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BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York

ACCELERATOR DEPARTMENT
Informal Report

AN INSTRUMENT FOR THE MEASUREMENT OF LARGE TOTAL
TRANSVERSE MOMENTUM: THE IMPACTOMETER

W.J. Willis

March 3, 1972

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Accelerator Department
BROOKHAVEN NATIONAL LABORATORY
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INTERSECTING STORAGE ACCELERATOR NOTES

An Instrument for the Measurement of Large Total
Transverse Momentum:
THE IMPACTOMETER

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"Certainly, one is building on an insecure foundation, who rests his work on hypotheses concerning the constitution of matter."

-J. W. Gibbs

I.

We know several facts about transverse momentum in high energy collisions. On the one hand, we know from studies of extensive showers and showers of nuons in the cosmic rays that the average transverse momentum of the particles produced by primaries of 1000 Tev or more remains at values of a few hundred Mev⁽¹⁾. On the other hand, we know from electron scattering, and to some extent from neutrino interactions, that the leptons are capable of delivering large momentum transfers to the nucleon in the deeply inelastic region.

Since we know very little about the hadrons in the final state, we cannot distinguish between the two extremes which suggest themselves for the distribution of the total transverse momentum among the hadrons. One would be the case with a jet along the direction of the exchanged system, in which the leading particles would then have large transverse momentum with respect to the beam⁽²⁾. The other extreme would imply multiplicities which increase fast enough to absorb the total transverse momentum without giving a large transverse momentum to any single particle, the "pulverization" process of Chou and Yang⁽³⁾. One might imagine that the actual events might lie rather continuously between these extremes.

Even if there is a transverse jet, the leading particle might have, typically, only one-half of the total transverse momentum. Since we are dealing

with rates which fall as high powers or exponentials, it makes a tremendous difference whether we measure the total transverse momentum, or just that of the leading particle. Of course, in the cases mentioned above, this is done automatically by looking at the lepton in the final state.

However, it is my purpose in this note to describe a unified method to study this general kind of process in e-p and p-p collisions with a number of different kinds of final states, as described in II, below. In many of these, it is necessary or very convenient to measure the total hadron transverse momentum, the hadron vector momentum, and the total hadron energy. A device designed to do this, an "Impactometer", is described in III.

II

In list below a number of different kinds of reactions which might be relevant to studies of large transverse momenta. Some of them have been widely discussed, but others require some comment.

(1)	$e + p \rightarrow e + \dots$	electromagnetic
(2)	$e + p \rightarrow \nu + \dots$	weak
(3)	$e + p \rightarrow e + \dots$	neutral currents, second order weak,
	$\rightarrow \mu + \dots$	internal conversion?
	$\rightarrow e^+ e^- + \dots$	
(4)	$p + p \rightarrow \mu^+ \mu^- + \dots$	electromagnetic
(5)	$p + p \rightarrow W +$	semi-weak
	$l + \nu$	
(6)	$p + p \rightarrow l + \bar{\nu} + \dots$	weak
(7)	$p + p \rightarrow \nu + \bar{\nu} + \dots$	neutral current
(8)	$p + p \rightarrow \dots$	strong
(9)	$p + p \rightarrow \dots$	electromagnetic

(10) $p + p \rightarrow \dots$ weak

Reaction (1) includes elastic and inelastic electron scattering, while (2) is the weak analogue of the electron scattering which inspired Mel Schwartz to suggest the e-p storage ring as a good approach to high energy weak interactions. These reactions will be used to illustrate the kind of analysis advocated here, and will also serve to motivate the (perhaps more important) application to the p-p reactions.

The instrument described in the next section measures the quantity we shall give the name "impact" defined by

$$\Pi(\Psi) = \sum_i^{\Psi} E_i \sin \theta_i^{\Psi}$$

where E_i is the energy of the i 'th particle, produced in a collision at angle θ_i , in an interval of the angle around the beam, Ψ , of width $\Delta\Psi$. The origin of Ψ is considered arbitrary, for the moment. We consider the approximation where all the particles are relativistic, so that this quantity is approximately the sum of the transverse momenta of the particles in the azimuthal interval $\Delta\Psi$. The width of the Ψ interval is chosen to be as large as the opening of the jet of hadrons. For these reactions, specification of the momentum vectors of the ingoing and outgoing lepton allows one to compute the velocity of the hadron system. Then, typical opening angles in the hadron jet are going to be smaller than the estimate γ_H^{-1} . A value of 30° for $\Delta\Psi$ is large enough for the energy region we are considering, and finer intervals would be useful in some cases. The idea of measuring the "impact" for the hadrons is, of course, that it can be approximately equated with the transverse momentum carried by the final state lepton in (1) and in the case of (2), where the lepton is not detected, it can be used as a substitute.

I have devised a plot which allows one to display all the interesting reactions in variables which are well adapted to the physics, and which allows one to compare two body and multibody reactions directly. (See Fig. 1.) The log of the differential cross section is plotted against Π^2 for values from 0 to 1 Gev, and against $\log_{e^{\frac{1}{2}}} \Pi$ for values of Π greater than 1 Gev. These variables are chosen because the differential cross-sections for the hadronic processes are exponential in Π^2 up to 1 Gev, while there is a suspicion that they become power laws at large Π , and the leptonic deep inelastic reactions are believed to follow power laws. Also, the device we are proposing to use has a resolution which is a constant percentage in Π , approximately, so that it is a fixed interval in $\log \Pi$. The peculiar base of the logarithm, $e^{\frac{1}{2}}$, is appropriate for two reasons. First, that particular value allows one to use the same absolute vertical scale, cm^2 , for both parts of the abscissa scale without a discontinuity in the ordinate at the boundary. Furthermore, a unit step in this log corresponds to a bin in Π of a width of about $\pm 23\%$, just somewhat larger than the expected resolution, or a very reasonable bin width. Thus the cross sections which are differential in this variable give directly the cross section for a single data bin, and the two body and multibody cross sections can be directly compared without the apparent suppression of the multibody cross sections which occurs in the usual plots. Note that a cross section which is constant in $d\sigma/d\Pi^2$ will increase like Π^{-2} in $d\sigma/d \log \Pi$, etc.

There are a number of curves on Figure 1. First let me draw your attention to curve (a), which gives the differential cross section for the scattering of two point charges of unit value, or Mott scattering. In this case, Π is simply the transverse momentum. In order to show the basic physical

features of the reactions this curve, and all the others with one exception, is drawn supposing that the center of mass energy is large compared with all the other variables. When plotted against $\log \Pi$, $d\sigma/d \log \Pi$ falls as Π^{-2} , a straight line on this plot. Unlike most of the reactions, this one continues as a power law below $\Pi = 1$ Gev, leading the curve on our plot to turn sharply upward.

In curve (b) we offer a prediction for reaction (1), the inclusive electron scattering off protons. The surprise in experiments carried out with Π greater than 1 Gev was that the Π dependence was like that of a point charge scattering. Accordingly, we have plotted curve (b) with the same Π dependence as the Mott scattering, but with the cross section reduced by a factor of five, which gives a better fit to the present low energy data. The important point is that if there is enough energy, this cross section remains measureable out to very large momentum transfers. Since unit intervals in $\log_{e^{\frac{1}{2}}}$ correspond to reasonable bin sizes, we can read the effective cross section for one data point off the scale in Figure 1. This shows that with a luminosity of $10^{32} \text{ sec}^{-1} \text{ cm}^{-2}$ and four-pi solid angle, we could reach a Π of 100 Gev, given enough energy, or for any lower energy machine, get fairly close to the kinematic limit. Whether this prediction is actually true, what the hadrons do in such events, whether multiple photon exchanges modify the picture drastically, whether there are indeed point-charge constituents which might even start to come out of the hadrons at some point, all of this is for us to learn in these experiments rather than to speculate on at the present.

The e-p elastic cross section is also shown, by curve (c). It drops out of sight rather soon, finally falling as Π^{-12} . It seems unlikely that it can be measured beyond $\Pi = 3$ Gev. At very high energies, there might be multiple

photon exchange effects which would be worth investigation, in the accessible region.

The weak interactions mediate reaction (2), which is shown by curve (d). This reaction is the inverse of the neutrino-proton reaction. The extrapolation of that measured cross section has been plotted, assuming unpolarized electrons. This extrapolation uses the hypothesis of point-like constituents, or alternatively, "scaling", as in reaction (1). Note that with the variables we are using, curve (d) rises, as a function of Π . Eventually, unitarity forces it to level off, and the plot has been carried far enough to show this effect, though we do not expect to reach these energies very soon. More likely, some sort of structure in the weak interactions will make itself shown before this point is reached. For example, the dashed curve (e) shows the damping due to a intermediate boson, W, with a mass of 40 Gev. If the effective cut off energy is larger than about 60 Gev, we may expect (2) to grow to a value larger than (1), and this may happen somewhat sooner, depending on the details of the model used for extrapolation. However, the cut off may lie lower than the cross over, or the energy at our disposal in a given machine may be less than the cross over value. Consequently, we should plan on studying (2) under a large background from (1), going to as low a value of Π as we can. Mel Schwartz pointed out, during the deliberation of the Fitch committee, that with a high energy proton ring and a low energy electron ring, you can begin to reach this interesting region.

Reaction (3) relates to processes not expected in current theories, or not calculable, so it is not easy to guess where on Figure 1 they might be found. It is clear though, that the chances of success in finding them are apt to be greater at large Π . There is something to be said for each of the

final states. The one with the electron has the possibility of enhanced sensitivity by interference of neutral weak currents with the electromagnetic process, while the one with the muon is more characteristic, and is more free of electromagnetic background of an uninteresting nature.

Reaction (4) is the production of lepton pairs through virtual photons of a large time-like momentum from proton-proton collisions. This process has been observed with a substantial cross section at the AGS, and this information has been used to extrapolate to high energies to give curve (f)⁽⁴⁾. Since the data from the AGS do not span a large range of energies, the kind of scaling used to make this extrapolation cannot be said to have the same kind of experimental verification as that for reactions (1) and (2), but the same kind of dimensional analysis would seem to apply to both cases. Reactions (4) through (7), which involve time-like momentum transfers, will have cross sections which fall off exponentially as Π^2 approaches s , the square of the center of mass energy. An example of this behavior will be shown for reaction (5) below.

For this reaction, the characteristic transverse momentum which defines Π for the apparatus proposed is that of one of the leptons. If the lepton distribution is isotropic in their center of mass, and the transverse momentum of the pair is small compared with the effective mass. $M_{\ell\ell}^{+-}$, then $\Pi = (\pi/8)M_{\ell\ell}^{+-}$. Since the predicted cross section is dropping with effective mass, the measurement of this variable causes the cross section to lie lower than it would if the effective mass were measured directly, more analogously with reaction (1). All the electromagnetic processes fall with the same power of Π , as one might expect on dimensional grounds.

A special case of this reaction is the production of a particle or

resonance which decays into a pair of charged leptons. One such is the B^0 of Lee and Wick. The cross section predicted by Lee, transformed to our variables, has been plotted as curve (j)⁽⁴⁾. It has the property of lying above the Mott scattering cross section, but it should be remembered that the significance of this curve is somewhat different from the previous ones. It is the locus of the tips of a family of sharply peaked curves corresponding to the production of a B^0 of unique mass. The width of the Π bins chosen is such that most of the cross section for the production of a B^0 will fall in one bin, and the value for that bin should lie on this curve.

The next reaction is called semi-weak because it involves the production of a real W, whereas an ordinary weak process has also the absorption of a W. Given CVC and the same scaling hypothesis for these time-like momentum transfers, curve (g) is predicted. As in the case of the B^0 , this is the locus of cross sections for the production of a W of definite mass, observed by the large transverse momentum of its decay products. If the mass of the W is very large, the width is greater than one of our bins, and the cross section per bin starts to fall, as the curve shows.

In the case of the W, we suspect that the mass might be comparable to the total center of mass energy, and it is especially interesting to see the effect of finite energy. The behavior in the non-scaling region has been evaluated by Lederman from his data on the muon pair production, and is shown by curve (h) for the production of W's by 200 GeV x 200 GeV proton collisions⁽⁴⁾. It will be seen that the cross section holds up pretty well until the kinematic limit is approached.

Aside from the production of the W, electron-neutrino or muon-neutrino pairs can be produced through the four-fermion interaction, reaction (6).

If the electromagnetic lepton pair production is known, CVC can be used to estimate the magnitude of the corresponding weak reaction. In the present case, one uses the same extrapolation here as for reaction (4), resulting in curve (i), taking into account once more the relation between $M_{\ell\nu}$ and Π , which results in a higher cross section in this case, since it is equivalent to a displacement along a rising curve. The unitarity limit is reached sooner in this case than in reaction (2), partly because of the variable used, partly because the energy is in a purely leptonic system, which gives fully "point-like" cross sections.

Although the cross section is small for this reaction, the luminosity in a high energy proton storage ring such as Isabelle can be very large, and the real limit on how small a cross section can be studied is the background from other reactions, and this as we shall see is very hard to predict at this moment.

Reaction (7) is clearly a difficult one to study, but we will describe in Section III how the apparatus we propose can be used for this purpose. The cross section might be like that of reaction (6), or of reaction (5) if there is a neutral particle, like the Z^0 of Weinberg⁽⁵⁾, coupled to leptons.

Despite the great amount of data we have in the kinematic region covered up to now, reaction (8) is the one for which we have the greatest choice of plausible predictions. (That doesn't mean that the other reactions couldn't be wildly different from our predictions!)

The most straight forward prediction is to take the fit to the ISR data, which is a Gaussian in the single particle transverse momentum, q and extrapolate that⁽⁶⁾. Then we have to ask how to relate q to Π which is a sum of the transverse momenta in an azimuthal interval. Three cases may be

distinguished. There may be a leading particle in the transverse momentum, or there may be a number of comparable particles, but with an angular spread which generally lies outside the azimuthal interval being used, or there may be a narrow jet of particles with comparable momenta. In the first two cases the Π distribution will resemble the single particle distribution, while the last case will be quite different, depending on the multiplicity. We will assume that the latter case can be subsumed in the broader Π distributions we will be considering. This extrapolation is shown as curve (k) in Figure 1. Another fit, which works out to a q of two GeV at least, at AGS energies, is exponential in transverse momentum, as shown in curve (l).⁽⁹⁾ Both of these curves fall very steeply for Π beyond a few Gev. In fact, they soon fall below the levels expected from the weak and electromagnetic interactions, so that the contribution from the strong interaction at $\Pi = 10$ Gev, say, would be completely unobservable.

However, we may ask what is the basis for such an extrapolation. It seems that the multiperipheral models predict exponential fall off, but it is not clear that other mechanisms do not intervene at large Π . Many people believe that the dependence will change to a power law at some point. They point to the elastic scattering, which seems to flatten out at large t , though that indication is somewhat ambiguous, since the part that flattens out is also falling with energy, at present energies.

One extreme is to suppose that the distribution becomes like the electromagnetic one at some momentum transfer, but at levels that are still much above the real electromagnetic scattering. This sort of behavior is shown by curve (m). The point at which the power law behavior begins is somewhat arbitrary, but it must lie beyond the region of present measurements.

If this is really the case in nature, the strong interactions will dominate the gross Π dependence, at least up to some enormous energy where the rising weak interaction cross sections may reach the same magnitude, just about at their unitarity limit, if they really do rise that high. Another possibility, and one which may be the most likely of the lot, is that there is a power law dependence, but with a steeper slope, say $d\sigma/d\Pi^2 = \Pi^{-6}$ or Π^{-8} . Curve (n) illustrates a sixth power dependence.

The elastic p-p cross section is shown by curve (o), for the asymptotic model of Durand and Lipes⁽⁸⁾. This model is not really consistent with the inclusive distributions which fall as exponentials, since the elastic curve should not cross the inclusive ones. Of course, a Regge model will predict much smaller elastic scattering, since shrinkage will continue. This would not seem consistent with ISR results at very small t , but the shrinkage at large values of t might persist up to very large values of t .

Reaction (9) is one we have not seen, and maybe we never will. Nevertheless, if we take a diagram for electron inelastic scattering, and replace the scattering electron by another disintegrating proton, we would seem to have another process whose cross section we could estimate:⁽⁹⁾

I suppose this cross section should lie as much below the e-p cross section as that lies below the point charge scattering cross section, invoking a kind of factorization of the two sides of the photon exchange, and the curve (p) is

drawn on that basis. It may seem strange that this cross section lies so far above curve (f), which describes another p-p electromagnetic process, but this is just because in this case Π measures the whole momentum while in reaction (4) it measures only a fraction of the momentum transfer, as discussed earlier.

Note that if the strong interactions really do fall off as curve (k), this process would dominate the distribution at Π as low as 3 Gev! On the other hand, if they follow a power law like curves (m) or (n), the electromagnetic scattering will stay out of sight. This is such an interesting question that I don't see how we can stand to wait too long to find the answer!

It may be protested that no one would believe that the electromagnetic scattering had taken over just because there was a kink in the Π distribution at the right place; and I agree. We would then have to make a test of isospin invariance, most easily by studying d-d collisions (if there is enough energy!) and comparing the number of charged and neutral pions, which can be done with the apparatus proposed. Actually, the even more obvious features of n-p, as compared to p-p, collisions would probably be most indicative of a change in the interaction.

If we have electromagnetic reactions like (9), we must expect weak interactions of a similar nature, reaction (10). We can scale them from e-p (weak) interactions, just as we scaled (9) from e-p interactions, resulting in curve (10). If no cutoff intervenes, this cross section will rise above the electromagnetic one for $\Pi > 50$ Gev. If the strong interactions have fallen enough so that this transition is visible, it should be quite a striking phenomenon. Proving that it is due to the weak interactions is another matter. The isospin properties can be discovered, but they are tangled up

with the comparable electromagnetic interactions. The best bet seems to be to see if there are enough lambdas at high momentum transfer to allow measurement of their longitudinal polarization. Our apparatus might do the job of finding out if the lambdas are there, and with a large solid angle, but a device with more resolution may be needed to make an accurate measurement of the longitudinal polarization, since this measurement is rather sensitive to momentum measurement accuracy. Whether the weak interactions will be obliging enough to provide an appreciable polarization, after summing over all final states, is another question.

It will be clear that all of these extrapolations are very speculative, and it's hard to know which ones are more speculative than the others, but it seems to me that there is an unmistakable scent of a rich vein of physics to be found in this area of many-particle, high momentum transfer reactions.

III

We need a detector which measures Π directly, electronically, so that we can select only those events in which we are interested, out of a background of many orders of magnitude more frequent events. It should have four-pi solid angle, and as little bias as possible against any particular configuration of events, so that one may be sure that one has detected all the events with a given Π , without prejudice against multiplicity or angular distributions. It should offer the possibility of identifying leptons, and reliably inferring the presence of neutrinos. It should rely on detectors of the highest time resolution, since we are talking about very small rates, and the luminosities promised in the storage rings are very high: it would be a shame to turn them down! It would be good to have measurements of the multiplicities of the particles produced, and if possible, measurements of the angles and energies of individual particles. It is essential that the measurements

include the detection and measurement neutrals with high efficiency. These goals should be attained with finite cost, and the use of well understood techniques.

A detector intended to satisfy these criteria is shown in Figure 2. It is based on an array of calorimeters covering the whole solid angle except for small holes for the passage of the beams. As shown in the section views, there are twelve sectors around the beam which provides bins of 30° in Ψ . The polar angle θ is divided into about 30 intervals of graded size by the use of 22 different calorimeters in a given Ψ bin, and some hodoscopy in the forward ones. Each calorimeter gives an estimate of the energy striking it at a given time, E_i . It lies at an average angle from the interaction region of θ_i . The outputs can be summed electronically to give $\Pi(\Psi) = \sum_i E_i \sin \theta_i$ within a given Ψ bin. These twelve signals may then be further processed by analog circuits, discriminators, and logic circuits to give a variety of interesting triggers, some of which will be mentioned below. The pulse height and time of each calorimeter would be recorded. These triggers can be used to strobe proportional wire chambers in high rate areas, and pulse spark chambers in low rate locations. Some ideas about these will be presented.

The first design consideration is to obtain sufficient resolution in Π . The design shown is based on the requirement that the resolution should be better than one Gev at Π of a few Gev. Such a resolution will create substantial distortion on a distributions like curves (k) and (l) of Figure 1, but will reproduce the others reasonably faithfully. The resolution has components due to energy resolution and angular resolution. To see the magnitude of the former, consider two extremes. Suppose there are four large angle pions ($\theta = 90^\circ$) with momenta of 300 Mev. If we are using iron-scintillator sandwich calorimeters, the energy resolution is quite poor at these energies,

$\Delta E \approx 250 \text{ Mev}^{(10)}$. Adding the uncertainties for the four pions in quadrature, we get $\Delta \Pi = 500 \text{ Mev}$. At the other extreme, consider a 200 Gev particle at a small angle, say 0.01 radian. At this energy, the resolution of the calorimeter is much improved, and we can predict that $\Delta E \approx 15 \text{ Gev}^{(10)(11)}$, giving an error in $\Delta \Pi$ from this source of 150 Mev. Intermediate cases are also favorable.

Angular resolution is somewhat more of a problem. There are three sources of this uncertainty. First, the interaction region has a finite size. For example, the low-beta, zero crossing angle interaction region at ISABELLE has most of the luminosity in a length of about two meters, with transverse dimensions which are not important. At 90° this source subtends a large angle at the calorimeter, but it is not the dominant source of angular error at small angles. There, the limitation will be the finite size of the hadronic cascade in the calorimeter, and the angle that width subtends at a given distance from the source of particles. That distance is limited by the free space between magnetic elements in the beam, and other practical considerations. On the other hand, the highest angular resolution is needed only over a limited range of angles. This suggests the use of uranium for the front portion of the most forward calorimeter. Extrapolation of data in iron calorimeters suggests that cascade localization to 3 cm would then be possible. We have assumed 5 cm wide hodoscope elements in the forward calorimeter, 10 meters from the source. For 200 Gev particles, this gives about 600 Mev resolution in Π . The third limitation is economic, in that we cannot afford to provide this kind of hodoscope resolution over the whole array of calorimeters. This turns out not to be a real limitation, because the resolution needed in the calorimeters rapidly approaches the source size,

as the angle θ increases. In fact, the number of calorimeter elements is partly determined by another consideration, the desire to keep the probability that two particles enter the same calorimeter element small. This eventuality does not really disturb the basic operation of the detector, but it would be very interesting to have the individual energies on at least a large portion of the particles. When one realizes that the events might have as many as fifty particles, one sees that a large number of calorimeter elements are called for.

We are left with the problem of bad resolution due to high energy particles which come off near 90° , with angles which are not very well determined due to the large source size. This improves as we increase the inner radius of the calorimeters surrounding the interaction region, but this rapidly increases the mass and the cost of the calorimeter. My comment on this problem is to note that the resolution is poor due to this effect only when Π is large. In that case, it does not affect the use as a trigger of the Π determined electronically by the impactometer. If there is a 100 Gev particle near 90° , Π can be off by 20 Gev. But whether the Π is 80 Gev or 100 Gev, we know we want to look at that event. If we have some way of improving our knowledge of the angles, this problem disappears in the analysis of the data. Accordingly, I would introduce either proportional wire chambers, or scintillation counter hodoscopes, into the space inside the calorimeter. With these, it is easy to determine the angle of a particle which deposited energy in a given calorimeter. Rather coarse spatial resolution is adequate for this purpose, given the one meter radial space as shown in Figure 2.

These additional counters will be very useful in refining the information

from the calorimeters on multiplicity and improving angle measurements. They will allow us to tell which of the particles absorbed in the calorimeters are charged and which are neutral. They have an important role in eliminating accidental tracks, and in muon identification, as will be described later.

Of course, decoding the information from these counters demands a certain amount of computer time, and thus limits the number of events which can be handled. However, this problem is enormously simpler than the corresponding one in the presence of a magnetic field. In the present case, we deal only with a number of straight lines, which should all meet at a point. The calorimeter hits tell you how to get started on the problem. I am sure the analysis can be done quite efficiently; I am not so sure that the same can be said of the problem of, say, fifty particles let loose in a magnetic field!

The calorimeters present no special problems in themselves, except there are quite a few of them. However, the whole array is not much larger than one of the NAL neutrino experiments. The radial thickness of the forward calorimeters does not have to be very great, since the particles are traversing them at small angles to the axis, but those near 90° must be thicker. One must consider just how much accuracy one needs near 90° , since these units make up a good deal of the total mass, and there may not be too many high energy particles coming their way. The simplest way to stack the plates is parallel to the beam, but one might worry about doing it that way for the calorimeters near 90° , for fear of anomalous sampling of the energy of particles very nearly parallel to the plates. This is probably not a very serious problem. More of a worry may be the stringency with which dead areas must be avoided.

The best method of calorimeter construction is probably that with liquid

organic scintillator and coated metal plates, as described by the experimenters of NAL proposal #1. It does not seem likely that loaded organic scintillators will be available, and since some of the particles to be measured have rather low energies, Cerenkov counters would not seem to be suitable, though this might bear more study. I continue to be attracted by the advantages of a homogeneous calorimeter, with liquid argon as absorber and scintillator, a material which is cheap, has a short radiation length, and is said to be a linear response with respect to varying ionization densities. Measurements by S. Read, P. Nemethy, and myself show the self-attenuation for at least a portion of its scintillation light is small.

The separation of electrons (and photons) from hadrons would rely on the rapid development of the electromagnetic cascade in high-Z material, compared to the average rate of deposition of energy by hadrons. Thus, the first part of each calorimeter would be viewed by a separate phototube, and should preferably be made of lead rather than iron, or, if cost permits, of lead glass. Note that there is a complete overlap of the forward calorimeters, so that a particle which starts its cascade in one calorimeter has its energy sampled in the next one as well. This information should afford additional discrimination between electrons and hadrons, since the hadrons of high energy will tend to deposit some energy at great depths of material, but the electrons rarely do. Hadrons should be rejected from the electron signal by at least two orders of magnitude, and photons rejected from the neutron signal by a larger factor.

Muon identification for the events giving a trigger on the basis of Π should be quite good. This is an interesting point. The use of a muon signal as a trigger at very high energies is not very easy or cheap, though certainly possible. But in our case, we are not relying on the muon for the trigger; all

we want to do is identify the muon on a sample of events for which we already have triggers. This is a much simpler and cheaper problem. The calorimeter already provides a rather good shield against hadrons, and if it is necessary to beef it up, one can add some more steel or concrete. You end up with a very large area to cover with detector, but the point is that since a trigger is available, and the detector can go in a region of low background levels, it can be the least expensive kind of detector we know, large area spark chambers. Furthermore, since it does not have to produce a real time signal indicative of a muon, the identification problem is much simpler. In a case where a trigger is needed, you have to worry about a single particle getting through. If a posteriori identification only is needed, a quite different strategy suffices. One scans the spark chambers for tracks and sees if they line up with a track in the interior of the calorimeter, within the allowance for multiple scattering. One also requires that the putative muon not give excessive energy loss in the calorimeter. This procedure gives much greater rejection, for moderate amounts of absorber, than a poor geometry measurement. One can easily reach the limit of π -mu decay background⁽¹²⁾.

IV

Here we will remark upon the use of the impactometer to study the physics described in Section I. One point is that the same facility would seem to be useful for e-p collisions as well as p-p collisions. From the point of view of physics, of course, the complementary information from the two kinds of reactions seems to very important. This may be the place to note some differences in operations with e-p and p-p. Even if the luminosity in the e-p

collisions were as high as in p-p, which is most unlikely, the trigger rates in the impactometer would be much lower in the e-p case. The elastic e-p cross section is large only at small momentum transfers which wouldn't even register, and the inelastic processes never reach large cross sections. Electron beams are usually thought of as having large background counting rates from electromagnetic processes, but these are much smaller when the only target is a proton beam. This means that the e-p collisions are very clean, experimentally. The luminosity could be run at its maximum value, and the trigger value of Π could be set at a low value.

This is in addition to the well recognized fundamental advantages of the e-p interactions for studying the weak and electromagnetic interactions, due to the simplicity consequent on the presence of only one hadron system in the initial and final states.

In the p-p reactions, though there may be very substantial counting rates at large Π . For example, suppose there are 10^7 interactions per second, and one wants to record events at a rate of one per second. Then, according to curve (k), the Π threshold could be set at 3 Gev, but according to curve (m) it would have to be set at 100 Gev! In the latter case, a more specialized trigger based on the segmentation in Ψ must be used. Events which do not satisfy the Π threshold criterion will often send low energy particles out at large angles, which will lead to substantial singles rates in the detectors. This means that if the interaction rates are indeed in the 10^7 to 10^8 /second range, there will be a good sprinkling of accidental counts in the real events, even though the detectors are those of the best time resolution. Turning down the luminosity is objectionable, since the whole idea is to look at the rarest events possible, though reducing the rate is still better than

reducing the solid angle. It may be worth noting that a fair accidental rate is tolerable. First of all, the amount of Π contributed by the accidentals during a time resolution interval is comparable to or less than the inherent error in Π of the instrument, in the overwhelming majority of cases, so that the trigger based on a Π threshold remains valid. A posteriori, one can determine the vertex of the event with large Π , and reject tracks coming from other points in the two meter long interaction region, eliminating most of the background. The rates must be small enough, per individual detector element, so that deadtime losses are acceptable.

The detailed logic used in the trigger, and the use of the segmentation in Ψ , are aspects which are flexible, and may often change, but it is interesting to describe some possibilities. The simplest is a threshold discriminator on the sum of $\Pi(\Psi)$ for all Ψ , but a sharper selection of the interesting events might be the OR of discriminators on the individual $\Pi(\Psi)$. More specialized possibilities follow from consideration of the anticipated distributions in Ψ for various types of events.

For example, Figure 3(a) shows a prediction of a typical Ψ distribution for a e-p interaction, for a single event. (The Ψ -bin with the largest signal is defined to be 0; and Ψ has been folded around this bin, so the range is 180° .) The scattered electron carries a large transverse momentum off on one side of the beam. A jet of hadrons carried an equal transverse momentum off on the other side. We don't know what kind of angles we will encounter in this hadron jet, but it seems quite likely that it will be rather collimated, just from kinematic considerations. The weak interactions in e-p collisions will have a similar hadron jet, but the neutrino which takes the place of the electron does not register in the calorimeters, leading to the striking

distribution shown in Figure 3(b), with an enormous apparent unbalance in transverse momentum. An electronic trigger can easily be formed from such events which would allow the threshold to be set at a much lower value of Π than for the common events, for a given rate. In this regard, it is amusing to point out that in this device, a muon will give a signal much like a neutrino. The ionization loss of a muon in the calorimeters is equivalent to a couple of Gev, while the energy of the muon might be tens of Gev, leading to a transverse unbalance almost the same as for a neutrino. The distinction would be clear in the detailed analysis, of course. The interesting question at that point is the level of rejection of hadronic or electronic background. Inspection of the pulse height spectra of adequate calorimeters illuminated by hadron or electron beams of greater than ten Gev shows that the fundamental rejection is at least several orders of magnitude. However, when it is realized that the calorimeters are essentially being used as vetos in neutrino (or muon) detection, it becomes clear that the danger to ward against is electronic deadtime. With updating circuits, veto rejections of a factor of $>10^4$ have been achieved.

In looking for neutrino events, it is clearly the Π summed over 180° rather than 360° , which is relevant. In preparing the curves of Figure 1, it has been assumed that this is the quantity studied in all cases, though this is just a matter of definition, given transverse momentum conservation. It is interesting to speculate about the distribution of Ψ due to hadrons in Reaction (8), for example. In events with large Π , will the Ψ distribution look like Figure 3(a), or will it be more uniform? Whatever the answer to this question, we may be sure that there will be interest in looking at the

uncommon categories, and this may be done in a very selective way with logic on the $\Pi(\Psi)$.

Detection of $\nu\bar{\nu}$ pairs is a more subtle matter. Should they be produced with large transverse momenta given to the pair, they will look like the single neutrino events, except that no charged lepton can be found, and the neutrino-like mass, which can be measured albeit crudely, may turn out to be huge. However, we might anticipate the situation where the $\nu\bar{\nu}$ pair had a large effective mass, but the system was produced with small transverse momentum. In that case, there is no large Π appearing in the hadrons to tag the events. The question arises whether one could look for rare events using longitudinal momentum balance, or total energy balance. This project will not get very far without a few extra tricks, because this is not just a matter of energy resolution. In a storage ring experiment, allowance must be made for interactions on the gas. To avoid background from these, one must require some minimum momentum in the direction of each beam, but a threshold of a few Gev will probably suffice, so this problem may not be fatal. It may be necessary to require enough visible Π to reduce the ordinary backgrounds substantially, and to avoid serious errors due to particles escaping down the holes where the beam enters the impactometer. Though this kind of experiment may be difficult, it is not at all clear that one must despair. It does emphasize the importance of the best possible vacuum over the intersection region. It will also be important to provide heavy shielding at each end of this device, to eliminate background from more distant gas interactions.

There are a number of measurements that pertain to the same sort of physics we have been discussing, but which can't be carried out with the impactometer. To some extent, some of this information could be obtained by

incorporating auxiliary experiments into the set up while retaining most of the advantages of triggering and nearly complete particle measurement. An example of this sort is charged hadron mass identification. It will certainly be important to distinguish between the behavior of mesons and baryons in these rare events. To some extent this is possible by the measurements on neutrons detected as neutral hadrons in the impactometer, to the accuracy that K_L^0 background can be evaluated, but the necessity of Cerenkov counters or equivalent will remain. One good way of doing this might be to remove one or more modules of calorimeter, and replace it with a gas Cerenkov counter, backed up with a big calorimeter, about twenty meters from the source. In this fashion, the impactometer information can be preserved and correlations of the particle of known mass with all the other signals can be studied, under any desired trigger condition.

Similar remarks can be made about the introduction of fancier lepton identification over a smaller solid angle, or apparatus for the more precise measurement of the decays of long lived hyperons and mesons. Another possibility is to use the device for studies of two body reactions. Here the attraction would be the factor of 10-100 in solid angle over a typical magnet spectrometer experiment.

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Figure 1

SECTION "A-A"
SECTION THRU TYPICAL QUADRANT

SECTION "B-B"

FIGURE 2

IMPACTOMETER
FOR 200 GEV PROTONS ON P OR E
MEASURES $\pi\psi = \sum_i E_i \sin \theta_i$

Figure 3