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THE INTERFACE BETWEEN THE PHYSICS OF HIGH-ENERGY COSMIC RAYS AND EXPERIMENTS AT PARTICLE ACCELERATORS

Lawrence W. Jones
University of Michigan

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THE INTERFACE BETWEEN THE PHYSICS OF HIGH ENERGY COSMIC RAYS AND EXPERIMENTS AT PARTICLE ACCELERATORS

LAWRENCE W. JONES*
University of Michigan
Ann Arbor, Michigan, U.S.A.

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1. Introduction

At the Vulcano Workshop in 1992 I was asked to discuss "Astroparticle Physics from Accelerators"; the request from the organizers to me for this conference was similar, and this presentation may be looked upon as a sequel to that earlier report, with emphasis on results and events of the intervening two years. Perhaps the most significant development to occur recently was the cancellation of the SSC by the United States Congress. Thus, as we look into the future, we can anticipate studying hadron physics at 2 TeV with the Tevatron Collider (equivalent to a cosmic ray proton of about 2 PeV incident on a stationary target) for the coming decade, and to the CERN LHC producing energies of 14 TeV in the center of mass (equivalent to a cosmic ray proton of 100 PeV) after about the year 2003.

Below I shall summarize recent Tevatron Collider results and results from the LEP electron-positron collider at CERN which may be relevant to cosmic ray physics. I will then discuss some smaller, specialized experiments particularly relevant to particle astrophysics. Finally, I will comment on recent discussions at CERN seeking to utilize the LEP detectors to study cosmic ray problems.

2. Tevatron Collider Results

The most recent news-worthy result from the Tevatron has been the reported evidence for the Top Quark. Recently the Collider Detector at Fermilab (CDF) group announced the observation of 12 events from 19 pb^{-1} of collider data which are consistent with the decay mode of the top quark into a bottom quark and a W intermediate vector boson, with either or both of these decay products in turn decaying leptonically (the W) or semileptonically (the b quark). The top quark mass quoted is 174 $\pm$ 17 GeV (where the error includes both statistical and systemmatic uncertainties) [1]. The group asserts that this identification is "99.75% certain".

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Other Tevatron results recently reported by the CDF group include new determinations of several inclusive $\bar{p}p$ cross sections, measured at 1800 GeV and 546 GeV c.m. [2]. These include the total, elastic, single diffractive, inelastic, and non-single diffractive cross sections. These values are summarized in Table I.

Table I. Elastic, Total, and Single Diffraction $\bar{p}p$ Cross Sections (CDF)

E_{cm}	1800 GeV	546 GeV
$\sigma_{\text{total}}(mb)$	80.03 ± 2.24	61.26 ± 0.93
$\sigma_{\text{elastic}}(mb)$	19.70 ± 0.85	12.87 ± 0.30
$2\sigma_{\text{single diff}}(mb)$	9.46 ± 0.44	7.89 ± 0.33
$\sigma_{\text{inelastic}}(mb)$	60.33 ± 1.40	48.39 ± 0.66
$\sigma_{\text{non s.d.}}(mb)$	50.87 ± 1.84	40.41 ± 0.89

The D0 group has also studied the question of "rapidity gaps" [3]. When two quarks scatter through the exchange of a gluon, the final state contains the exchanged gluon stretched as the excited quarks separate, and mesons are created and radiated along this stretching gluon. The result is that the region in rapidity space between the two final-state jets is populated by smaller meson-initiated jets. However, if the exchanged quantum is "colorless", e.g. is a meson or a "Pomeron" (of diffraction scattering fame), there is no final state radiation along this exchange, and the two jets are cleanly separated. A measure of this may be obtained by studying events where there is a gap in rapidity space between two energetic final-state jets. This is illustrated in Figure 1. The results of the D0 search for rapidity gaps is shown in Figure 2, where the fraction of events with no tagged particles between the two leading jets is plotted as a function of the gap between jets as measured in units of pseudo-rapidity.

While the probability distribution of events with rapidity gaps agrees with QCD calculations for small $\delta\eta_c$, the observed fraction with a gap significantly exceeds calculated color-gluon exchange for $\delta\eta_c \geq 3$.

3. LEP Physics

The CERN electron-positron collider has completed 5 years of data collection with the four LEP detectors operating on and near the Z Intermediate Vector Boson mass (about 91 GeV). Recently a report has appeared with a summary of important parameters of the Z derived from a statistical averaging of results from the four independent experiments [4]. Table II below is a summary of these results. All of the results are in good agreement with predictions of the Standard Model, where these predictions exist. A point worth following is the small (about 2 standard deviations) disagreement between the CERN and Stanford determinations of $\sin^2\theta_w$ [5].

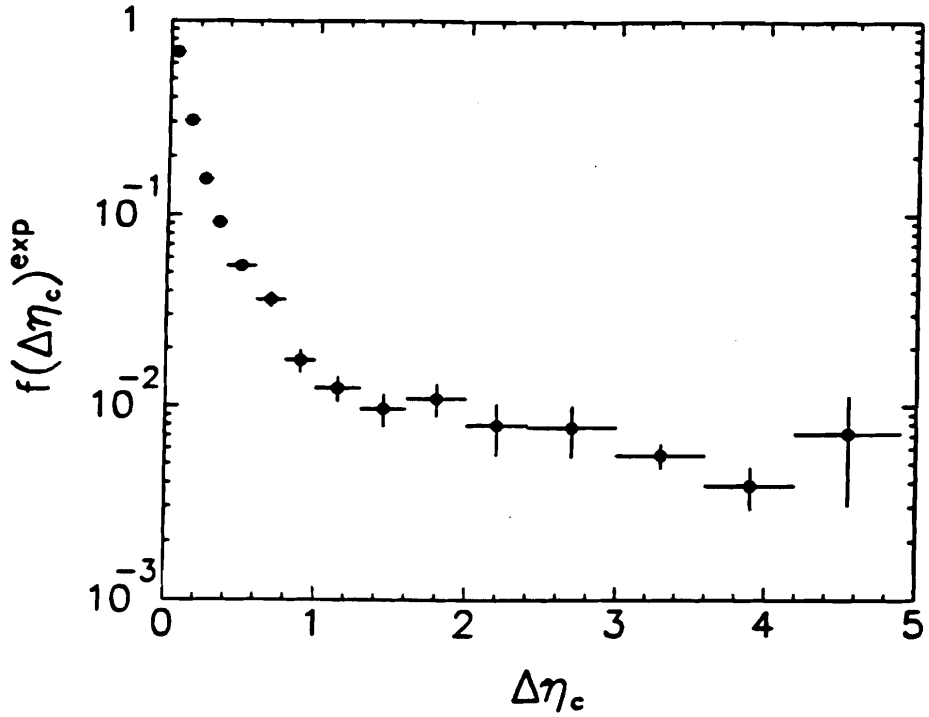

Figure 1. D0 observed fraction of events containing a rapidity gap as a function of gap width $\delta\eta$. Statistical errors only.

Beyond these confirmations of the Standard Model, LEP has reported no evidence for a host of other postulated objects. Searches have been made and negative results reported for the following: the (neutral) Higgs boson of m≤60 GeV, heavy (excited) leptons, super-symmetric particles, and other objects. An intesting set of 4 events was reported last year by the L3 group where these events appeared to include a pair of gammas with an invariant mass of about 60 GeV [6]. As more data has been collected, including more high mass gamma pairs, the statistical significance of these events has declined.

Table II. LEP $e^+e^-(M_z)$ Summary ALEPH · DELPHI · L3 · OPAL

M_z = 91.183 ± 0.007 GeV	Γ_{inv} = 497.6 ± 4.3 MeV
Γ_z = 2.489 ± 0.007 GeV	g_v = 0.0359 ± 0.0018
N_v = 2.980 ± 0.027	g_A = -0.50093 ± 0.00082
Γ_ℓ = 83.82 ± 0.27 MeV	α_s = 0.123 ± 0.006
Γ_h = 1740.3 ± 5.9 MeV	$\sin^2\theta_w^{eff}$ = 0.2321 ± 0.0007
SLD: $\sin^2\theta_w^{eff}$ = 0.2292 ± 0.0009 (Stat) ± 0.0004 (Syst.)	

4. The Landau-Pomeranchuk-Migdal Effect

The Landau-Pomeranchuk-Migdal (LPM effect was calculated many years ago by these Russian authors; it predicts a departure from the classical Bethe-Heitler bremsstrahlung expressions (as well as those for pair production) due to multiple Coulomb

scattering in a short-radiation-length radiator for high energy electrons. This basically quantum mechanical effect considers the uncertain energy and momentum of a final state system following exchange of a virtual photon between an energetic electron and a nucleus. If, in the context of the Heisenberg Uncertainty Principle, the electron experiences another photon exchange (e.g., Coulomb scatter) before the Bremmstrahlung photon has been radiated, the effect is to suppress the radiation [7]. The effect is most important for soft photons radiated by high energy electrons in radiators of short radiation length. Specifically, the effect is important for photons of energy below a threshold given by:

$$\begin{aligned} E_\gamma &= E_c^2/E_{LPM}, \text{ where} E_{LPM} = 7.6\ X_o\ TeV, \\ E_c & \quad \text{is the incident electron energy, and } X_o \text{ is the radiation length in cm.} \end{aligned} \quad (1)$$

This effect is clearly important for cosmic ray photons of energies of 100 TeV and higher, and it is not readily apparent at accelerator energies where most of the quantitative verifications of QED have been carried out. There have been qualitative verifications of the effect from cosmic ray emulsion exposures and from an early experiment with 40 GeV electrons at Serpukhov [8].

At the Dublin International Cosmic Ray Conference, we proposed undertaking a quantitative study of the effect with a 350 GeV electron beam at Fermilab, and we subsequently made a formal proposal to Fermilab [9]. This proposal is still under discussion, and we are optimistic that we may undertake this measurement.

However, in the meantime, a young and energetic group at Stanford has carried out a very clean measurement at the Stanford Linear Accelerator Center with a 25 GeV electron beam there. Although the effect is only apparent at very low energies there, they none-the-less have very nice data [10], some of which is displayed in Figure 2.

5. A Search For Antiproton Decay

A Fermilab group has made a proposal to search for evidence of antiproton decays, and has recently published a preliminary lifetime limit orders of magnitude longer than older established data [11]. The obvious astrophysical and cosmological interest in this measurement is to explain the apparent matter-antimatter asymmetry of the Universe. Although there may well be other explanations (through CP-violating interactions in the early Universe), and although a decay lifetime of the antiproton different from that of the proton would violate CPT, never-the-less an antiproton lifetime of even 10^8 years would comfortably explain the particle-antiparticle asymmetry observed. If such a measurement is possible and straight forward, it seems well worth doing.

The experiment, known as APEX (AntiProton Experiment) looks at a high-vacuum section of the 8 GeV antiproton accumulator ring at Fermilab, and, with an array of track chambers, scintillators, and lead-glass calorimeters, seeks evidence for decays in flight leading to $e^-\pi^o$ and other final states. Their preliminary data already set a lower limit of about 1000 years to the antiproton lifetime, and they expect to push below a million years with a new, specially engineered vacuum tank and detector improvements [12].

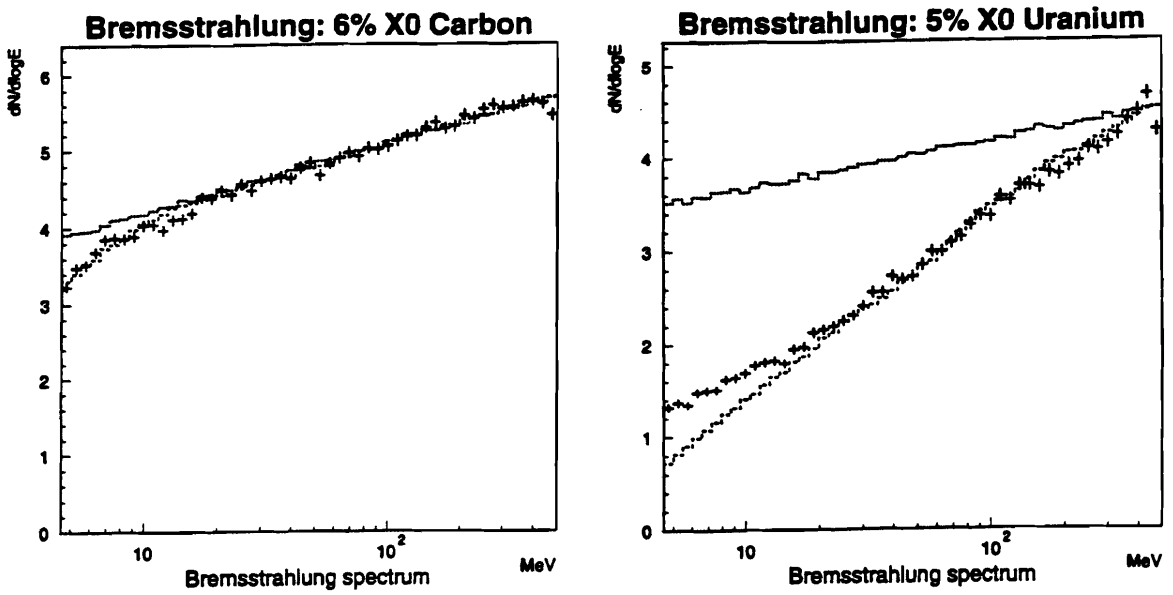

Figure 2. Bremesstrahlung spectra from 25 GeV electrons on 5% radiation length U and 6% radiation length C illustrating the LPM effect. The lines are the Bethe-Heitler predictions, the dashed lines are the LPM prediction, and the pluses are the data.

6. Neutrino Oscillation Searches

Three problems in particle astrophysics may relate to neutrino oscillations. First there is the apparent deficit of solar (electron) neutrinos as recorded in the various solar neutrino detectors [13]. Second, there is the disagreement between the ratio of electron neutrinos to muon neutrinos from cosmic ray interactions in the atmosphere, as seen by the proton decay experiments (IMB and Kamiokande) [14]. And, third, if neutrinos have mass, the eigen states of mass are probably not the eigen states of the generations, and oscillations between these states would occur. Then, the heaviest neutrino, the tau neutrino, could have a mass of 10 - 100 eV; sufficient to account for the missing "hot dark matter" in the universe.

There have been many neutrino experiments at accelerators in the past, although none have seen any evidence for oscillations. Currently there are two large experiments planned at CERN (referred to as "Nomad" and "Chorus") and one at Fermilab (E-803). The emphasis in these newer experiments is on the search for $\nu_\mu - \nu_\tau$ oscillations; the earlier accelerator experiments had focused on searches for evidence for $\nu_\mu - \nu_e$ oscillations. From the E-803 proposal, the limits which they and one of the CERN experiments hope to achieve on mass differences and mixing angles between the muon- and electron-neutrinos and the tau neutrino have been plotted; this graph is reproduced in Figure 3.

Beyond these short base-line experiments, there are experiments planned for the large proton accelerators to search for oscillations over a longer base-line, extending well beyond the boundaries of the accelerator laboratories. For example, the KEK proton accelerator in Japan will direct a neutrino beam towards Super-Kamiokande. The Nomad and Chorus experiments will get underway first; it will be some years

before E-803 and the longer-baseline programs begin taking data.

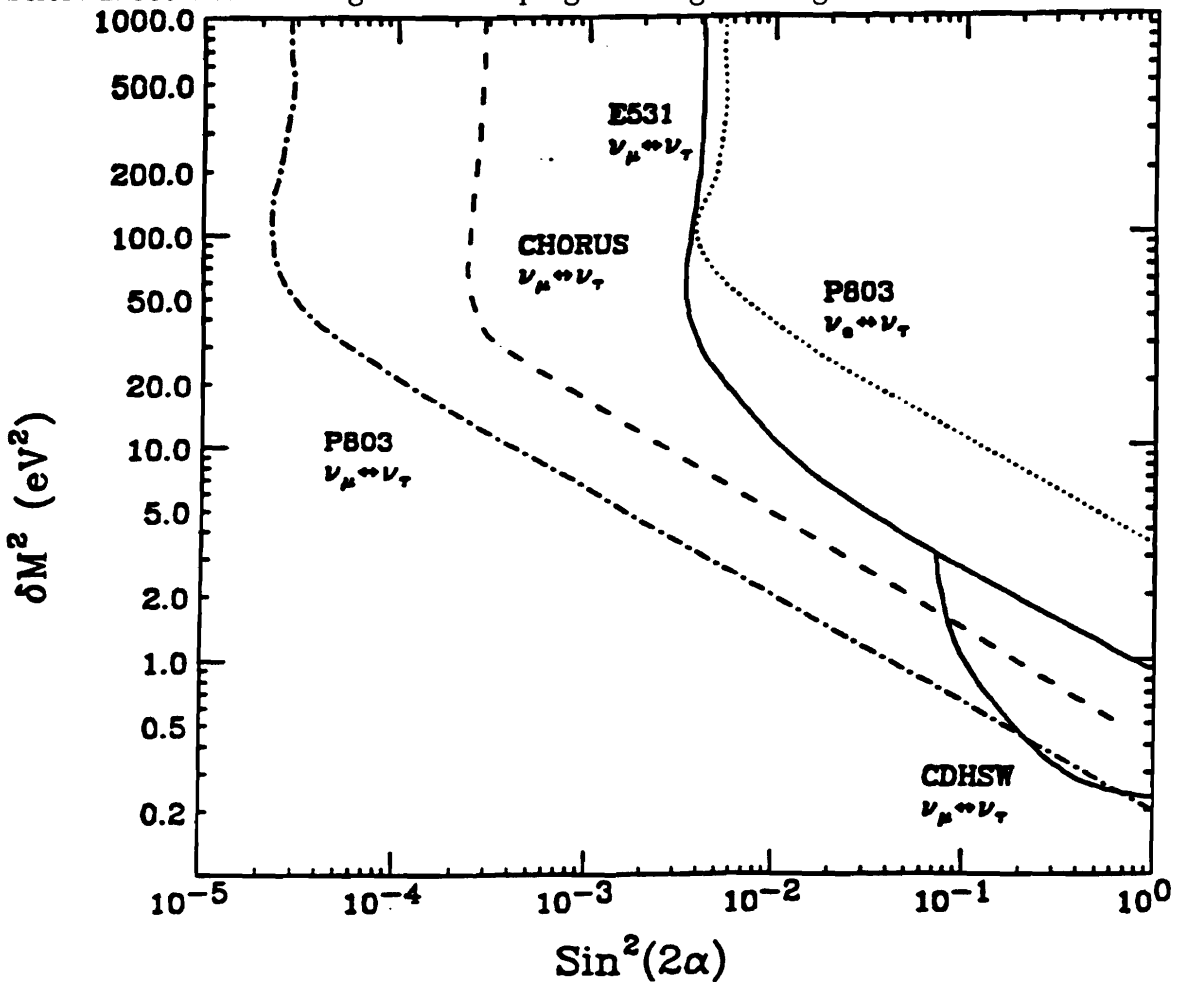

Figure 3. Oscillation limits for $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_e \leftrightarrow \nu_\tau$ short-baseline experiments. Existing limits are given by the solid curves; and the anticipated CHORUS limit by long dashes. The P803 $\nu_\mu \leftrightarrow \nu_\tau$ projected limit is given by the dash-dot curve.

7. Centauros and Anticentauros

For many years a Brazil-Japanese collaboration has had a research program at the Mt. Chacaltaya Laboratory (elevation 5200 m) in Bolivia wherein they have exposed emulsion chambers of very large area (33m^2) to collect information on the energetic components of primary cosmic rays and their reaction products. Note that, at this elevation, the detector is under only about 500 g/cm^2 of atmosphere. These emulsion chambers employ layers of nuclear emulsions and X-ray film separated by layers of lead; the entire system employs one such stack as the upper layer, with a layer of about 30 cm of pitch (hydrocarbon) directly beneath, and another emulsion-lead stack about 150 cm below the pitch. An interaction in the atmosphere above the system produces gamma cascades in the top emulsion stack (from π^o decay gammas and their air shower progeny) and another set of cascades in the lower chamber induced by hadrons (charged pions) interacting in the pitch layer (as well as the continuation of EM cascades which originated in the upper stack).

In 1971, this group recorded a most unusual event; an energetic hadron interacted in the atmosphere about 50 m above the array (as determined from direct triangula-

tion from tracks in the nuclear emulsions), producing 43 hadrons detected in the lower chamber and only 1 certain EM cascade in the top chamber (reproduced in Figure 4). Because this event appeared to be a very different "beast" as seen below (in the lower chamber) than as seen above, the group named it after the mythical Greek "Centaur", half-man and half-horse. Subsequently the group searched for other Centauro candidates and reported four others; the properties of these are summarized in Table III (from the papers of the Brazil-Japan Collaboration [15]). Note that the detectors "see" only the electromagnetic energy, as manifested in EM cascades; from this "visible" energy, the energy of hadrons must be estimated (roughly twice the visible EM energy). There is also a minimum energy, about a TeV, below which a gamma cascade is not seen. The typical event energies are in the range of a few hundred TeV.

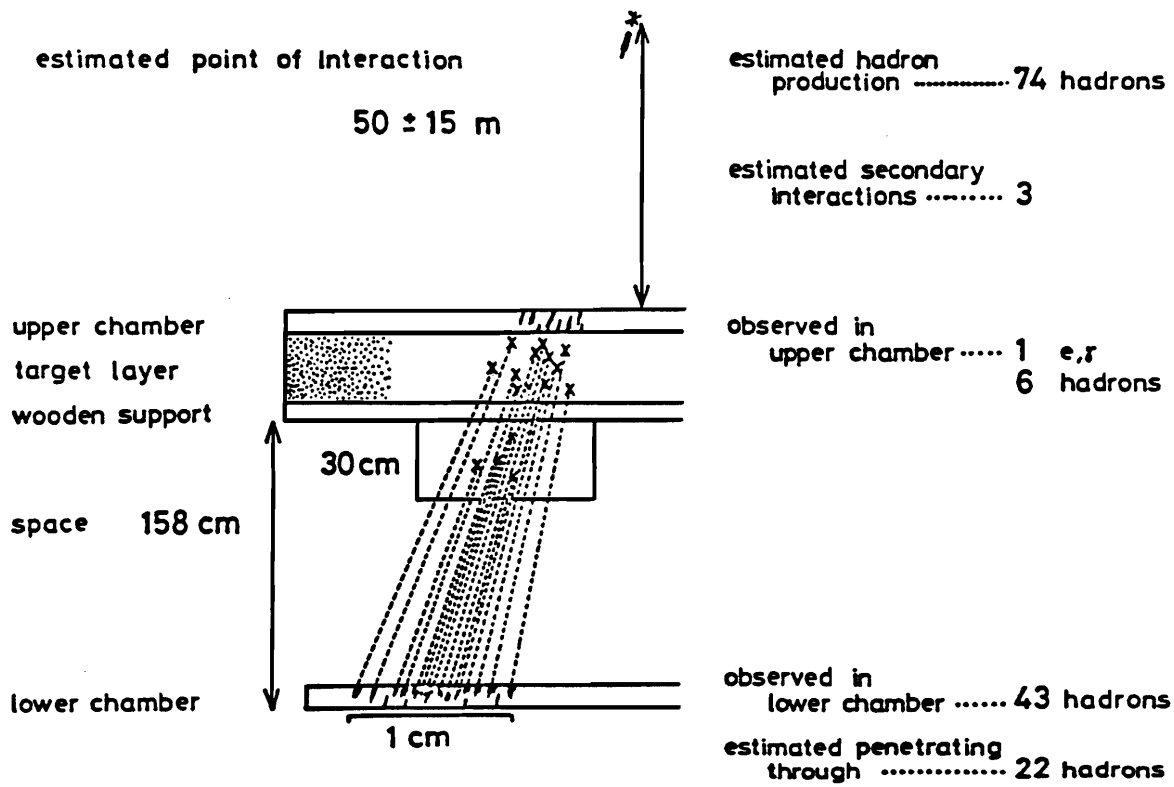

Figure 4. Centauro I, as reported by the Brazil-Japan Emulsion Chamber Collaboration.

Another very different experimental program has been undertaken by a Japanese-American Collaboration flying nuclear emulsion chambers in balloons near the top of the atmosphere. This Japanese-American Collaborative Emulsion Experiment (JACEE) uses a smaller version of a nuclear emulsions/lead stack with a low-Z plate "target" interspersed with emulsions above it for identification of the incident primary cosmic ray nucleus and observation of hadronic secondary interactions. Because of the limited time duration of the balloon flights and the limits on payload, the exposure (area-solid angle-time product) is much less than the Chacaltaya experiment, however the exposure is under only about 5 g/cm^2 of atmosphere, so that the shielding of several interaction lengths of atmosphere is avoided. This group has contributed very valuable data on the primary cosmic ray composition at energies above a TeV as well as studies of properties of the nuclear interactions [16].

They have reported one unusual class of events, in studying the distribution of charged and neutral (gamma rays) secondaries from a high-energy interaction. Some events are seen to have regions of "phase" space (really space in units of pseudorapidity vs azimuthal angle) populated almost entirely by gamma cascades. One such event is reproduced in Figure 5, where the initiating proton energy was about 100 TeV. As this is obviously just the opposite of the phenomenon reported by the Mt. Chacaltaya group, such events have been referred to as "Anti-Centauros".

8. Disordered Chiral Condensates

J.D.Bjorken [17] and Cyrus Taylor [18] have discussed "Disordered Chiral Condensates" (DCC) as a mechanism which might explain the otherwise-puzzling Centauro (and Anti-Centauro) phenomenon. Briefly, their idea is that, following a hard quark-quark collision, the expanding volume of the excited vacuum may have the isotopic spin vector frozen is isospin space, such that, when the vacuum "materializes" to pions, etc., there is a high probability that the resulting pions will be all neutral or all charged. Quantitatively, the prediction is that the distribution in the region of pseudo-rapidity - phi space occupied by the resulting pions will follow the following:

$$dN/df \propto f^{-\frac{1}{2}}, \text{where} f = \frac{N(\pi^o)}{N(\pi^o) + N(\pi^{\pm})}. \tag{2}$$

Otherwise, one would expect just a binomial distribution in f (based upon charge independence and simple statistics) peaked at f = 1/3.

One can argue that such effects are easily masked in the central region of a high energy interaction due to the large number of processes contributing to the large pion flux and that it is particularly relevant to look in the less-populated regions of the final state; e.g. at extreme values of rapidity. Of course the energies at which the Centauro phenomena are reported are altogether comparable to the energy of the Fermilab Tevatron collider (about 2 PeV; equivalent to 2 TeV c.m.). However, as noted in 1992 by Gaisser [19], the Tevatron experiments have focused largely on the central regions of pseudo-rapidity, optimal for searches for the top quark, studies of W and Z production, etc., whereas the cosmic ray observations are strongly weighted toward forward production, as they are really sensitive to energy flow. In this context, then, it may not be surprising that DCC have not been observed at the Tevatron and still have been seen in the much poorer statistical sample of cosmic ray events.

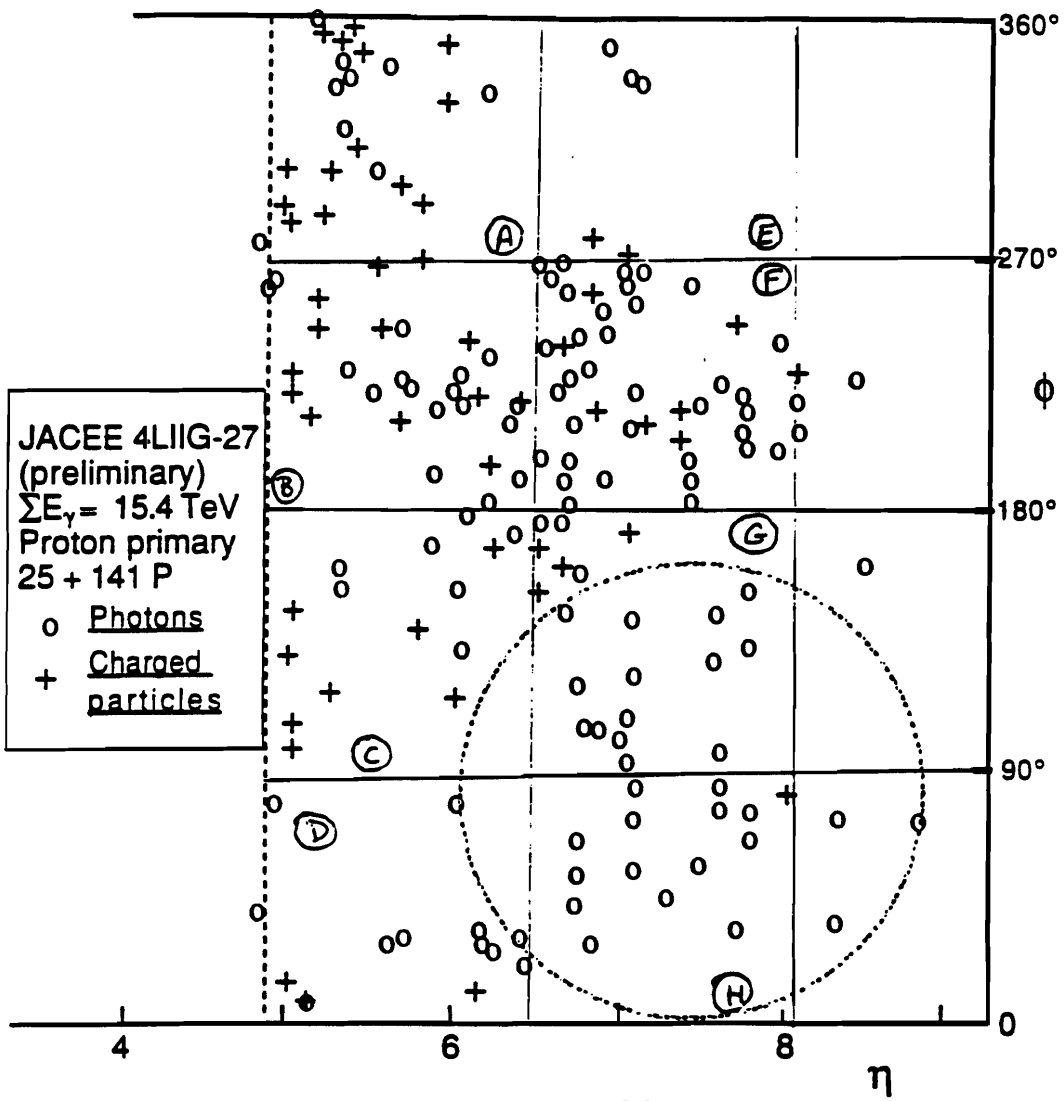

Figure 5. An event from the JACEE collaboration [4]. The region of $\eta - \phi$ space within the dotted circle contains an anomalously high ratio of gammas to charged secondaries.

9. Minimax

In order to study this concept and to seek evidence for DCC in accelerator data, a small test experiment has been set up in a colliding beam area at the Tevatron. This experiment, called "Minimax", is basically a proportional wire chamber telescope of 16 chambers "looking" at the $\bar{p} - p$ collision region at an angle of about 50 milliradians (η about 4) together with appropriate trigger scintillators, a lead converter, and an array of lead-scintillator EM calorimeters. The region of phase space subtended is about one-half unit in radius in eta-phi variables. The objective is to study, on an event-by-event basis, the numbers of gammas and of charged hadrons (pions) in this solid angle. The experiment [20] is sketched in Figure 6.

Although the chambers, counters, electronics, and data collection are all assembled and operating successfully, no definitive data have yet been taken due to serious background from the accelerator beam pipe. A new vacuum tank is being fabricated and

will be installed at the end of this year.

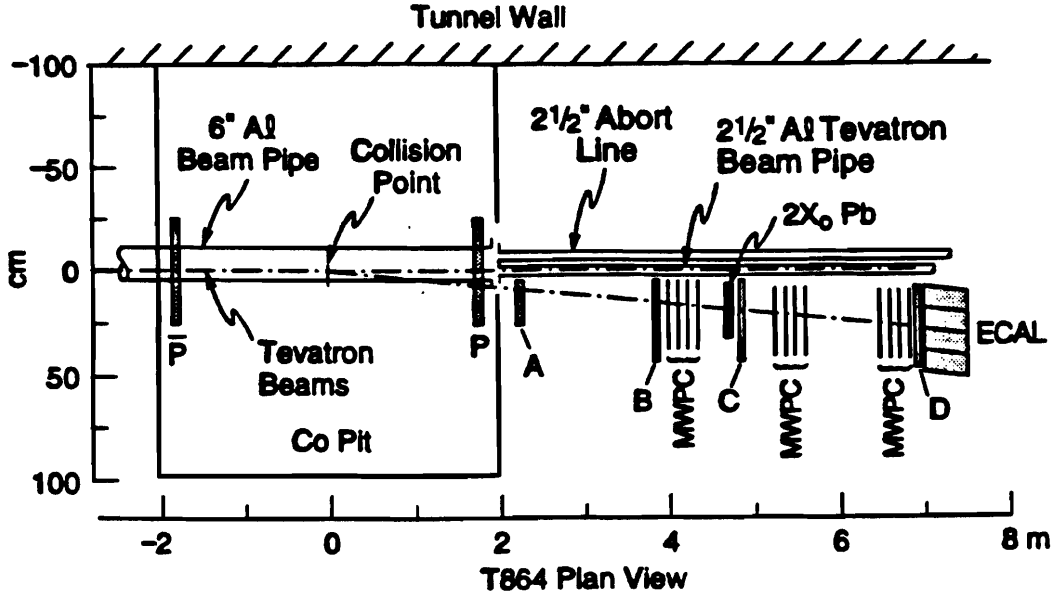

Figure 6. Layout of the MiniMax detector now installed at the C0 interaction region at Fermilab.

10. LEP and Cosmic Rays

The CERN Large Electron Positron (LEP) Accelerator-Collider has four major detectors located on the corners of a square with sides of (approximately) 6 km. Each detector subtends an area of tens of square meters. The electron and positron beams collide for much less than a microsecond with 22 microseconds between collisions. It occured to several experimentalists that there might be interesting cosmic ray questions which could be explored during this idle time between beam crossings.

Within the L3 collaboration, three ideas have been discussed. This detector is under 30 meters of earth, and its largest detector component is a system of high-precision drift chambers for the study of muons from the e^+e^- collisions. These chambers cover a projected horizontal area of about 88 square meters. The first idea is to make a precision, high-statistics measurement of the muon flux vs. energy, over the range between about 25 GeV and 2 TeV. This would be useful in the context of understanding the discrepency between calculations and data on the ratio of electron neutrino and muon neutrino interactions as observed in the proton decay detectors. Existing, older data are accurate to only about 20%; it should be possible to reduce this error by an order of magnitude.

The other idea is to look with high statistics and fine angular resolution at the source distribution of muons on the celestial sphere. A decade ago there were a number of reports, albeit all with marginal statistics, of point sources of muons. Although not confirmed by subsequent investigations, it would nevertheless be interesting to search for sources in the large data sample of muons which could be readily collected. The muon energy range to which the L3 detector is sensitive has not been previously explored for evidence of point sources.

A third concept has been advanced by H. Wachsmuth of the Aleph collaboration. Referred to as COSMOLEP, he suggests looking for coincidences between the 4 LEP detectors; i.e., looking for cosmic ray events which may produce parallel and simula-

neous muons in the four detectors. No one knows what might produce such events, but a simple experiment by Swiss cosmic ray physicists has reported evidence of marginal statistical significance for coincidences between four scintillation counters located over 100 km apart (Bern, Geneva, and two other intermediate locations) [21]. Such an experiment would be totally exploratory.

11. Conclusions

Altogether, there is a growing liason between the experimental groups doing particle physics with accelerators and cosmic ray experimentalists. The joint attacks on physics problems in areas of overlap will surely result in a more rapid resolution of puzzles recognized by both groups.

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