R / r \tag{6}$$

Since α is generally small, we can use (2) to find:

$$p \geq R - r = \delta r \tag{7}$$

where R is the radius of the exit surface and r is the flight distance of the decaying particle. In the general three-dimensional case, the exact calculation is very complicated. Using relation (26) from Ref. [2] and assuming small particle angles with respect to the beam axis, we can derive a more general relation becoming, to first approximation:

$$\delta r = p\cos\phi$$

, where ϕ is the azimuthal emission angle of the (Cherenkov photon. This relation can be satisfied only if--$90° \leq \phi \leq 90^{o}$, which excludes half of the Cherenkov photons. The condition indicates also that only a limited part of the particle path is useful. The background photons from particles emerging from the interaction point never satisfy the total-reflection condition since their impact parameter is zero, they are largely transmitted.

3.3 Monte Carlo simulations results

The production of $B\overline{B}$ pairs in proton-proton collisions has been simulated using the PYTHIA [5] program, for 0.9 TeV incident energies on a fixed target. The program assumes ,gluon-gluon fusion and quark-quark interaction for $B\overline{B}$ production.

Figure 2 shows the momenta distribution and Fig. 3 the azimuthal angular distribution of the produced B mesons. The mean momentum is 180 GeV and the mean azimuthal angle about 20 mrad. The distance of the vertex of B decay particles from the interaction point is of the order of 15 mm as shown in Fig. 4. This distance is certainly a little higher than the B-meson expected mean path length. However it includes a small part of any D-meson path produced *in* B-meson decays. This is favoured by our optical trigger, since it raises the mean impact parameter of charged particles produced. As shown in Fig. 5 the impact parameter is of the order of 1 mm. The average momentum of B-meson decay particles shown in Fig. 6 is 20 GeV. Their azimuthal angle, shown in Fig. 7, is quite large ($\approx$ 50 mrad), which also favours our experimental technique.

The main message coming from the above study is that the impact parameter is significant ($\approx$1 mm) for Tevatron energies.

With a 1 mm thick radiator, we can have a first estimation of the number of photoelectrons collected in the photodetector. Using relation (1), the number of photons produced

$$N/(eV \cdot cm) = 370 \sin^2 \theta_{Ch} = 185 \quad [\text{or } N/(eV \cdot mm) = 18.5]$$

Assuming that only a part (~ 0.5.(cos ϕ)) of the photons are lost because they do not satisfy the total reflection condition (the exact number should come from a full Monte Carlo), a quantum efficiency of 30%, neglecting losses due to absorption, and taking 1 eV as the photon energy acceptance of the photodetector, the number of detected photoelectrons per charged decay particle is

$$N/(.5 \text{ eV} \times 1 \text{ mm}) = 0.5 \times 0.3 \times 18.5 \langle\cos\phi\rangle = 2.8$$

The number of detected photoelectrons per charged particle should be multiplied by the average charged particle multiplicity in $B\overline{B}$ decays. Assuming an average of 4 particles per $B\overline{B}$, the total number of photoelectrons detected is about 22. This high number can hopefully compensate for some possible optimism in our calculations, but gives a reasonable order of magnitude. A reserve factor is the thickness of the radiator, but here we also add nuclear interactions and delta rays of the target-originated tracks.

3.4 The Cherenkov radiator

A possible, but not unique candidate for the Cherenkov radiator is LiF, chosen for its low Z and absence of scintillating light. For λ = 300 (500) nm, the index of refraction is 1.405 (1.395), corresponding to an angular dispersion of few milliradians. This is a very comfortable region since a normal photomultiplier with Pyrex window can be used. A selection filter is not necessary; the energy bandwidth is automatically defined between the threshold of the photocathode and the cut-off of the window used.

Other crystals having relatively low refractive index are MnF_2 and NaF. The first has about the same index as LiF, it does not seem to scintillate, and it is a stable and reliable material. Some liquids like hydrocarbon~ (heptane, C_2H_2, ...) are attractive because of the low dispersion index in the visible, and of their high radiation and interaction lengths, but they need to be enclosed. However they are not a priori excluded, since at low temperatures their crystals can also be considered. A systematic search may lead to the discovery of other potential candidates for the Cherenkov radiator. The possibility to lower the refractive index of other crystals by doping them, or by changing the temperature or the pressure, can also be considered.

3.5 The photodetector

As a photodetector, one can use any photomultiplier having the right photon acceptance, with the highest possible quantum efficiency. Therefore it must be of the reflective type (head-on), requiring an optimum angle between the photocathode plane and the incident photon beam. As was shown in the previous section, the Cherenkov photons are emitted with little dispersion, since the charged particles have an angular distribution of the order of 50 mrad. By choosing the right angle, large quantum efficiencies $\approx$ 50% can in principle be obtained. Another important feature of a good photomultiplier is its high gain ($\geq 10^6$), permitting excellent single photoelectron detection spectra. Hence, imposing an on-line threshold on the collected charge should reduce the backgrounds. Finally the fast photomultiplier response, combined with the fact Cherenkov light, permits its operation in a very high rate environment (> 10^8 interactions per second).

Silicium photocathodes have very high efficiencies, in particular in the ultraviolet region, but they are not, in general, able to detect single photoelectrons. However, techniques are under development to obtain high gains. A new type of photodiode, presented by Atac [4] at Snowmass, which has high granularity, high quantum efficiency, high gain, should be considered. Although its quantum efficiency is high, 60% between 300 nm and 600 nm, its response is not very fast. It may be possible to bring the rise-time of this detector to the 10 ns level, with further development.

4 A FIRST DESIGN OF AN OPTICAL TRIGGER DETECTOR

Only a full Monte Carlo program, simulating not only the detector and the event generation, but also secondary interactions in the crystal, plus possible physical backgrounds, is required to have a final design of our device. However, calculations under certain approximations and a first Monte Carlo detector simulation program confirm our preliminary calculations, and a tentative design is presented. Since only the last millimetre or so of the track generates light in the radiator, it is possible to choose a configuration different from that of Fig. 1. This consists of a narrow shell, 2 mm thick, between two parallel spherical surfaces, having a radius of curvature of about 50 mm. The thin target sits at the centre of curvature of the crystal. Figure 8 illustrates the principle: photons satisfying the total reflection condition (7) are totally reflected and, after multiple reflections (about 30), are collected at the edges and detected. The quality of the crystal's surface must be excellent to ensure losses less than 1% per reflection. This is technically possible for small objects. Obviously, after 30 reflections, background photons from target-originated tracks that manage to be reflected should be completely attenuated, and antireflecting coating on the surface is not necessary. The Cherenkov photons are polarized and the reflectivity on the radiator surface is polarization-dependent. In our calculation, we have taken these effects into account; they alter our conclusions by only a negligible factor.

Assuming a perfect response of our device, the main limitation will come from hadronic interactions and delta rays in the crystal producing secondary particles with a high impact parameter. By having only 2×10^{-3} of the interaction length with 2 mm LiF and additional reduction of secondary interactions due to the beam hole, this should reduce the background-induced trigger rate by two or three orders of magnitude.

The factor of fifty to several hundred gain as a zero-level trigger suppressor then gives the on-line data acquisition system time to add further requirements to the event, e.g. a fast tracker that identifies the radiator as the source of the trigger, transverse-momentum cuts, and at the level 2 or level 3, a vertex processor that confirms the presence of a secondary vertex.

This method can meet the challenge of a high-rate fixed-target experiment. First simulation results show that an efficiency well over 20% can be obtained. Figure 9 shows the expected B meson detection efficiency as a function of the B path length. The efficiency is better than 50% for paths greater than 1 mm, containing more than 30% of the produced B mesons. The previous considerations and the first Monte Carlo simulation results are encouraging; further work and tests are necessary to confirm the virtues of the trigger.

5 FUTURE POSSIBLE IMPROVEMENTS

Improvements of this system will come from the design of photodetectors which will be insensitive to the background emerging from the target. In photomultipliers, the Cherenkov radiation produced in the glass forces heavy shielding or requires that the crystal shell be as far as possible from the target. With proper shielding, scintillation counters surrounding the photon detector may be useful, imposing an additional veto to the optical trigger signal. With solid-state photodiodes, the problem is similar, and even worse because of the direct detection of the charged particles.

Gaseous detectors, with CsI photocathodes, of the type recently developed [6] would be an ideal solution, since high quantum efficiency (40%) has been measured in the UV region. Further development is necessary to show if a shift to the visible is possible. However, operation in the UV region of a CsI photocathode with absorbed TMAE is possible [9] and compatible with our device. This has the advantage of being much less sensitive to direct ionization from charged particles, since the gaseous detectors can be filled with helium gas [7] or with mixtures of gas at very low pressure (≈ 1 Torr) [8].

Improvement could also come from the transfer of the light, emerging from the crystal, to a safe distance from the target, with an appropriate optical system made of mirrors and lenses, shaping the end of the crystal.

6 CONCLUSIONS

Our study has shown that using the optical properties cf the Cherenkov light produced in a radiator of appropriate shape, it is possible to separate photons produced by particles. emerging from the target, from those produced by a particle decaying at some distance from the target.

While the parameters corresponding to $B\overline{B}$ pairs produced by a 0.9 TeV accelerator are appropriate for this approach, it seems that it can be of quite general use, with accelerators at different energies or with other types of unstable particles.

The optical trigger is best suited for rejecting high-intensity unwanted events since it avoids the overloading of the triggering counters by drastically reducing their signals.

Acknowledgements

We would like to thank A. Coudert, G. Prost and M.-S. Vascotto, for their competent help in preparing this paper for publication. One of us (LML) acknowledges the support of the U.S. Department of Energy.

REFERENCES

[1] J. C. Anjos et al., Phys. Rev. Lett. 60 (1988) 1379.

[2] D. M. Kaplan et al., Fermilab proposal E-789 (1988).

[3] D. Kania and co-workers, Expression of Interest SSC EOI-9 (1990).
D. Kania et al., submitted to Appl. Phys. Lett. (1990).

[4] T. Ypsilantis, preprint CERN-EP/89-150, talk given at the Workshop on Particle Identification at High Luminosity Hadron Colliders, Fermilab, 1989.

[5] M. Bengtsson, et al., The Lund Monte Carlo Programs, long writeup, CERN, 1

November 1989.

[6] R. Atac et al., talk given at DFP Summer Study on High Energy Physics in the 1990's, Snowmass, 1990.

[7] J. Seguinot et al., preprint CERN-EP/90-88 (1990).

[8] D. Anderson et al., preprint Fermilab-Pub-90/182 (1990), submitted to Nucl. Instrum Methods.

[9] G. Charpak et al., Nucl. Instrum. Methods **161** (1979) 19.
Y. Giomataris et al., Nucl. Instrum. Methods **A279** (1989) 322.

[10] A. Breskin et al., Nucl. Instrum. Methods **220** (1983) 349.

[11] V. Fitch and R. Motley, Phys. Rev. 101 (1956) 496.

Figure captions

Figure 1 Schematic of a decay particle passing through a crystal, having a spherical surface, of refractive index $n = \sqrt{2}$. Here OA is the flight of B^0; ABE is the decay particle; BC is the Cherenkov photon; θ_{Ch} is the Cherenkov emission angle in a medium of refraction index n; θ_i is the angle of incidence of the photon with the exit surface.

Figure 2 Laboratory B-meson momenta distribution in a pp interaction, with 900 GeV incident proton energy.

Figure 3 Laboratory angular distribution of B mesons.

Figure 4 B-meson path length in millimetres.

Figure 5 Impact parameter of B-meson decay particles.

Figure 6 Momenta distribution of charged particles, emerging from B meson decays.

Figure 7 Laboratory angular distribution of charged particles emerging from B-meson decays.

Figure 8 Illustration of a tentative design of an 'optical trigger'.

Figure 9 The detection efficiency of the optical trigger for B mesons, as a function of their path length.

APPENDIX IV

Institutions Currently Participating in the Fermilab Research Program

ABILENE CHRISTIAN UNIVERSITY
IHEP, ACADEMIA SINICA (TAIWAN)
UNIVERSITY OF ATHENS (GREECE)
IHEP, BEIJING (PRC)
UNIVERSITY OF ALABAMA
UNIVERSITY OF SOUTH ALABAMA
ARGONNE NATIONAL LABORATORY
UNIVERSITY OF ARIZONA
BALL STATE UNIVERSITY
BRANDEIS UNIVERSITY
UNIVERSITY OF BRISTOL (ENGLAND)
BROOKHAVEN NATIONAL LABORATORY
BROWN UNIVERSITY
CALIFORNIA INSTITUTE OF TECHNOLOGY
UNIVERSITY OF CALIFORNIA, BERKELEY
UNIVERSITY OF CALIFORNIA, DAVIS
UNIVERSITY OF CALIFORNIA, IRVINE
UNIVERSITY OF CALIFORNIA, LOS ANGELES
UNIVERSITY OF CALIFORNIA, RIVERSIDE
UNIVERSITY OF CALIFORNIA, SAN DIEGO
CARNEGIE-MELLON UNIVERSITY
CBPF (BRAZIL)
CEN-SACLAY (FRANCE)
CERN (SWITZERLAND)
UNIVERSITY OF CHICAGO
UNIVERSITY OF COLORADO AT BOULDER
COLUMBIA UNIVERSITY
DELHI UNIVERSITY (INDIA)
DUKE UNIVERSITY
ELMHURST COLLEGE
FERMILAB
UNIVERSITY OF FERRARA (ITALY)
FLORIDA STATE UNIVERSITY
UNIVERSITY OF FLORIDA
COLLEGE DE FRANCE (FRANCE)
INFN, FRASCATI (ITALY)
FREIBURG UNIVERSITY (GERMANY)
GENERAL ELECTRIC R&D CENTER
INFN, GENOVA (ITALY)
UNIVERSITY OF GUANAJUATO (MEXICO)
HARVARD UNIVERSITY
UNIVERSITY OF HAWAII AT MANOA
UNIVERSITY OF HOUSTON
UNIVERSITY OF ILLINOIS, CHICAGO CIRCLE
ILLINOIS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF ILLINOIS, CHAMPAIGN
INDIANA UNIVERSITY
IOWA STATE UNIVERSITY
UNIVERSITY OF IOWA
JADAVPUR UNIVERSITY (INDIA)
JOHNS HOPKINS UNIVERSITY
KAZAKH STATE UNIVERSITY, ALMA-ATA (USSR)
KEK (JAPAN)
INP, KRAKOW (POLAND)
KYOTO UNIVERSITY (JAPAN)
LAPP, D'ANNECY-LE-VIEUX (FRANCE)
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF LECCE (ITALY)

LEHIGH UNIVERSITY
INP, LENINGRAD (USSR)
LOS ALAMOS NATIONAL LABORATORY
UNIVERSIDAD DE LOS ANDES(COLUMBIA)
LOUISIANA STATE UNIVERSITY
UNIVERSITY OF LOUISVILLE
UNIVERSITY OF MARYLAND
UNIVERSITY OF MASSACHUSETTS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MAX-PLANCK INSTITUTE (GERMANY)
MCGILL UNIVERSITY (CANADA)
MICHIGAN STATE UNIVERSITY
UNIVERSITY OF MICHIGAN
INFN, MILANO (ITALY)
UNIVERSITY OF MILANO (ITALY)
UNIVERSITY OF MINNESOTA
UNIVERSITY OF MISSISSIPPI
ITEP, MOSCOW (USSR)
NANJING UNIVERSITY (PRC)
SUNY AT ALBANY
SUNY AT STONY BROOK
NEW YORK UNIVERSITY
UNIVERSITY OF NORTH CAROLINA
NORTHEASTERN UNIVERSITY
NORTHERN ILLINOIS UNIVERSITY
NORTHWESTERN UNIVERSITY
NOTRE DAME UNIVERSITY
OHIO STATE UNIVERSITY
UNIVERSITY OF OKLAHOMA
OSAKA CITY UNIVERSITY (JAPAN)
UNIVERSITY OF PADOVA (ITALY)
UNIVERSITY OF PAVIA (ITALY)
PENNSYLVANIA STATE UNIVERSITY
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INFN, PISA (ITALY)
UNIVERSITY OF PITTSBURGH
PRAIRIE VIEW A&M UNIVERSITY
PRINCETON UNIVERSITY
UNIVERSITY OF PUERTO RICO
PURDUE UNIVERSITY
RAJASTHAN UNIVERSITY (INDIA)
RICE UNIVERSITY
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UNIVERSITY OF ROCHESTER
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UNIVERSITY OF WISCONSIN-MADISON
UNIVERSITY OF WUPPERTAL (GERMANY)
YALE UNIVERSITY

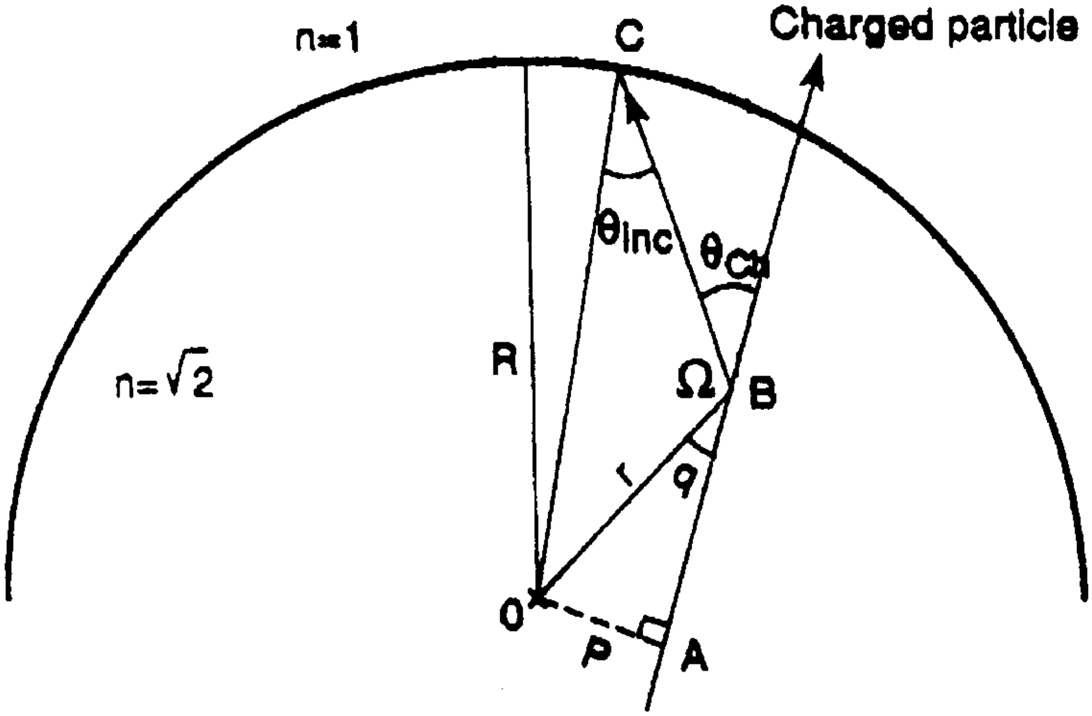
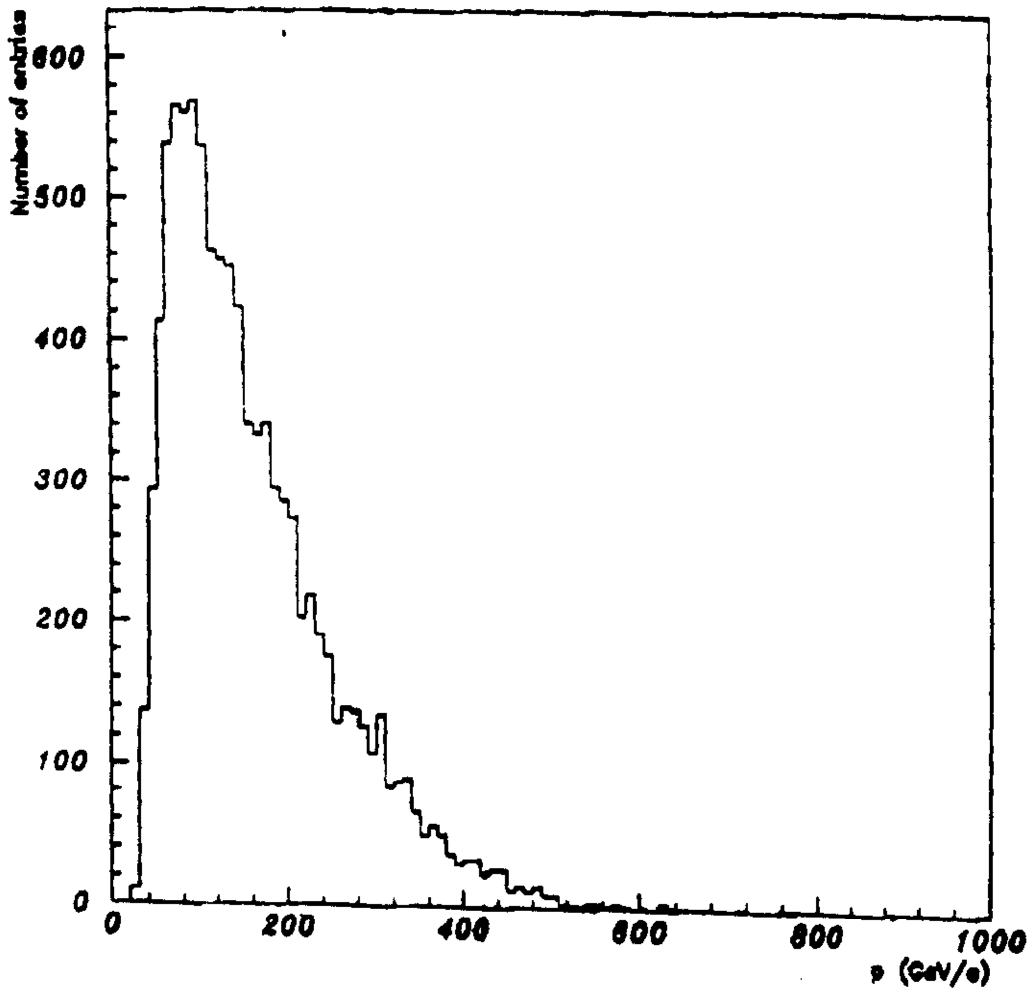


Fig. 1



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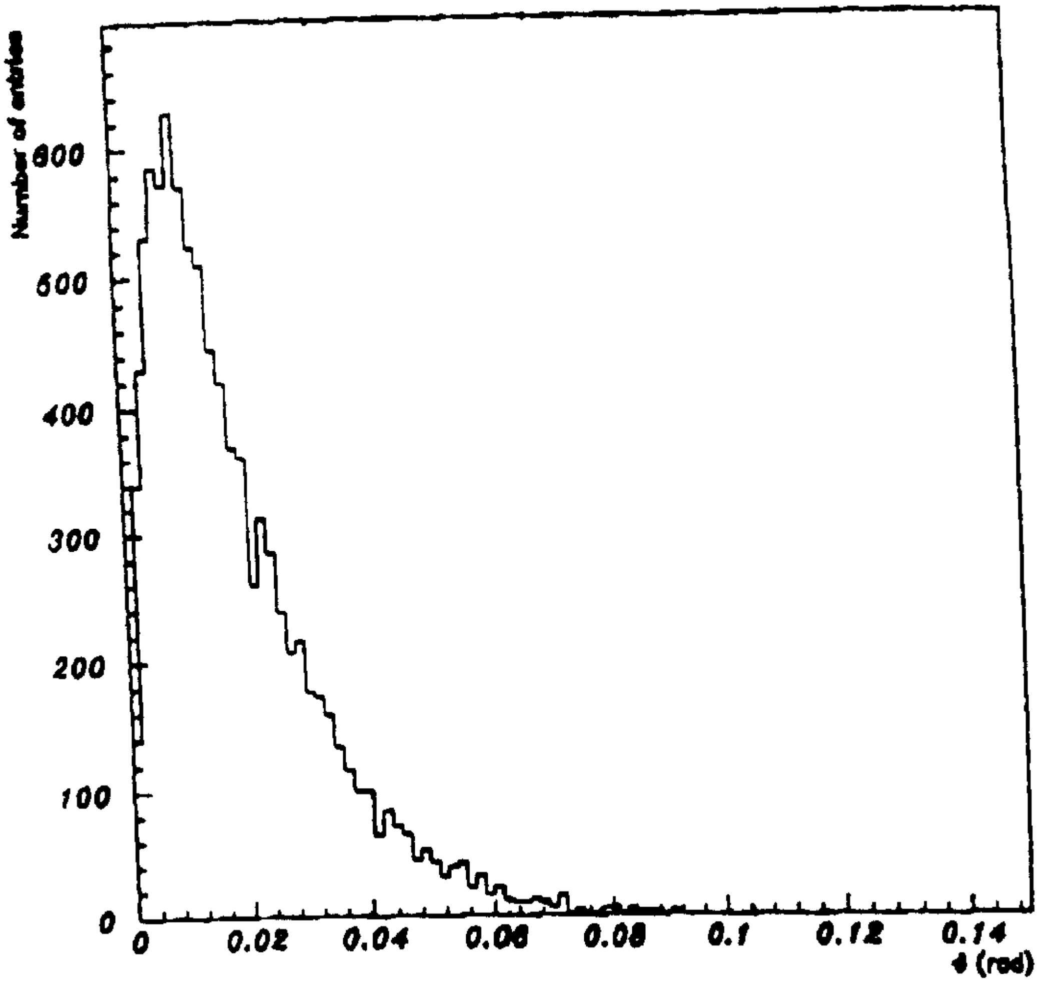
100
0
0
200
400
600
800
1000
p (GeV/c)

Fig. 2



Number of entries
600
500
400
300
200
100
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
ϑ (rad)

Fig. 3

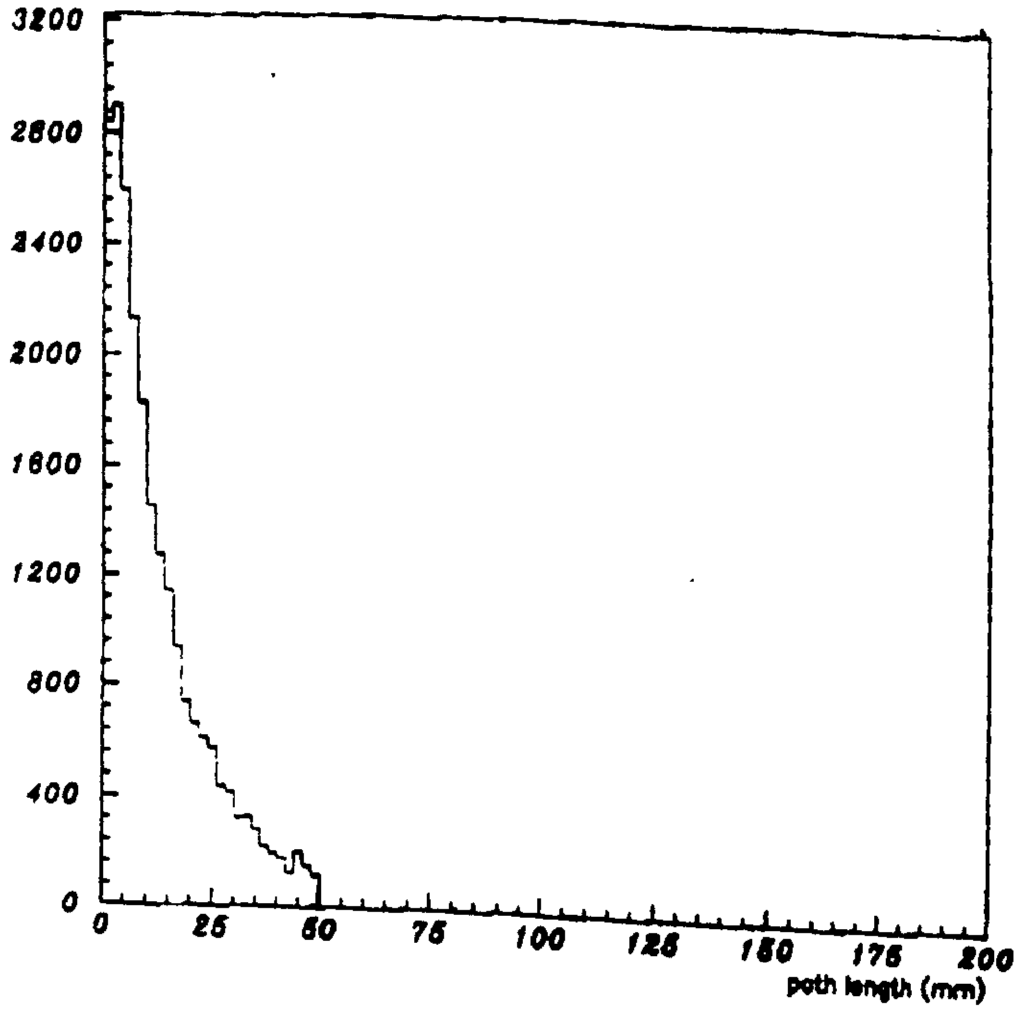

3200
2800
2400
2000
1600
1200
800
400
0
0
25
50
75
100
125
150
175
200
path length (mm)

Fig. 4

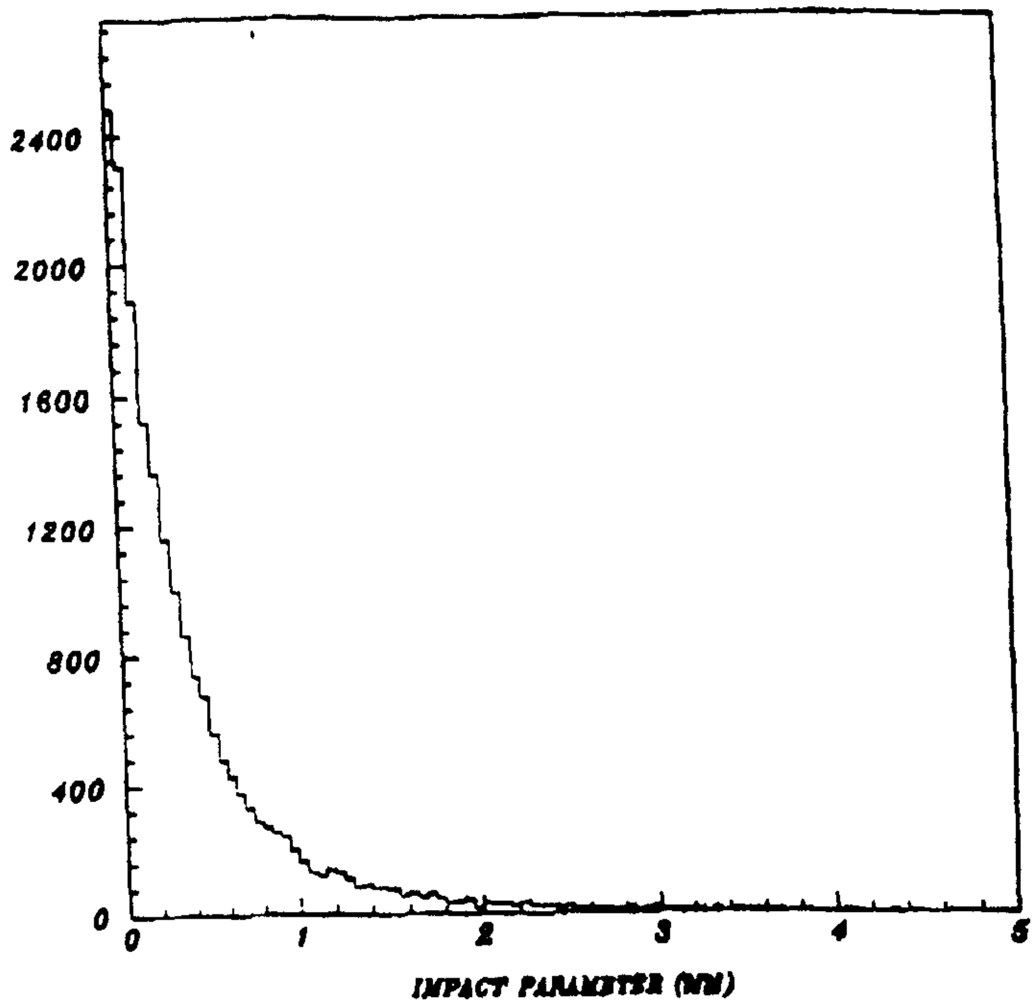


Fig. 5

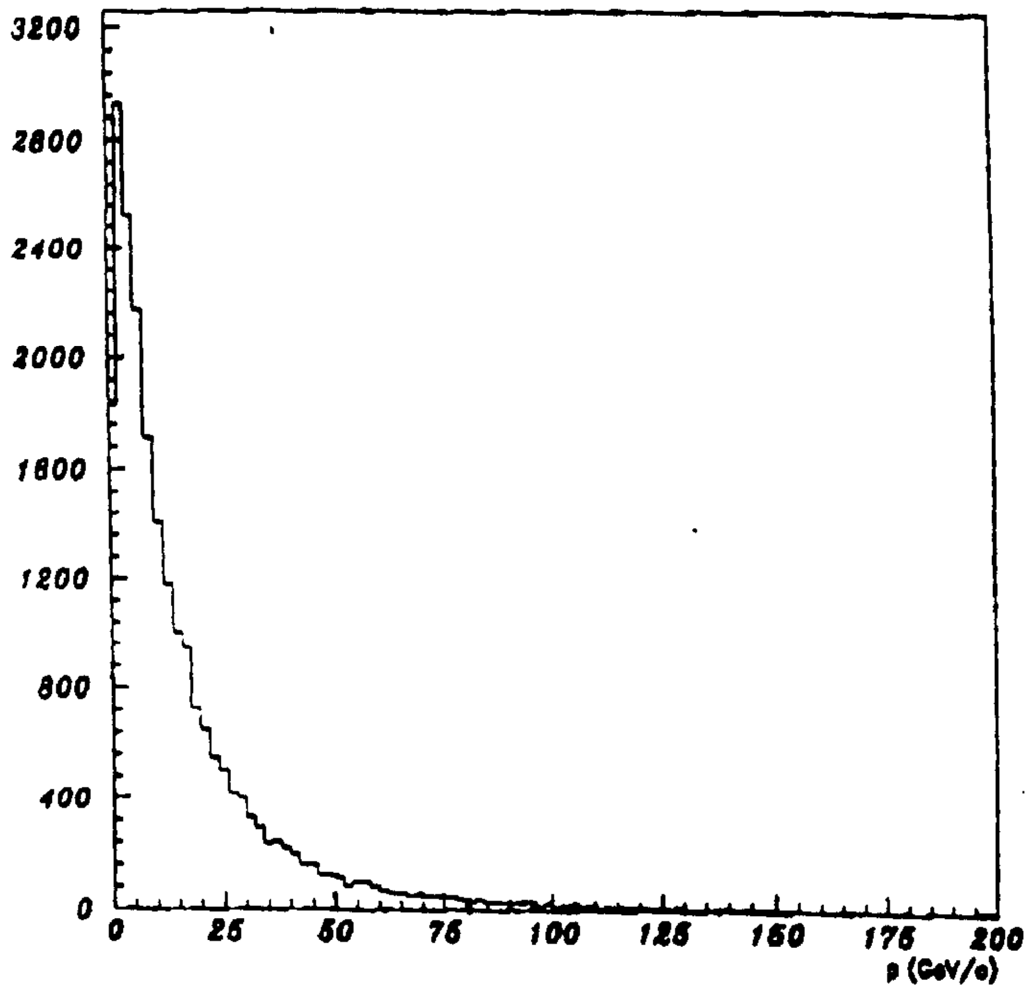
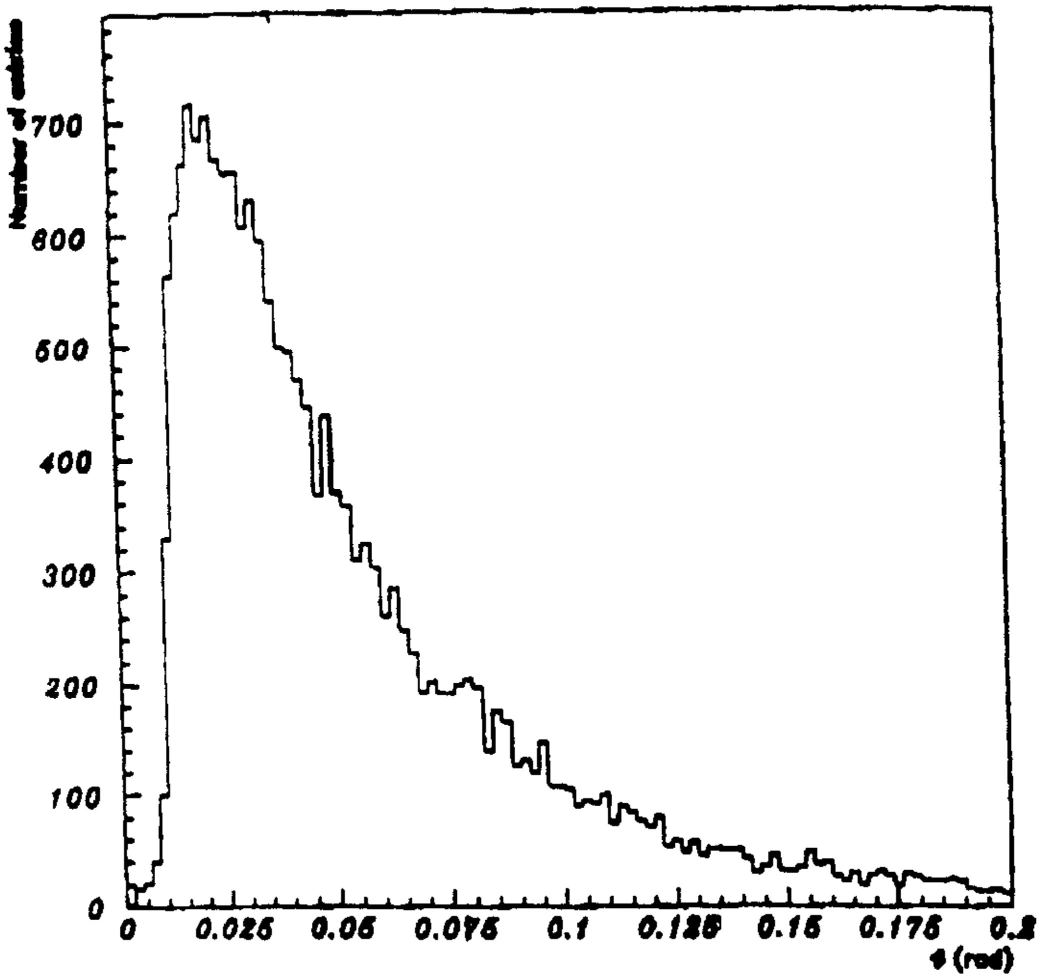

3200
2800
2400
2000
1600
1200
800
400
0
0
25
50
75
100
125
150
175
200
p (GeV/c)

Fig. 6



Number of entries
700
600
500
400
300
200
100
0
0
0.025
0.05
0.075
0.1
0.125
0.15
0.175
0.2
φ (rad)

Fig. 7

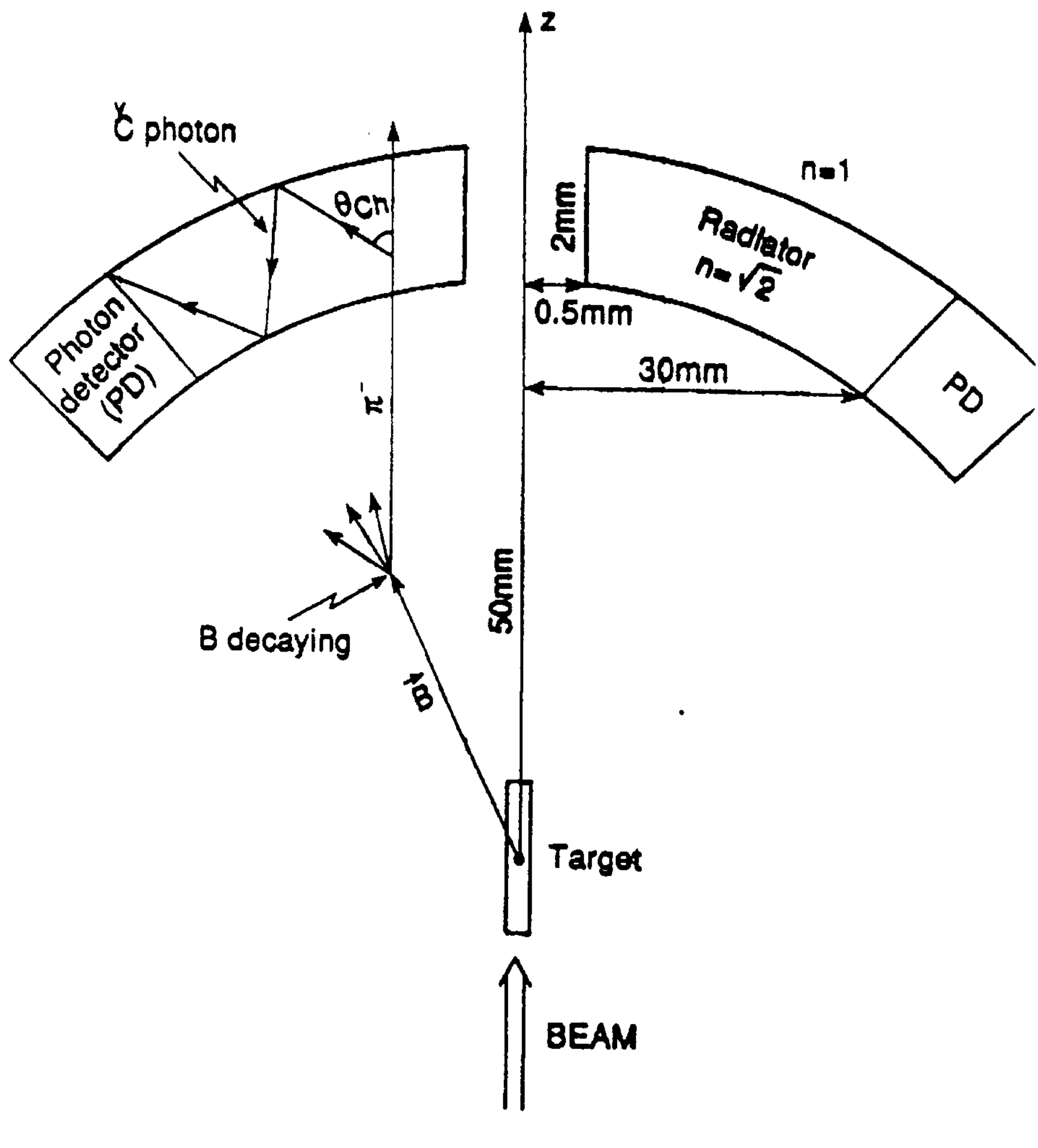

z
Č photon
θCh
n=1
2mm
Radiator
n=√2
0.5mm
Photon
detector
(PD)
30mm
PD
π⁻
50mm
B decaying
B
Target
BEAM

Fig. 8

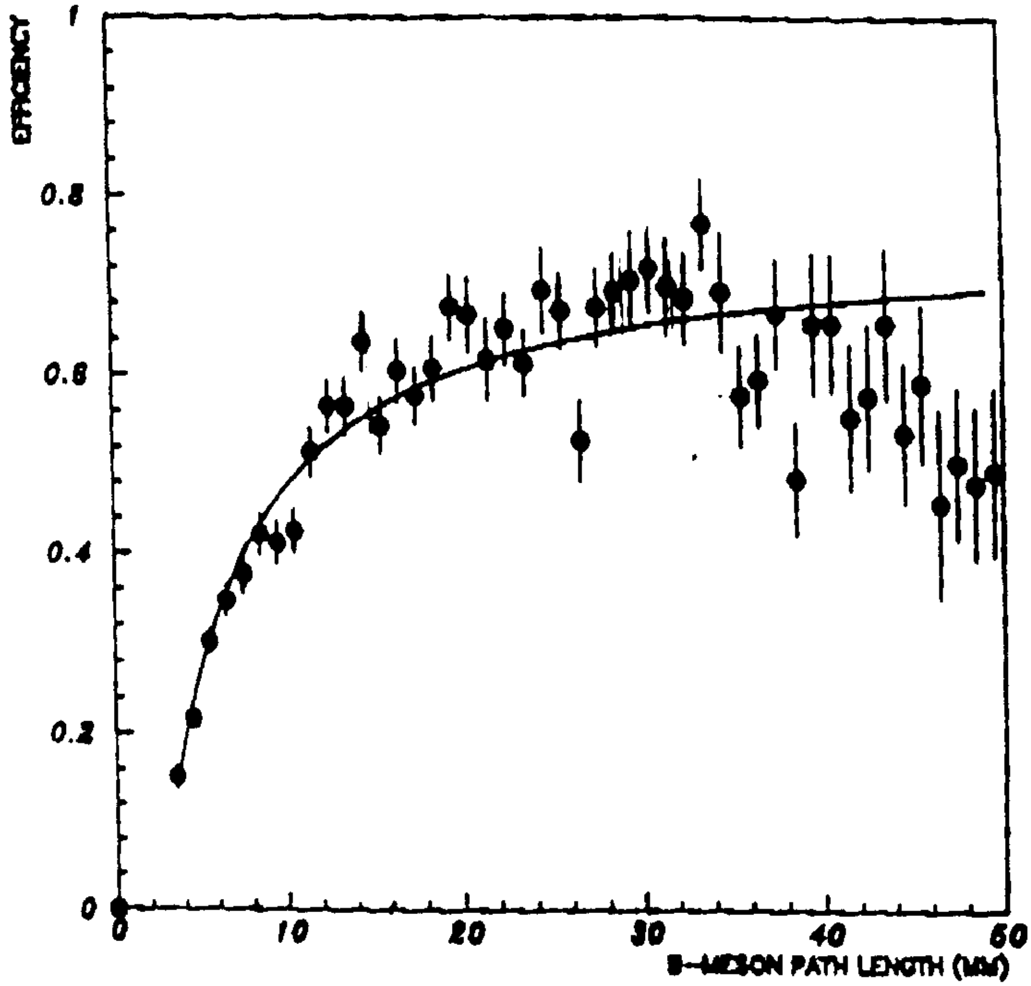


Fig. 9