* 29 May 1996

Full Acceptance Physics at a C0 MiniCollider Region

K. L. Kowalski & C. C. Taylor
Case Western Reserve University

H. R. Gustafson, L. W. Jones & M. J. Longo
University of Michigan

J. D. Bjorken
Stanford Linear Accelerator Center

1 Introduction

A C0 MiniCollider region in Tevatron Run II offers a unique opportunity for a compelling program of physics complementary to that of CDF and D0. A comparatively modest detector, developed in conjunction with the redesign of the magnetic architecture of the C0 straight section, would be able to detect diffractively scattered protons and p-bars, provide a zero-degree channel for neutrals, and be sensitive to inelastically produced particles of generic transverse momenta over (almost) all of the kinematically allowed range, with particular emphasis on reaction products at high pseudorapidities ($|\eta| >\sim 4$). Such a detector, with good pattern recognition over all of phase space, will be able to pursue a substantial physics agenda largely inaccessible to the present or improved CDF and D0.

2 The Concept

Collisions at the Tevatron produce particles of generic transverse momentum over more than 16 units of pseudorapidity. We address physics in which all particles (charged hadrons and gammas) of generic transverse momentum are seen, and their momentum well measured. While there will be compromises which have to be made, we believe that it is particularly important that the ability to detect rapidity gaps not be compromised.

3 The Physics Agenda

The agenda of a full acceptance detector of the sort we envision is vast, and largely inaccessible to CDF and D0. The items on the agenda address questions of substantial theoretical and/or experimental interest; some of these are subjects of great controversy. Other items involve directly confronting claims that new physics has been seen in cosmic ray experiments. The detector we envision can be definitive in either confirming these discoveries or laying the claims to rest, at least at Tevatron energies. Finally, other items on the agenda represent solid programmatic physics which it has been physically impossible to pursue at CDF or D0 simply because of the constraints of the machine lattice.

A more comprehensive summary of the physics agenda can be found in the appendix. The principal items:

- **Rapidity gaps (diffraction)**

  Measurement of soft double diffraction, hard diffraction, Ingelman-Schlein production, onset of BFKL enhancement, rapidity gap tags for new physics...

  These measurements, largely inaccessible to CDF and D0, will provide valuable information on the structure of the pomeron (complementing the recent HERA results), on the transition between the perturbative and non-perturbative domains of QCD, and will confront predictions of non-perturbative enhancement of various processes with data.

- **Enhanced heavy-flavor production in the forward direction**

Both theoretical considerations and cosmic ray experiments suggest that there may be substantial non-perturbative enhancements of heavy flavor production in the forward direction. At present, not even strangeness production has been measured in the forward direction at Tevatron energies (though MiniMax, T-864, may be able to report results on K_s and Λ production).

- **Forward particle spectra and associated studies**

  The measurements of leading nucleon spectra and the associated question of the spectral distributions of the forward production of secondaries (including checks of scaling violations) are of intrinsic interest, and would for example give direct input to the analysis of the ν e and ν μ crises in cosmic ray neutrinos. It would also be valued by the cosmic ray and astrophysics communities (such as the Auger project) as input into air shower simulations.

  The ability to tag leading particles opens up a variety of tests of the fate of valence quarks in collisions at collider energies, as well as the possibility of tagging meson-nucleon or meson-meson interactions at collider energies. The measurement of inclusive yields and spectra of forward neutrals will be breaking new ground at collider energies. Taken together, these measurements will go far towards the elucidation of many anomalies reported by cosmic ray experiments.

  A substantial class of exotic new particles, e.g. "heavy long lived strongly interacting neutrals", can be very effectively and economicaly searched for with the forward neutral channel. Such particles are suggested by a variety of speculative theoretical ideas.

- Multiparticle and multijet production and correlation studies

  A variety of issues as color coherence, studies of the fractal nature of QCD phase space, disoriented chiral condensates, the onset of norperturbative effects in QCD, anomalies in low p_t production, etc. can be confronted with data.

4 Design considerations

4.1 Magnetic Architecture

The principal difficulties involved in designing a fulll acceptance detector arise from the need to coexist with elements of the machine lattice throughout the straight section. Indeed, elements of the machine lattice should be thought of as part of the magnetic architecture of the detector.

Much of the period of the C0 MiniCollider study was spent trying to understand constraints imposed by the long-term goals for the region as a low β intersection point. While we have hope that potential difficulties involving aperture restrictions and very limited free transverse space for detectors in the design of the low β lattice can in fact be overcome, this is well beyond the scope of what could be accomplished during the study period.

Perhaps more importantly, it appears that it is unlikely that C0 will make the transition to a low β region until several years after Run II begins (and after the civil construction proposed for 1998). We believe that this offers a remarkable window of opportunity in which a full acceptance detector could be implemented with comparitively minor modifications to the lattice of the C0 straight section.

We do not present a complete design of the new straight section; in addition to being beyond the scope of what could be accomplished in the study period, the optimum configuration depends on a variety of questions of resource availability. Instead, we review the current C0 lattice structure, and use that to argue that a solution to the problem exists. We then present a schematic of what the modifications to the magnetic architecture might look like.

Figure 1 is a diagram of the present C0 straight section in the upstream proton direction, and illustrates many of the issues involved in the design of the detector we envision.

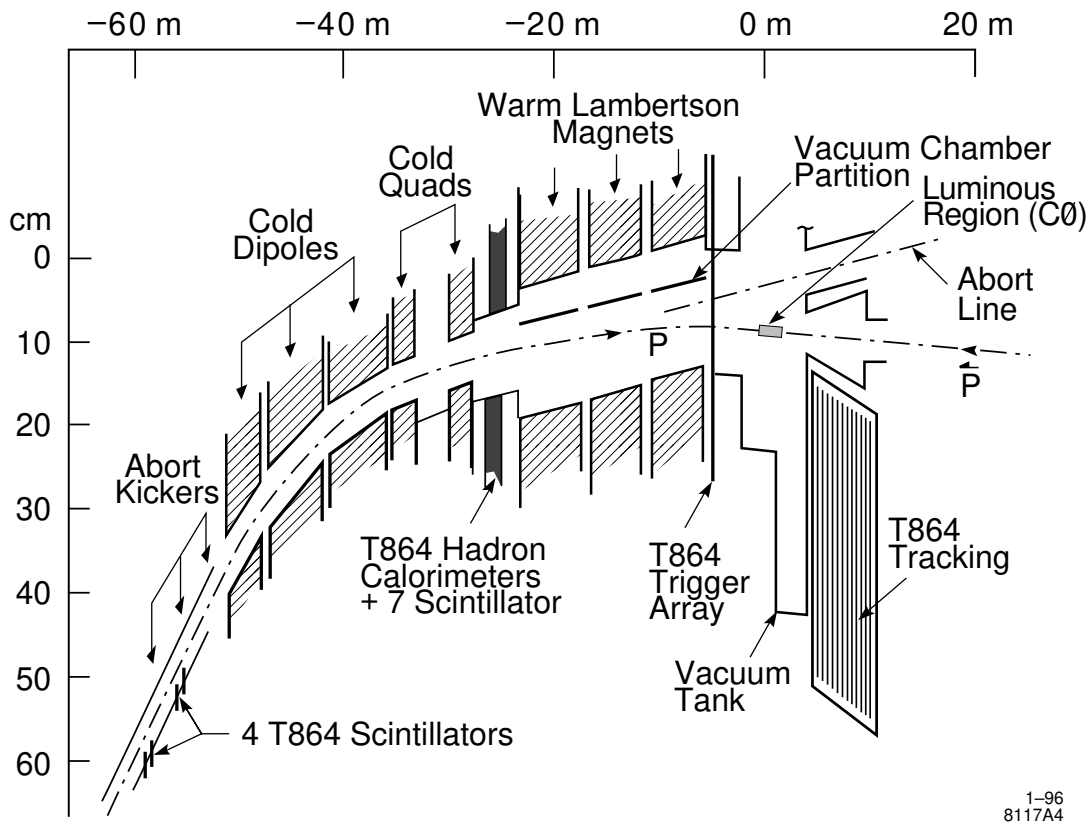

Figure 1: T-864 upstream instrumentation. Downstream C magnets not shown.

First, we note that on this side of the collision point, there are three significant regions of free space, permitting the installation of detectors: 5m from the collision point to the first Lambertson magnet, 4m meters between the third Lambertson magnet and the (cold) quadrupole (23-27 m upstream of C0), and 2m at B48 (58-60 m upstream) at the location of a "missing" fourth kicker".

Next, note that the C0 straight section is not straight! Each of the three Lambertson magnets bends the beam by 1.836 mrad. As a result, the roughly two meters of free space between the Lambertsons and the quadrupoles become a wonderful location for detectors. There is (almost) a zero degree neutral channel (approximately 2.5" from the beam at this location). Unfortunately, the vacuum chamber partition within the Lambertson presents approximately an interaction length of material to the neutral beam, greatly complicating analysis with this configuration. Nevertheless, T-864 was able to tag events (crudely) using two hadron calorimeter modules placed on the outside of the 4" beampipe running through this section.

The opposite (downstream proton) side of C0 is somewhat more complicated in the present configuration. There is some 9 m of free space, followed by 2 C magnets, each with a bending power of 1.49 mrad. Because of the smaller bending power, shorter lever arm, smaller aperture and interference from the Tevatron abort, T-864 did not attempt to instrument this region.

In Run II, C0 need not be used for the Tevatron abort. One can thus imagine improving on the present configuration fairly easily, in a fashion which would be well-suited to full acceptance physics. The rough idea would be to replace the present Lambertson and C magnets with larger bore and field magnets, probably configured with a central magnet (or a central split dipole) with additonal forward spectrometer magnets. The integrated bending power of these magnets would be comparable to the roughly 28 T-m which the Lambertson and C-magnets currently represent.

4.2 Instrumentation and resource considerations

We envision tracking and calorimetry wherever possible. The precise technologies (chambers outside the beampipe, silicon detectors or scintillating fiber detectors in Roman pots, etc.) will depend on what can be scrounged, as well as on the final choice of magnetic architecture. We are certain that it will be possible to instrument the detector in a suitable fashion, though we

do emphasize that if this is worth doing, it is worth doing properly. Choice of technology will necessarily interact with issues of the beampipe design, which is also non-trivial. We are confident, based on our experience with T-864, that these problems can be solved.

We have been specifically asked to comment on the R&D value of the experiment, on the possible sources of funding new equipment for the experiment, and on the size of the community interested in the project. These three questions may be very closely linked. In this context, it is important to note the existence of FELIX, a possible Full Acceptance physics under study for the LHC at IP4[1]. While FELIX is not yet a collaboration, more than 150 physicists have expressed interest in the project. We regard this as a measure of the scope of interest in Full Acceptance physics. The possibility of conducting a full acceptance experiment at the Tevatron early in run II, before the C0 MiniCollider region moves to low β, is very attractive in the context of these plans at the LHC. One can envision a situation in which European physicists would play an active role in the C0 MiniColllider project, developing detectors and other pieces of equipment, which, after use at C0 could then be transported to the LHC. (Note that even the analysis magnets proposed for FELIX are well matched for the C0 straight section). We believe the potential for synergy, maximizing the discovery potential of both the Tevatron and the LHC in a staged fashion, is extremely attractive.

Similarly, it seems eminently possible that the full acceptance environment envisioned here could play an important role as a testbed for a B-physics experiment to be mounted after the C0 region proceeds to low β. Again, the opportunities for synergy are probably too great to be overlooked.

5 Requests to the Director and PAC

Fermilab has an opportunity to pursue a unique program of full acceptance physics at a C0 MiniCollider facility in Run II. We ask the Director and PAC to endorse the idea, and work with us to make this opportunity a reality.

[1]See http://www.cern.ch/FELIX/

APPENDIX: Physics Agenda

A General Philosophy

Collisions at the Tevatron produce particles of generic transverse momentum (0.5 GeV) over more than 16 units of pseudorapidity, from $-8.3 < \eta < 8.3$. A detector sensitive to particles of generic transverse momentum over the kinematically allowed range will be able to isolate and study interesting classes of events via their pattern structure in individual events. The physics agenda of such a detector is vast, and by definition, largely complementary to that of the major collider detectors which concentrate on rare, high p_t processes. The physics agenda includes (but is not limited to):

B Physics of rapidity gaps (diffraction)

The physics of events with rapidity gaps is of considerable intrinsic interest, both theoretically and experimentally. In addition to providing a framework in which to study the transition from perturbative to non-perturbative behavior in the strong interactions, rapidity gap tags may be useful in isolating new physics, or non- perturbative enhancements of perturbative processes. These categories of events also provide a good way to benchmark the performance of a "full acceptance" detector.

In discussing the physics of rapidity gaps, we divide the subject into two categories, soft and semi-hard. The distinction is important as far as the design and performance of the detector is concerned: soft processes only require that one be able to observe the presence of a "gap" in the production of particles of generic pt with good efficiency, while the semi-hard processes also require the ability to identify jets, at least in the forward directions.

B.1 Soft processes

The simplest inelastic events with rapidity gaps arise from single diffractive scattering. In such events, one of the incident particles is scattered, intact, down the beampipe, while the other softly dissociates with the debris going

down the beampipe in the opposite direction. Such events are characterized by a large gap in pseudorapidity in which there are no particles produced. The process is attributed to the exchange of a "pomeron", understood in QCD terms as a complicated non-perturbative color singlet composite object. Single diffraction at the Tevatron has been studied by CDF using the central detector in conjunction with forward Roman pots to tag the diffracted proton; a full acceptance experiment at C0 would complement these studies, presumably improving both statistics and the kinematic range studied.

A related process is soft double diffraction. In such processes, both the incident proton and the incident pbar dissociate softly, with a large rapidity gap between he debris products of the incident particles. This process has not yet been studied at the Tevatron.

Pomeron-pomeron interactions can be studied by isolating events in which there are two rapidity gaps. Measuring these processes, together with those above, would go a long way towards providing the experimental input needed to elucidate the basic physics of inelastic soft diffraction.

B.2 Semi-hard processes

In the past several years there has been substantial theoretical and experimental interest in the transition between the non-perturbative behavior of processes mediated by a "soft" pomeron, and the domain of validity of perturbative QCD. Particularly important are several processes involving rapidity gap events with jets by which one can begin to understand the structure of the pomeron.

First, one can study rapidity gap events with two jets on the same side of the gap. This process, suggested by Ingelman and Schlein, provides an operational definition of a parton distribution of the pomeron, though this function may not be universal. Interesting questions include the fraction of dijet events as a function of the gap width, and the transition to soft double diffraction as the jet energy decreases.

Dijet events in which the jets are on opposite sides of the rapidity gap provide a signal of "hard diffraction." This process has been seen at CDF and D0, though their studies would benefit from the ability to have larger gaps fit into their detectors. In particular, resummations of perturbative QCD through the BFKL equation suggest that there can be significant enhancements of the process in the limit of large s and fixed t. This could manifest

itself as an enhancement of gap fraction with increasing gap width. The onset of the energy scale of the enhancement is uncertain, so one cannot view this expectation as a firm prediction, but if seen, it would be important for the development of theory. It seems very unlikely that CDF or D0 will have the coverage to see the anticipated enhancement of events with large gaps.

C Enhanced heavy-flavor production in the forward direction

Perturbative QCD, applied to very high energy quark-quark (or quark-gluon, gluon-gluon) interactions at fixed impact parameter or transverse momentum scale, appears to break down: quark-quark interactions become strong in this limit and are subject to nonperturbative absorption corrections. This happens even at short distances, and is related to multiple gluon radiation as described by the BFKL evolution equation. The enhancement over naive low-order estimates can be orders of magnitude at cms subenergies in the multi-TeV range and p_t scales of 10-30 GeV. Mueller and Navelet have noted that because of the short- distance nature of this phenomenon there is no suppression of heavy flavors relative to light in this regime, and therefore the production of c and b quarks might likewise be enhanced by large factors over the naive estimations based on low order calculations.

If this is the case, there may be reason for exploratory searches for anomalously large amounts of charm, or even bottom production, in the forward region at Tevatron energies. We note that there are again in cosmic ray experiments claims of very large forward charm production (the "long-flying component").

There is no data at Tevatron energies that bears on this question of heavy flavor production in the forward direction. Indeed, the only hope for a measurement even of strangeness production in the forward direction comes from a preliminary analysis of MiniMax (T864) data which indicates that K_s and Λ production may be accessible.

A silicon microvertex tracking system might therefore be able to contribute to this question, even in the absence of sophisticated magnetic analysis or particle identification, in just setting rough limits on (or measurements of) the forward heavy-flavor yield.

D Forward particle spectra and associated studies

In this section we discuss a variety of studies which are possible with compact instrumentation (tracking and calorimetry) in the very forward direction. While many of these studies are of intrinsic interest, and some are of importance in other areas, such as cosmic ray studies, none of these basic measurements have been made at collider energies. The reason for this is not hard to find: one needs space for the relevant detectors amidst the machine elements. In this regard, a C0 MiniCollider region offers a unique opportunity. The current machine lattice at C0 would permit many of these studies; design of the new straight section with these physics goals in mind should preserve this opportunity.

The present C0 straight section has two significant regions of free space in the upstream far forward region. In between the cold quadrupoles and the abort Lambertsons (in the upstream proton direction from C0) there are two meters of free space. Because the beam is bent in the magnetic field of the Lambertsons, there is a zero degree channel which can be accessed at this point. Zero degree neutrals exit the Lambertson flange on the outside, and pbars of Feynman $x \sim 0.5$ exit the flange on the inside. This geometry was exploited in T-864 (MiniMax) by placing two hadron calorimeter modules on either side of the beampipe at this location, thus tagging pbars and neutrons, respectively. Unfortunately, containment is poor, complicating any quantitative measurement of the spectra, further complicated by the fact that the neutrals pass through approximately one interaction length of material before exiting the pipe. Nevertheless, this experience, together with the experience Zeus is gaining with their zero degree calorimeter , lead us to conclude that such a forward neutral channel will be of great value, and should be preserved and improved in any redesign of the C0 straight section.

D.1 Leading nucleon spectra

The fate of the valence quanta in collider collisions has never been well studied. Not only is this of fundamental interest in its own right, but it also is of great importance for the cosmic-ray community, who would value it as input to simulations of air showers. A fundamental parameter in such studies

is the fraction of primary energy carried forward by the leading secondary, usually a neutron or proton. This question bears on the issue of primary composition of cosmic rays and ultimately on the question of their origin, a matter as yet unsolved, and of considerable interest to the astrophysics and cosmic ray communities.

In view of Fermilab's involvement in the Auger project, such data is directly in the laboratory's interest. An air shower array is essentially a one-layer calorimeter, with sampling detectors in a plane buried at 10 interaction lengths (or 30 radiation lengths). Although checked by a Fly's eye detector, the precision of the interpretation of the surface array signal depends on the confidence in the Monte- Carlo simulation of the cascade development, which in turn depends on the understanding of the character of the interactions at energies (currently) 8 orders of magnitude beyond existing direct measurements!

In addition to the spectral distributions of the "surviving nucleon" (valence quarks), data on the forward production of secondaries is also relevant. Cosmic ray observations have been perennially confounded by the problem of the extent of Feynman scaling violation in forward particle production.

D.2 A zero degree neutral channel

The existence of a zero degree forward channel opens up an attractive menu of physics, including searches for quasi-stable massive neutrals, such as are suggested in some supersymmetry models, as well as measurement of the inclusive yield and spectra of neutrons, gammas, pi-zeros, etas, etc. These measurements have not been made in the forward direction since fixed target CM energies of about 25 GeV (early Fermilab fixed target data).

D.3 Tests of limiting fragmentation

Complementary to the measurement of leading particle spectra is the observation of the remaining energy produced in the event. Simulations of cosmic-ray phenomena which are based on straightforward extrapolations upward from lower energy fail badly. Not even the perturbative QCD scale-violating effects suffice to explain the data. Observation of the leading pion spectra and the general leading-fragment event structure would again be of great use for the cosmic ray community Is it possible to scale up from the lower energies?

Comparison of leading-particle rapidity distributions in beam-gas (or wire target) and beam-beam interactions directly provides information on energy dependences which is relatively insensitive to detector efficiencies and biases.

D.4 Leading particle tags

In events with leading nucleons observed, it can be argued that at most one quark from each beam interacted. This is a simple subset of the total event sample and it is therefore of interest to see whether there is a distinction in the nature of the global event structure, e.g., multiplicity, correlation structure, jet production, etc. If these events are indeed simpler in their structure, they may be a cleaner subsample (with respect to their underlying event structure) to be used in new physics searches.

D.5 Elucidation of cosmic ray anomalies

A variety of anomalies in cosmic ray events (Centauro events, multi-muon bundles, . . .) have been reported which would correspond to production in the forward region at Tevatron energies. There has been a good deal of theoretical speculation recently concerning the origin of these anomalies. A C0 MiniCollider region of the sort envisaged here could contribute a good deal towards the elucidation of these phenomena.

Although it is easy to discount many cosmic ray observations as indirect and statistically weak, perhaps we should take note of the assertion of serious, careful physicists in this area that there is evidence that there is a fundamental change in the character of the interactions of cosmic ray primaries with energies above 10^{16} eV.

E Multiparticle and multijet production and correlation studies

Generic multiparticle production and correlation studies should be pursued. The ability to see both charged particles and photons would permit the extension of these studies into largely unexplored territory where many theoretical ideas have been proposed with little in the way of data to discriminate between them. The analysis of multijet global patterns (with and without

rapidity gaps) will permit the study of the onset of color coherence and color bleaching effects.

One example of such studies is the search for Disoriented Chiral Condensates (DCC). A first generation experiment, MiniMax (T-864), has been an excellent experiment considering the scale of the cost and the effort. While the (preliminary) analysis indicates that DCC is not jumping out, the pioneering study of charged/neutral fluctuations that is being carried out will be of substantial value as a probe of multiparticle production as well as a probe of possible new physics. A detector able to attack the questions raised above will automatically be ideally suited for such a second generation DCC probe.