A LARGE SOLID ANGLE MAGNETIC DETECTOR
FOR HIGH TRANSVERSE MOMENTUM EVENTS AT 1000 × 1000 GeV

D. Drickey
University of California, Los Angeles

and

L. Hand
Cornell University

Introduction
At least one principle has remained valid in particle physics since the time of Rutherford: The study of large momentum transfer reactions yields information about the structure of the system under study down to small distances. With the 1000 × 1000 GeV proton storage ring proposed for NAIR observation of 100 GeV/c momentum transfers becomes at least kinematically feasible even in highly inelastic collisions thus giving us a microscope with a resolution of 1/500 of the proton radius. If one accepts the hypothesis that the proton is a complex system of as yet unknown constituents, then a principal goal of particle physics is to determine and isolate the nature of these constituents by observing elementary collisions and, possibly, annihilations between them. On this very short distance scale the traditional separation between strong, weak and electromagnetic interactions may become less convenient and new ways of looking at these currently rather disjoint types of interactions more fruitful. In this connection we note that the cross section for the weak interaction between point leptons is \( -10^{-33} \) cm\(^2\) \( \times X_L X_R \) where \( X_L, X_R \) are the fractions of 1000 GeV carried by the hypothetical constituent leptons. Even with \( X_L, X_R \sim 1/5 \) or less we might expect observable effects from the weak interactions provided they are not swamped by backgrounds from more common and possibly less interesting processes. Another interesting measure of what constitutes "high" momentum transfer can be derived from the cross-over between the relative strengths of weak and electromagnetic interactions: \( p_T > \sqrt{\alpha/G} \) where \( p_T \) is the momentum transfer and \( \alpha \) and \( G \) are the electromagnetic and weak coupling constants. This criterion gives \( p_T > 30 \) GeV/c. Still another measure of what transverse momenta may become important comes from asking what masses can be produced "coherently" in a pp collision at \( S = 4 \times 10^6 \) (GeV)\(^2\). If we ask that \( q_{\text{min}} \) be < 200 MeV/c, corresponding to a 1 fermi "size" for the coherence length, the produced mass must be < 650 GeV, leading to \( p_T < 325 \) GeV for the decay products of such an object--hopefully observable as hadron jets or low multiplicity decays.

Requirements for the Detector
We have imposed the following constraints on the detector, based on what we feel will be necessary to interpret the observed high \( p_T \) events:

(a) A measurement is to be made of the energy transmitted in the direction of the incident beams ("beam pipe jet"). This allows a transformation into the center-of-mass of the "elementary" collision without advance assumptions about the final states in such a collision. No detailed
measurements of individual particles in the "beam pipe jets" are necessary, just the total energy and momentum not directly involved in the production of high transverse momenta.

(b) Particle identification for hadrons (as a group), electrons, photons and muons should be available.

(c) A sign determination for charged particle momenta up to and beyond 100 GeV/c is made--hence a magnetic field is required.

(d) The detector must fit into a straight section of minimal length, since very long straight sections are extremely expensive.

(e) A "split field" magnet causes the proton beams to collide in a collinear geometry and also serves to separate the neutral fragments in the beam pipe jets from the beams themselves.

(f) The detector must have a large solid angle to permit the viewing of very rare processes and to give an unbiased view of the collisions themselves. Since high luminosities (= $10^{32}$ or greater) will be used, backgrounds must be carefully considered. This again led to the use of a magnetic field in the wide angle region.

**Physics: Examples**

We have been guided by consideration of two possible reactions:

1. Parton-antiparton annihilation into lepton-neutrino pairs.
2. Parton-parton collisions resulting in two large transverse momentum jets.

Figure 1 shows a schematic diagram of how each of these interactions may appear. In the first reaction the parton is assumed to have $1/3$ of the beam momentum, while the antiparton has $1/20$. This picture is consistent with the results from deep-inelastic electron scattering as has been discussed by many authors but has not yet been verified by independent experiments. In this example, the beam pipe jets have 800 GeV and 950 GeV respectively and these energies must be known in order to transform into the center-of-mass of the parton-antiparton collision. We note the kinematic formula

$$\sin^2 \theta = \frac{1}{2} \frac{1}{1 + R}$$

where $E_q$ and $E_{\bar{q}}$ stand for the energies in the lab of the parton and anti-parton. For the example chosen, $\sqrt{q^2} = 1.25$ and the square root makes this very insensitive to variation in $R$. $90^\circ$ in the c.m. of the collision transforms to $45^\circ$ in the laboratory, suggesting that detecting the angular range from $45^\circ$ to $135^\circ$ in lab angles gives enough c.m. angular coverage to differentiate the $\sin^2 \theta$ distribution expected for spin $1/2$. The maximum $p_t$ is given by $\sqrt{q^2}/2 = 100$ GeV/c.

We note that $S_{qq}$ is $4 \times 10^4$ GeV$^2$, comparable to the unitary limit of $p_t \approx 300$ GeV/c for lepton collisions via the weak interaction. Thus we wish to observe 140 GeV/c electrons or muons emerging at $45^\circ$. At $90^\circ$ in the lab the observed transverse momentum has decreased to $70$ GeV/c---still a unique and striking signature for the reaction.

The kinematics of hadron jets is similar except that probably higher fractions of the incident proton momenta are involved leading to higher values of $S_{qq}$ and nearly collinear jets. In either type of collision a large background of "pionization" pions probably exists with a typical
average momentum of ~300-1000 MeV/c. At these c.m. energies the average charged multiplicity extrapolated from lower energy data is ~20-30 \pi^+ with fluctuations in the rare events up to twice that value or more. This background must be separated from the parton jet and could lead to analysis problems in some experiments.

**Description of the Detector**

With all of these requirements in mind we propose the detector shown in Fig. 2. A solenoid 5 meters long by 4 meters in diameter surrounds a 1 meter long interaction region. At either end of the solenoid two 5 meter long (20 cm \times 40 cm gap) dipoles each provide 5 GeV/c of transverse bend. Beyond each of the split field magnets the proton beams diverge at an angle of 10 mrad. The fields used here are all \sim 30 kG and all three magnets are superconducting. Such magnets are in the planning or prototype stage now and would not seem to present severe problems on the time scale of the 1000 x 1000 GeV storage rings. The field and diameter of the solenoid were chosen to give an unambiguous charge separation for \pi^0 particles. The analysis power of such a solenoid may be characterized by the formula for the sagitta of the circular arc which the track makes when projected onto the plane perpendicular to the field direction.

$$S = A \frac{\sin^2 \theta}{p^2 L}$$

where \theta is the angle of the particle with respect to the beam, \(p^2\) is the transverse momentum in GeV/c and A is given by

$$A = \frac{L^2 B}{(464 kG \text{-meters})}$$

For \(L = 2\) meters and \(B = 33 kG\), \(L/c\) is the time the particle spends in the magnetic field \(s = 50 \text{ cm} (\sin^2 \theta/p^2)\). The difference between \(e^+\) and \(e^-\) at 45° and \(p^2 = 100 \text{ GeV}/c\) is 5 mm, which should be adequate for sign determination. Clearly the determination of the sign of the lepton is essential in understanding the basic interaction, at least based on our current naive thinking. \(e^+\) (or \(\mu^+\)) event should dominate \(e^-\) (or \(\mu^-\)) events by the ratio of 2 to 1 if the simple quarks model is correct. Such a dominance is immediate evidence for the weak interaction.

The radius of curvature of a 300 MeV/c transverse momentum particle in the 33 kG field is 30 cm. Most of the pionization products will be curled up inside twice this radius and piped to the ends of the solenoid where a calorimeter will measure the total energy in the low energy component. Leakage flux outside the highly saturated iron of the calorimeter will be contained by a superconducting shield.

All particles with \(p^2 > 1 \text{ GeV}/c\) will not be confined by the magnetic field of the solenoid and, if the angle \theta is greater than \sim 45°, will strike the coil of the solenoid. Just outside the coil (2.2 m radii, lengths) at a radius of 2.2 meters \(J_{\text{avg}} \sim 10.3 \text{ kA/cm}^2\) for a 20 cm coil) is a shower detector. This might consist of 36 modules of 15-20 radiation lengths of lead alternating with 10 layers of scintillator. The overall dimensions of each module would be 40 cm \times 30 cm (radial dimension) \times 5 meters in length. The scintillator might be liquid scintillator. If
phototubes are present at both ends and the signals are added, a relatively uniform response can be obtained. As an example assume a 2.5 meter attenuation length, this gives a pulse height 65% as high at the center as at either end, a variation which can easily be corrected out if the shower position is known. (Similar counters 8 ft long have already been used by the UCLA group at SLAC and have a pulse height in the center equal to 96% of that at either end.) A resolution of better than 2% at 100 GeV should be possible with such a detector.

Outside this radius is a calorimeter—muon identifier which consists of alternate layers of iron and scintillator. A calorimeter 1-2 meters in thickness is capable of $\sigma/E_0 = 8\%$ for $E_0 = 200$ GeV. Better resolution can be obtained by increasing the granularity. Muons are identified by a combination of pulse height (absence of a hadronic shower) and curvature in the magnetic field. It might be desirable to use the iron of the calorimeter as a flux return path although not all of the flux would be returned in this way.

**Remarks About the Design**

The crucial factors in dictating this design are:

1. Observation of the total energy in the beam pipe jets.
2. Large solid angle in the center-of-mass ($>2\pi\text{ sr}$) of the "elementary collision." This helps both with the interaction rates and the interpretation of the collisions observed.
3. Reduction of backgrounds by the use of a strong solenoid field. If the total cross section at these energies is 70-90 mb$^5$ and the luminosity is $10^{32}$ we have a 7-9 mHz interaction rate or 1 interaction yielding 20-30 charged pions every 120 nanoseconds. The beam pipe calorimeters will be limited by accidentals to luminosities below $10^{32}$. For some purposes in which a rare reaction is sought in the large solenoid the beam pipe jet detectors can be turned off and the luminosity increased by at least one order of magnitude. Low energy $\pi^0$'s and most products of nucleon fragmentation will not be visible. If we estimate that $10\%^0$'s with a mean energy of 500 MeV are produced per interaction, then a "dc level" of 5 GeV/10 nsec will be deposited on the shower counters (at $L = 10^{-3}$). This would not seem to be a serious problem when one is looking for 100 GeV electrons.

If the requirement of large solid angle were dropped, then a large $p_L$ detector similar to the one described by Lederman$^6$ for the ISABELLE Study would be desirable. The principal differences are the absence of the interaction region field and a reduction in solid angle by a factor of 4-5 due to the use of a transverse field. This type of design was not advocated by us due to the feeling that a total energy measurement which determines the $q^2$ of the semileptonic reaction will be extremely valuable plus the advantage of having the c.m. in full view.

**Conclusion**

After being stimulated by the exhortations of the discussion leaders at the 1973 Aspen Summer Study we have designed a magnetic detector for large transverse momentum events in 1000 x 1000 GeV proton storage ring collisions. Our design is intended to be complete in the sense that no reasonable physicist could ask for a more elaborate detector. Surprisingly enough, the detector still fits into a relatively short straight section and is perhaps comparable in cost to some detectors now being constructed. We have attempted to keep detection concepts quite
general so that improvements in detection technology can be easily incorporated into the detector—

after all, this detector would not be in use until 10 years or more from now and the great develop­
ments in technology in the last decade may well be repeated in the next.

References

1 E. J. N. Wilson, private communication. The assumption was made of bunched proton beams
and collinear collisions. We could also have assumed unbunched beams and a slight (~1 mrad)
crossing angle.

2 D. Cline, SS-73/197, 1973 Aspen Summer Study has discussed this reaction in detail.

3 K. Berkelman, 1972 XVI Int. Conf. on High Energy Physics; H. Kendall, 1971 Cornell Confer­

4 See the review by W. S. Gilbert in the proceedings of the 1973 Particle Accelerator Conference

5 E. Malamud, private communications. This is based on an extrapolation of the cross section
rise observed at the ISR, assuming log^2 s.

SPACE FOR POSSIBLE PARTICLE IDENTIFIER; TRANSITION RADIATION (?)

FIG. 2a

FIG. 2b

BEAM JET CALORIMETER

MAGNETIC FIELD

SOLENOID

+ MAGNETIC FIELD

20cm x 40cm x 5cm 33Kg + FIELD

5m, 33Kg SOLENOID

20-50m (SET BY MACHINE DESIGN)

20cm x 40cm x 5m 33Kg - FIELD

BEAM JET CALORIMETER

P_T = 500 MeV/c

NEUTRAL PARTICLES

BEAM PIPE

SHOWER COUNTER

CALORIMETER

DRIFT CHAMBERS

INT. REGION

DRIFT CHAMBERS

SET BY MACHINE DESIGN

-180-
FIG. 2c CROSS SECTION OF LARGE SOLENOID

1 OF 36 SHOWER COUNTERS

SECTION OF CALORIMETER IDENTIFIER

CYLINDRICAL DRIFT CHAMBERS IN THIS REGION

INTERACTION REGION

3.5 METERS

2.0 METERS

LIMIT OF 300 MeV/c \( \pi \)