HIGH TRANSVERSE MOMENTUM PHENOMENA AT THE CERN ISR

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ABSTRACT

An extensive study of high transverse momentum phenomena at c.m. energies of 31.5, 45., and 62.4 GeV has been performed with two large arrays of lead glass blocks and a superconducting magnetic spectrometer. The inclusive production cross section is measured to 15 GeV/c P_t. The cross section is observed to deviate from the P_t^{-8} behavior measured at lower transverse momenta to a form ~ $P_t^{-5.5}$. Data on the correlations of the associated charged particles are presented indicating that high P_t meson production is associated with a jetlike structure similar to what is seen in e^+e^- anihilation. An analysis of massive meson pair data, taken with a symmetric trigger, is discussed. This two particle system is described in an approximation of the rest frame, yielding the mass and angular dependence of the production in a manner independent of models and apparatus. If it is assumed that high P_t phenomena are related to the elastic scattering of the constituents of nucleons, then these data represent a measurement of the energy and angular dependence of their interaction.

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4. DATA ANALYSIS

The analysis proceeded in three parts: the study of the inclusive cross section for single production, the correlations of charged particles to the high P_t triggers, and a more detailed analysis of the scattering by using the symmetric trigger. All of these studies had the early stages of the data reduction in common which was accomplished in two stages. The first analyzed raw data tapes producing the first level data summary tapes (DSTs). The second took the first level DSTs and increased the number of events per tape by a factor of twelve to simplify the data analysis. These levels also differed in the amount of information written on them and the extent to which the event selection process had been executed. The final data sample consisted of approximately two million events. This is a reduction from ~ twenty million triggers written to tape.

The first level of reduction was based on the energy distribution patterns in the lead glass. This cluster algorithm was used extensively in various forms and is described as follows. The digitized pulse height of each block is multiplied by its pulse height energy equivalence constant (see Appendix I) to calculate the observed energy. The energy clusters are then found. The clusters in the lead glass were formed by finding all 3 X 3 submatrices centered on blocks (seeds) satisfying a minimum energy requirement of 300 MeV. These seed blocks were never in the outer perimeter of an array. All such submatrices containing common blocks were then merged into larger clusters. At this level a cluster was rejected if its vertical or horizontal extent was greater than four blocks. (This cut in the first level processing was later removed on the single arm triggers in order to investigate backgrounds.) The total energy of the cluster was then corrected for an angular factor determined from test beam data with electrons.

A search was then made for "B" counters associated with the cluster. If the "B" counters had registered a pulse height large enough to indicate an electromagnetic shower, the cluster energy was corrected by an energy and angular dependent factor also determined from electron test beam data. The energy centroid of the cluster was calculated and the momentum components found from the total energy and the direction cosines to the center of the interaction region. These would then be transformed to the PP center of mass.

Tracks were reconstructed from the drift chamber points only for events which satisfied the offline lead glass requirements. The track fitting is discussed in Appendix II. The single arm triggers were processed if the linear sum of the transverse momenta of the clusters in one arm exceeded a threshold value. This calculation (using the calibration constants) sharpened the threshold considerably rejecting ~ 50% of the single arm triggers. The track fitting was by far the most time consuming part of the first level analysis, so by rejecting events on the basis of the patterns observed in the glass a considerable amount of computing was avoided. The offline thresholds were equal to the hardware thresholds except for a considerable fraction of the high threshold 62.4 GeV data. For the data in which the drift chambers were not in their best condition (a luminosity of ~ 6 X 10^{37}) the offline threshold was raised to 8.5 GeV/c from the value of 7 GeV/c which corresponded to the hardware value. This was mainly done to save computing time. To further avoid processing an excessively large number of events, only a P_t dependent fraction of the events would be processed (selecting the events at random to avoid systematic effects) for the first 1.5 GeV above the threshold. The fraction processed at the summed P_t evaluated for an event, was written with each event to avoid confusion (for example due to a change in calibration constants after the processing was done). The pair events were processed if the two clusters formed a mass of greater than 7 GeV for the 62.4 GeV data and 6.25 GeV for the 45 GeV data. By taking two independent triggers the efficiency of each could be measured and was found to reach 100%. The pair threshold was evaluated on the basis of the energy on each side so the 100% efficiency was not really in terms of the mass but in terms of the energy per side.

The second level of reduction consisted of increasing the density of events per tape. This was mainly achieved by writing only the track parameters necessary to recalculate a complete description of each track. (On a CDC 7600 it turns out to be faster to recalculate things sometimes than it is to unpack them from tape.) The other drift chamber information was left out (the list of space points and times). By doing this the number of events per tape was increased from approximately 4500 to 55,000 and the reading time decreased from 8 to 2 millisec/event. Approximately 70 packed 60 bit words were written per event. The times include recalculating track parameters.

All data analysis was done at the CERN computer center using the CDC 7600 system there (a 7600 with a 6400 and 6500 for front ends). Extensive use was made of the multifile managing facility (FELIX) in order to simplify the data processing as much as possible.

4.1 INCLUSIVE ANALYSIS

To measure the inclusive cross section four things are required: the acceptance, the absolute energy scale, the luminosity, and a background free spectrum. Though the hadronic interaction probability in lead glass is not very large, the fraction of triggers due to halo particles and upstream interactions became significant at high P_t since the inclusive cross section decreases to levels of 10^{-35} cm at 10 GeV/c P_t. This means that in order to reach the highest transverse momenta and smallest cross sections attainable with the collected luminosity, this fraction has to be understood. The problem is further compounded by the high instantaneous luminosity. The large interaction rate and the long "memory" of the drift chambers (drift times up to 600 ns and tracks reconstructable up to ~ 50 ns out of time) cause approximately 2.5% of randomly generated triggers to have reconstructable (i.e. "real") events.

4.1.1 SUPPRESSION OF BACKGROUNDS

The first effective rejection against backgrounds was the clustering algorithm. Monte carlo calculations indicate that given the distance of the lead glass to the interaction region, (1.2 m to the front face) the 2 photons of a pion decay cannot be individualy resolved. The spatial separation is so small that at 3 GeV/c P_t the two photons will be fully contained within a 3 X 3 array ~ 97% of the time. Hadronic showers caused by particles entering the sides of the arrays will satisfy this criteria infrequently. Consequently requiring that the energy cluster be contained within a 3 X 3 submatrix, with essentially no energy in the bordering blocks, is an effective elimination of background. To insure that the energy was contained in the lead glass, the event was rejected if the largest energy block was in the edge of the array or if the centroid of the cluster was outside a fiducial area (10 X 12 blocks). Another background source was electronic breakdown in a phototube. This was rejected by requiring that the largest energy block contain less than 95% of the total energy of the cluster. A neutral pion induced shower will have this property less than 1% of the time. This was determined by monte carlo and examining data in background free region (P_t < 9 GeV/c).

These clustering requirements were not sufficient for arriving at a background free spectrum. Several more cuts proved necessary. First it was required that a reconstructed event be observed in the inner spectrometer. This consisted of requiring that four A counters satisfy certain criteria discussed below, and that a vertex be reconstructed in the interaction region.

As the times of the discriminated A counter signals were digitized and recorded for the phototubes on both ends of each counter, a much finer coincidence could be required offline than in hardware. The offline coincidence required that the times of the two ends not be separated by more than 15 ns and that each time be within a gate of -7.5 ns to +9 ns about its own average zero time. Due to the large charged multiplicity in the central region of high P_t events (P_t > 3 GeV/c), this cut was evaluated to be 95% (+/-1.5%) efficient assuming a poisson distribution for good events.

The vertex (see Appendix III) was required to have at least two tracks with good A times and be within an interaction region defined as $|Z| < 25$ cm, $|Y| < 2.5$ cm, and $|X| < 10$ cm. Events with trigger transverse momenta ($P_{t\ trig}$) less than 8 GeV/c satisfying the 4 A counter cut also satisfied the vertex requirement 95% of the time. The efficiencies of these two cuts were evaluated in the region 7 GeV/c < P_t < 9.5 GeV/c in .5 GeV wide bins. In this P_t range the 2 arms of the spectrometer produced the same cross section and as these efficiencies were very high (the random backgrounds already discussed would only satisfy these requirements ~2.5% of the time) and P_t independent, it is assumed that backgrounds are low.

Above a P_t of 11 GeV/c this was no longer true. The inside array produces more triggers than the ratio of the solid angles would indicate whether, either, neither, or both of the above cuts were used. In fact above 13.5 GeV/c the event spectrum (dN/dP_t) on the inside becomes essentially flat (Fig. 13). This background is believed to be due to halo particles and upstream interactions because the inside array was not as well shielded as the outside due to the positioning of the compensation magnets for the low quadropoles. In this very high P_t region the two spectrometer cuts removed approximately 95% of the events satisfying the clustering requirements. Considering that 2.5% of the randomly triggered events satisfied these cuts, the background problems above 13 GeV/c are not surprising.

An additional cut removed this inner outer discrepancy. To insure that the source of the energy observed in the lead glass is associated with the event observed in the inner spectrometer, it was further required that at least one of the photons from the pions decay have converted in the coil. As the scintilators presented a very small solid angle to particles coming from upstream which hit the arrays, this served as a good directional requirement for the clusters energy source. The conversion was indicated by the observation of pulse height in the 2 B counters associated with the cluster. It was required that the pulse height be greater than 1.5 times that typically observed for high momentum hadrons after having subtracted the pulse height expected for the observed hadrons hitting the counters in question. The times associated with the B counters were also required to be within gates approximately 1.5 times wider than those for the A counters.

After making these additional requirements the spectra observed in the two arms of the spectrometer were within good agreement (Fig. 14) to the maximum observed P_t ~15 GeV/c. As the two spectra had been brought into agreement and as the outside arm had never exhibited any indications of backgrounds (all cuts had reasonably P_t independent effects on this side), it seemed reasonable to assume that the spectra were background free.

4.1.2 CORRECTIONS TO THE SPECTRUM

Hadrons passing through lead glass cerenkov radiate and produce -rays even if they do not interact hadronically. A correction to the lab energy of the cluster was made in the event a charged track was observed to pass through the triggering cluster. This was observed to occur ~15% of the time. Approximately 50% of these occurrences could be explained by either dalitz decay (1.5%), or conversion of one of the two photons in the beam pipe or the first drift chamber module (3% of a radiation lenght). Due to the short lever arm of the magnet these electrons were not deflected far spatially and hence their energy still included in the cluster (and the pion energy correctly measured). To correct for the hadrons but not the electrons, opposite signed tracks which formed low mass vertices at the beam pipe or the vertex were declared "electrons". For the remaining "hadrons" 450 MeV was subtracted from the cluster for each hadron with enough energy to pass through the coil (~500 MeV). There was no correction for the "electrons". The removal of this assumption had no more than a 5% effect on the cross section.

To calculate the cross section from the event spectrum, the spectrum must first be corrected for the analysis efficiency. This was analyzed in detail over the range from 3 to 9.5 GeV/c P_t for each arm and found to be P_t independent within errors. The bulk of the correction was due to the conversion requirement. The fraction of events which converted was found to be 81% and 84% for the inside and outside arms respectively. This fraction was P_t independent to a level of 2% for 4 GeV/c < P_t < 8 GeV/c. The conversion fraction expected for a two photon decay would be 79% and independent of energy for a 1 radiation length converter[56]. The difference from this value is most likely due to very low energy photons faking a conversion of the triggering photons. The correlation analysis (next section) would indicate that such an effect would be P_t independent as low energy particles show little or no correlation to the trigger. Only the low energy particles could be involved as high energy photons would still be seen in the glass. When the conversion fractions were studied in great detail[57] and the events were required to have no observed particles (charged or neutral) overlapping the scintillators in front of the trigger cluster, the observed conversion fractions decreased by only ~1%. The P_t variations can be accounted for by the effect of 3 and K_s 2 . 2 would give the same conversion fraction for P_t > 4 GeV/c, below this the probability of asymmetric decays being accepted caused the conversion fraction to drop by ~ 1.5%. Decays of other mesons have negligible effect due to low values for branching ratio times the acceptance of the cluster requirements.

4.1.3 COMPUTATION OF THE CROSS SECTION

To compute the cross section, use is made of the identity

$$Ed^3 /dP^3 = d^3 /P_t dP_t dYd$$

which holds if the mass of the particle can be ignored...therefore

$$Ed^3 /dP^3 = dN/dP_t \ X \ 1/(\ *L*\langle P_t\rangle * \ Y \ )$$

where is the analysis efficiency, L the integrated luminosity. $\langle P_t\rangle$ is the mean value of P_t within the bin and Y the rapidity times azimuthal interval (evaluated in the PP c.m.).

The cross sections were computed for the two sides individually and a constant ratio of 1.2 was found. A factor of this size corresponds to roughly a 2% difference in the energy scales of the two arrays since the data when fit to a pure power law (with no X_t dependence) is approximately proportional to P_t^{-10} (Figure 15). Given, for example, a small error (~1%) between the average calibrations of the two sides and an absolute average scale error within the estimated uncertainty (~5%), the ratio can easily be accounted for. An absolute scale error acts like an inside-outside average calibration difference due to the lorentz transformation to the c.m. As the two cross sections agreed within the statistical and systematic uncertainties (at all s), the event spectra were added together and the final cross sections computed. The errors were increased by the inside-outside difference divided by 2 2 evaluated point by point. The data for the three values of center of mass energy are shown in Table IV and Figure 16. The errors stated do not include the systematic errors discussed in the next section.

4.2 DISCUSSION OF SYSTEMATIC ERRORS

Due to the slope of the spectrum (proportional to P_t^{-10}, see Figure 15) the fits will be very sensitive to small (~1%) uncertainties in the value of the abscissa that is assigned to each bin. There are four effects which can move the plotting points from the midpoints of the bins. The first three are simply the slope of the spectrum, the smearing due to resolution, and the absolute scale uncertainty. The fourth is the coil correction and the uncertainty in its exact value and energy dependence and some detail is necessary to understand this systematic uncertainty.

4.2.1 THE ENERGY CORRECTION FOR CONVERSION

An electron passing through the 1 radiation length of the coil will lose between 50 and 80 MeV through ionization loss. If the energy is measured with lead glass however, an apparent energy loss as determined by the change in observed pulse height of approximately 230 MeV is in fact seen. When the same test was done using sodium iodide for detection, a 60 MeV loss was observed. This would indicate that the large energy "loss" observed with the lead glass might have more to do with light collection than ionization. An attempt to investigate this was made by using a sophisticated version of the SLAC EGS monte carlo modified to integrate the cerenkov power output along the path of each electron in the electromagnetic shower in the glass. For the monte carlo simulation not only is the ionization energy lost from the shower but also the first radiation lengths' cerenkov light as the first radiation length of the shower development takes place in the coil. The practical use of the monte carlo was limited since it only generated 200 events/hour, severely limiting statistics. As it was necessary to follow each electron, standard random sampling techniques of monte carlo generation could not be used, leaving no reliable way to generate the large sample of monte carlo events needed to study resolution and coil effects.

As the cross section could be analyzed independently for the converted and unconverted events at low P_t (where there were no appreciable backgrounds), a study of various parameterizations for the coil correction could be made. It must be realized that the effect of the coil could only be measured for electrons in the limited energy range of the test beam (2 to 4 GeV). This must then be related to the correction needed for pions decaying into two photons over an energy range of 3 to 17 GeV (lab energies). The forms investigated to describe the energy dependence of the coil correction ranged from constant values to logarithmic-energy dependent to polynomials of second order. Similarly several extrapolation schemes to the electron data were tried. The differences between these assorted forms became negligible above transverse momenta of order 7 GeV and tended to cross each other at around 5 GeV (see Figure 17). These uncertainties produced the major systematic errors in the low P_t region. The final correction used was the larger of 0.185ln(E/1.68) and 0.185 (energies in GeV see Figure 17).

This scheme of matching the functional forms of the unconverted and converted spectra takes care of two effects simultaneously: the exact form of the correction and the effect on the resolution due to the event to event variations in the actual coil loss. The conversion probability is expected to be energy independent to a 1% level and the conversion fraction is in fact observed to be extremely flat as stated earlier. The relative normalizations of these two spectra are ignored but the P_t and s dependence is required to be the same for the two spectra. The contamination of the spectrum due to single photons can be evaluated as no larger than 15% (90% cl) by the observed energy behavior of the conversion spectrum and previous experimental measurements in the low P_t region. It should be pointed out that small variations in the conversion fraction (due to changing production ratios of other mesons) would have a nonexistent effect on these fits since this is just a change in the normalization of one of the spectra and rapid changes are needed to affect the fits. Ten to twenty % relative variations between s spectra in a few GeV are needed to change the fit parameters significantly.

4.2.2 RESOLUTION CORRECTIONS

The effect of the resolution and slope on the spectrum was studied by smearing energies with a parameterized resolution and calculating the effect on a monte carlo generated spectrum. It would have been preferable to generate the fluctuations with a shower development monte carlo but this was unfeasible for statistical reasons as stated earlier. The effects which were considered were the intrinsic resolution of the glass and the variations in the absolute block to block calibration. The coil correction variations were taken into account as already mentioned. This technique was verified by recalculating the energies of each block in clusters from real data, by randomly assigning miscalibrations to the blocks, and smearing the energies with the measured resolution of lead glass. The effect on the real spectrum was then compared with the shifts indicated by the parameterized monte carlo. This assumes that the displacement of each bin is symmetric about the observed spectrum which is expected if the smearing effect on each bin is only a small shift in the horizontal position (~100 to 300 MeV). The two methods produced agreement giving confidence in the calculation.

4.2.3 ABSOLUTE SCALE UNCERTAINTIES

The overall scale uncertainty was estimated to be less than 5% from the uncertainty in the beam momentum during the calibration of the NaI sources and the uncertainty in their deterioration with time. A change in the calibration scale between the time the 62.4 GeV data was taken (1978) and the 45 and 31.5 GeV data (April and May 1979) would have to be less than .5%. This was deduced from the agreement in cross sections for two sets of low and medium threshold data (better than 3% over a P_t range of 3 to 6.5 GeV) taken at 62.4 GeV during two time periods separated by six months (fall 1978 and spring 1979).

The last systematic error evaluated was the uncertainty in the relative nomalizations of the various data samples (ex. s=45 and 62.4 GeV). This would be due to a relative error in the luminosities[58] for the data samples. A relative error is expected to be less than 3% and the effects of such an error are included in the stated systematic errors for the fits. An overall error in the luminosity of 5% due to the method of measuring the luminosity is an upperbound. This affects only the overall normalization. The combined effects of the systematics on the normalizations of the three data samples (added in quadrature) is estimated as 40% (moving all data samples together).

4.3 RESULTS OF FITS

The usual form chosen for parameterizing the data

$$A*F(X_t)/P_t^n \qquad (4.1)$$

is motivated by the theoretical suggestion that high P_t meson production is related to the scattering of constituents of the proton (seen in deep inelastic lepton scattering) with the power "n" revealing something about the nature of their interaction. The scaling function "F" used in the usual fitting form is related to the expected scaling behavior of parton related processes. In this case it would reflect the convolution over the parton structure and fragmentation functions. Two forms for the scaling function are standardly used.

$$(1-X_t)^m \text{ and } \exp(-bX_t)$$

In fact the form is quite irrelevant as the power "n" can be found by use of the identity

$$(\ s_1,X_t)/\ (\ s_2,X_t) = (P_{t2}/P_{t1})^n = (\ s_1/\ s_2)^n$$
$$n = \ln(\ (\ s_1,X_t)/\ (\ s_2,X_t))/\ln(\ s_2/\ s_1)$$

and a fit must produce the same result. Fitting indicates the constancy of the power through the quality (chisquare) of the fit. A sum of processes, with the necessary sum of terms like (4.1), would result in a poor fit if more than one term made a significant contribution. Such fits however have an enormous number of free parameters and are consequently not very informative. Thus what is referred to as scaling in this case means the ability to describe the data in the simple form of (4.1), and requiring only one term, this is the scaling that had been observed in the previous generation experiments.

Of the two formats indicated above the exponential form has slightly lower correlation coefficients between the fit parameters. Both forms were used extensively and always gave the same power "n" within errors. A global fit to all the data (using the exponential form showing the authors preference) yields the following fit

$$A=5.6 +/- .5 \times 10^{-28}$$

$$b=18. +/- .2$$

$$n=5.94 +/- .05$$

errors do not include the systematic

uncertainties just discussed

The of the fit is quite unacceptable being 150/49. Refitting using only the higher two values of s leaves the fit parameters essentially unchanged and gives a of 132/41, equally bad. These /d.f. have a confidence level of $< 10^{-4}$.

This deviation from the scaling behavior seen at low P_t with n~8 has been reported by all ISR experiments capable of measuring it[59, 60, 61]. A more illuminating way of discussing the functional form of the data is to perform a series of fits in selected regions of P_t or X_t. This also provides a more detailed way of studying the sytematic uncertainties of the experiment. For this purpose the data was divided into two regions, above and below a P_t of 7

GeV/c. Fitting only to the two higher values of s, again using the exponential form, produces at low P_t (P_t< 7 GeV/c).

$$A = 2.2 \pm .4 \text{ statistical } + 1.3, -.9 \text{ systematic} \times 10^{-27}$$

$$b = 15. \pm .7 \text{ statistical } \pm 1 \text{ systematic}$$

$$n = 7.2 \pm .2 \text{ statistical } \pm .7 \text{ systematic}$$

$$\text{chisq/d.f.} = 8.6/14$$

and at high P_t (P_t> 7 GeV/c)

$$A = 2.5 \pm .4 \text{ statistical } + 1.5, -1. \text{ systematic} \times 10^{-28}$$

$$b = 18. \pm .4 \text{ statistical } \pm .4 \text{ systematic}$$

$$n = 5.6 \pm .1 \text{ statistical } \pm .3 \text{ systematic}$$

$$\text{chisq/d.f.} = 37/27$$

where the effects of the systematic errors, discussed in the previous section, were added in quadrature. In both cases the systematic error was dominated by a single contribution. At low P_t the dominant error was the uncertainty in the coil correction. At high P_t the uncertainty in the calibration (and the resolution uncertainty that caused) was the dominant systematic.

An additional systematic effect comes from the contribution to the cross section of other mesons. This affects the fits through the P_t dependence of the production ratios times the cluster algorithm acceptance. Decays other than , , and K_s need not be considered as the acceptance of the cluster algorithm, times the branching ratios exclude them from making relevant contributions. The additional contribution to the cross section from these decays assuming constant production ratios of / = .55[62] and K_s/ = .4 (which seemed reasonable from the data presented and refered to by Cronin et al[63]) is shown in Fig. 18. The P_t dependence of the conversion fraction could be well accounted for by these sources only, indicating a negligible contribution from direct photons[57]. Further as a conversion was required in this analysis, and the correction made was for the conversion probability of two photon states, any contribution from this source was reduced by 33%. The corrections indicated in Figure 18 would lead to a change in the value of "n" only in the low P_t region, increasing its value by ~.5. In the high P_t region it will only affect the normalization constant.

A series of local fits were also performed in bins of X_t. This allows a study of the variations in "n" in a more gradual form. A useful identity can also be used with the cross sections from two different energies evaluated at the same X_t.

$$(s_1,X_t)/ (s_2,X_t) = (P_{t2}/P_{t1})^n = (s_1/ s_2)^n$$

$$n = \ln((s_1,X_t)/ (s_2,X_t))/\ln(s_2/ s_1)$$

A plot of "n" calculated in this way for the two highest values of s is shown in Figure 19. Also shown in that plot are the values of "n" found from fits for all three energies in the following bins of X_t.

$$.1 < X_t < .3$$

$$.2 < X_t < .4$$
$$.30 < X_t$$
$$.35 < X_t$$
$$.40 < X_t$$

The gradual drop in "n" is clearly demonstrated. The values of "n" calculated from the highest two energies continue only to X_t=.35. The systematic error due to uncertainty in the resolution corrections dominate above this value.

The systematic uncertainties of the experiment are large at low P_t due to the coil correction, and at very high P_t due to the block to block calibration errors. In the region from 5 to 11 GeV/c these uncertainties are lowest. This is shown by the small systematic error found for the fit in the region P_t>7 GeV/c. This fit is dominated statistically by the region from 7 to 11 GeV/c (the weighting of the events spreading out the region dominating the fit). It is in precisely this range (5 to 11 GeV/c) in which the large variation in "n" occurs leaving the plot as shown reasonably free of large systematic effects.

4.4 CORRELATIONS OF CHARGED PARTICLES TO THE TRIGGER

The study of the associated particles reveals whatever evidence exists for the nature of the scattering constituents and whether or not this is a constituent scattering process at all. The strong correlations observed put severe constraints on models attempting to explain the production of high P_t mesons. With the large multiplicity in the central rapidity plateau observed by the detector, an almost infinite number of variables can be generated.

It proves extremely useful to consider the leading models (the scattering models..CIM,QCD-quark model) to steer the investigation when searching for potentially illuminating correlations. Both of these models predict a recoiling "jet" in the opposite hemisphere from the trigger. The two models have very different predictions on particles spatially close to the trigger and the correlations of the recoiling system to the trigger particle. In the quark model hypothesis the triggering meson is similarly part of a "jet" though very distorted with respect to the recoiling one. The CIM (and the Quark Fusion models which are rather similar) predict that the triggering particle is an isolated meson. Even with these theoretically motivated guides the number of possibilities have only been reduced from a denumerably to numerably infinite set. What will be discussed here will be the finite subset the author thought most clearly and simply describe the final state.

To reduce biases in the correlation analysis, the event selection criteria were changed. This can easily be done as the P_t region in which there are a sufficient number of events to do such an analysis has no serious background problems (P_t < 12 GeV/c). The event selection criteria were simplified to only require a reconstructed vertex in the interaction region, eliminating the additional multiplicity bias of the 4 A counter requirement. Though the apparatus is symmetric in the lab system, it is not in the c.m. To simplify the analysis and not require a monte carlo for acceptance corrections, the polar angles for neutrals and charged were reduced to the polar angles subtended by inside (where it is smallest). This means a rapidity acceptance for neutrals of $|Y|<0.5$ and for charged of $|Y|<0.7$. The full azimuthal range of each of the arrays was kept (even though unequal) as the charged particle acceptance was the full 2 . As only correlations of charged particles to the trigger were being investigated, each event could be reoriented with respect to the azimuthal direction of the trigger. To insure full acceptance over this region it was necessary to restrict the z position of the vertex, $|Z_v| < 25$ cm. The high magnetic field acted as a shield against low P_t particles. The reconstruction was not fully efficient over the full azimuth unless the charged particle transverse momentum ($P_{t\ ch}$) exceeded 300 MeV/c in the c.m. (note..in the correlation section all variables are evaluated in the c.m. unless otherwise stated). For the correlation studies with charged particles, only data with all chambers working were used (ie..no broken wires, high current chains only). This reduced the high threshold 62.4 GeV luminosity to 2×10^{37}.

The first types of correlation coefficients to study are the two particle correlations where one of the particles is the triggering meson. As hadronic interactions tend to produce flat rapidity distributions in the central region, a good set of variables for describing a particle is P_t,Y, (being the transverse momentum, rapidity, and azimuthal angle). Table V lists the definitions of variables used with Figures 20 through 22 illustrating them. (The symbol will mean $_{trig}$ - $_{charged}$ throughout unless otherwise stated)

As the transverse momentum dependence is always very steep, any distribution integrated over any P_t (of the trigger or the secondary for example) will effectively be the value of the distribution evaluated at the lower limit. Therefore in order to study correlations, distributions must be made in bands of trigger P_t and in general $P_{t\ ch}$. Different distributions are always made for each c.m. energy.

The first distribution of interest takes advantage of the full azimuthal acceptance of the apparatus. Figures 23 through 25 show the distribution in of charged secondaries with respect to the trigger (i.e. $_{trig}$ - $_{charged}$) in bands of $P_{t\ ch}$ for the three thresholds at s = 62.4 GeV. The plots are broken into two halves covering the full azimuth so that the enhancements on both sides can be easily seen.

The distributions in the region near = 0 are badly distorted by conversion electrons and hadrons depositing energy in the glass in the same region as the trigger and simulating a much higher energy neutral meson. The solid angle covered by the overlap region corresponds to ~.15 sr which is unfortunately exactly at the peak of the correlations. To estimate the effect of these particles, same side distributions are made including and excluding particles which overlap the triggering cluster. This was the most reliable and easiest way of dealing with this difficulty and changed none of the conclusions that will be reached. Figures 23a through 25a, already mentioned, excluded the overlap region Figures 23c through 25c are the same distributions including these particles. The effect of including the overlapping particles is striking on the high $P_{t\ ch}$ distributions.

A commonly used way of parameterizing the widths of the enhancements is the mean value of the variable "P_{out}" defined as the component of the transverse momentum of the secondary particle perpendicular to the plane defined by the trigger particle and the beams, or

$$P_{out} = P_t\ |\sin(\ )|$$

The mean value of P_{out} as a function of $P_{t\ ch}$ is shown in Figures 26 through 29 for the recoil side (cos $<$ 0) for the various thresholds at the three c.m. energies. The observed values rise with $P_{t\ ch}$ to very large levels (~ 1 GeV) and fall with increasing threshold ($P_{t\ trig}$). They also exhibit a slight steepening with increasing c.m. energy (Figure 29).

The distributions on the same side are so badly distorted by the particles overlapping the cluster that at high $P_{t\ ch}$ the true values are completely unknown. At small value of $P_{t\ ch}$ the distributions exhibit a different peculiarity as shown in Figure 30. A jacobian peak appears in the dN/dP_{out} distributions at large values of P_{out}. This can be explained as a flat background in .

$$\text{If } dN/d\ \sim \text{const.}$$

$$\text{then } dN/dP_{out} \sim (1/P_t)\ dN/d\sin$$

$$\sim \text{const}/(P_t \cos\ )$$

which peaks at large values. The combined effect of these two problems makes the values found for P_{out} on the same side dependent on exactly what is done and consequently not meaningful numerically.

Phenomenologically what is of interest is that the distributions exhibit strong enhancements on both sides and a more detailed description of the correlated secondaries is desired. In order to separate the two peaks from the flat background between them, the azimuth is divided into four regions (with respect to the trigger). A region of +/- 60 centered on the trigger, a similar region centered 180 from the trigger, and two remaining regions of +/- 30 (see Figure 21) The two regions around 90 are added together and called the spectator region, thus the azimuth is divided into three equal regions of 120 , same side, away side, and spectator. As always $|Y| < 0.7$.

The distributions in transverse momentum of the secondaries

$$(1/N_{events})\ dN/dP_{t\ ch}$$

for the three regions are shown in Figures 31 through 33 for 1 GeV bands in $P_{t\ trig}$ for the three c.m. energies. Also shown (for the 62.4 GeV data) are the distributions for zero threshold (requiring only a scintillator on line and a vertex off line) normalized to 1/3 the azimuth (same solid angle normalization Y ~2.93). The same side and spectator distributions (Figures 31 a,c and d through 33 a,c and d) exhibit an independence of the threshold value, the distributions being only a function of $P_{t\ ch}$. The name spectator is now clearly justified as the distibutions of secondaries in this region are the same even to the level of normalization to those found for "minimum bias" triggers. These "minimum bias" distributions were made from events which were triggered by the firing of a single A counter. The events were further required to have a reconstructed vertex. The away side region shows a strong increase in the yield with $P_{t\ trig}$ while the same side region seems to only require a high P_t trigger, whether the overlap particles are included or not.

4.5 SCALING AND JET FRAGMENTATION

The scattering models previously mentioned predict a "jet" recoiling from the triggering meson. The exact nature of this jetlike structure is not very clearly specified however. The usual expectations are that the distribution of the fragments will scale in some variable like

$$Z = P_{fragment}/P_{jet}$$

and that the fragments will be clustered around some central core (ie have some limited momentum perpendicular to the jet axis). These predictions are for the most part an extrapolation of the hadronic final states of e^+e^- interactions to other phenomena.

In high P_t studies it has become standard[64, 65] to describe scaling through the use of the variable "X_e" defined as the fraction of transverse momentum parallel to the trigger.

$$X_e = P_{t\ sec} \, |\cos(\ )| / P_{t\ trig}$$

where the subscript "sec" refers to secondaries. The normalized distributions in X_e for charged secondaries in the two 120 regions exhibiting strong correlations, the same side and away side, are shown in Figures 34 through 36 for the 1 GeV bands in $P_{t\ trig}$ for the three c.m. energies. The away side shows excellent agreement with the scaling hypothesis as has been seen in other experiments. On the same side this is not observed whether the overlapping particles are included or not and it would appear that the best description of these correlated particles would be that they are just a function of $P_{t\ ch}$.

Another way of investigating the scaling or nonscaling behavior of the associated particles on the same side is the fraction of the total momentum in the same side region taken by the trigger. Again a "jet" type model suggests a way of doing this. If the azimuthal direction of the jet can be approximated by the direction of the triggering meson (which turns out to be valid as the trigger carries most of the momentum) then the total transverse momentum of the "jet" will be approximately

$$P_{t\ jet} = P_{t\ trig} + \sum_{\text{all sec}} P_{t\ sec} \cos$$

$$Z_{trig} = P_{t\ trig}/P_{t\ jet} = 1/(1 + \underset{\text{all sec}}{X_e})$$

limiting the secondaries only to those in the same side region and assuming charge symmetry (i.e. neutral = 1/2 charged)

$$Z_{trig} = P_{t\ trig}/P_{t\ jet} = 1/(1 + 1.5\ \ X_{e\ ch})$$

and

$$\langle Z_{trig}\rangle = 1/(1 + 1.5\langle\ X_{e\ ch}\rangle) \qquad (4.2)$$

This quantity is plotted in Figures 37 and 38 as a function of $P_{t\ trig}$ for all three values of s. The two figures differ by the exclusion of the overlapping particles. The difference in $\langle\ X_{e\ ch}\rangle$ between including and excluding these particles is ~ 4% within errors for every point. The average fractional momentum that the conversion electrons might contribute would also be ~ 4% breaking down as

0.75% from 1.5% (Dalitz decays) X 0.5 (fractional momentum of one photon)

3.0% from 3.0% (conversion on beam pipe or DC1) X 0.5 (fractional momentum of one photon) X 2 (two photons)

= 3.75%

This might seem odd when one recalls that overlapping particles were observed with a frequency of ~ 15%, but the hadrons will in general be very low momentum (~ 400 mev). The additional momentum then is ~ 40 MeV/c. The change in $\langle\ X_{e\ ch}\rangle$ is then ~ $.04/P_{t\ trig}$ ~ 1.2% at 3

GeV/c and decreases. The inside outside difference, which serves as an estimate of the systematic error and is included in the plotted errors, is on occasion this large so this aspect can be safely ignored.

If the fragmentation scaled, $\langle Z_{trig} \rangle$ would be a constant which it clearly is not. This however ignores the kinematic limit of s/2, one might expect[52] that this quantity would be a function of X_t. When plotted in this manner the data regains a scaling behavior one might have anticipated. Figure 39 was made excluding the overlaps, as their effect seemed well acounted for by only the conversion electrons.

Along with the "jet" an additional momentum, equal to what is seen on average for a minimum bias type event (in a similar solid angle), might reasonably be assumed to have been mistakenly included. The already large fraction of the "jet" momentum attributed to the trigger particle becomes even larger if a contribution for these spectator particles is subtracted (~375 MeV/c Figure 40). The uncertainty in the subtraction (~ +/- 40 MeV/c) and its s dependence make this plot lose much of its meaning as an additional error (which is not shown) of order 2-3% results. By subtracting such a large constant momentum (375 MeV/c, approximately 50% of the accompanying momentum observed), much of the dependence on $P_{t\ trig}$ is removed (just because the value of $\langle Z_{trig} \rangle$ has become so large). The removal of the X_t dependence was due to using a subtraction independent of s and could be a spurious result. The point was just to see the magnitude of the effect. The value of the momentum to be subtracted was found by using events triggered on a single A counter (~ minimum bias) and calculating the centered component (P_x) of the total transverse momentum in a solid angle defined by $|Y| < 0.7$, = 120 . The value found at s = 62.4 GeV was 375 MeV/c and 360 MeV/c at 45 GeV. This would indicate that in fact the subtraction is s dependent. There was no data at s = 31.5 GeV so rather than extrapolating, a single value was used for the subtraction (375 MeV/c). The point that should be stressed is that the "jet" can be approximated to a 90% accuracy by just the trigger particle.

The values of $\langle Z_{trig} \rangle$ would indicate that though the same side secondaries are best described in a nonscaling manner (just a function of $P_{t\ ch}$), this method of description seems to have restored a form of scaling. It is worth reconsidering the distributions of charged secondaries in the same side region in view of this effect. On careful examination the distribution of secondaries (as a function of $P_{t\ ch}$, $dn/dP_{t\ ch}$) shows a slight dependence on s. The normalization increasing slightly with s but for each value of c.m. energy being independent of $P_{t\ trig}$.

Using the scaling variable where it does seem to describe the distribution of secondaries (on the recoil side), the mean values of P_{out} are found for bins in $X_{e\ ch}$. As before the entire half azimuth (cos < 0) is integrated over. The values are shown in Figures 41 through 44.

4.6 VECTOR SUM ANALYSIS AND EVIDENCE FOR JETS

To this point no evidence has been presented which actually demonstrates the validity of the "jet" assumption, which framed the direction of the correlation analysis. In fact nothing has even demonstrated that high P_t phenomena have anything to do with a constituent scattering process. (After all momentum must be conserved.) These two questions are the central issues in the investigation and until they are clearly answered it is difficult to proceed further, or even justify some of the analysis done so far.

In hadronic interactions it is difficult (and as will be argued, perhaps impossible) to define and identify what is usually referred to as a "jet". Part of the problem is that this is not a well defined object intrinsically. Its properties cannot be calculated and in normal (i.e. complicated) hadronic interactions its constituents cannot even be identified uniquely. The concept of a jet is a qualitative one and what this concept means must first be addressed before attempting to find such an object.

A jet as the name suggests would seem to be a collection of high momentum particles tightly correlated together. In high P_t hadronic interactions there are two problems in identifying such an object. First hadronic interactions produce a cloud of particles produced essentially flat in rapidity in the central region. Consequently if a "jet" occupied any sizable solid angle it could have a non-negligible number of particles from the cloud alongside and indistinguishably mixed in. This point is strongly illustrated by looking at the multiplicity distributions for all events (high threshold $s = 62.4$ GeV for example) in the spectator and away side regions. There is not an overwhelming difference in the mean values of the two distributions (Figures 45 and 46) which demonstrates that a "jet" signal is not going to be a trivial thing to find. The excess multiplicity expected from the presence of a jet in the away side region does not seem to be exhibited in terms of the average. On an event by event basis clearly not much can be done about this but statistically the spectators would be uncorrelated to the core of the jet. The second difficulty is that no well defined signal for when a jet is actually in the apparatus seems to exist (this is not a resonance for example). In either case the problem is one of signal to noise and it remains to be seen how clearly a jetlike structure can be seen above the background.

The concept of a recoiling jet comes from the idea that the scattered parton fragments into hadrons in an isolated manner. If this were true a vector sum of the momenta of these hadrons would be equal to the momentum of the scattered parton. It is through a vector sum that the core structure will be identified.

In making such a construction the major input is the selection of which particles to include. It is clear that what is of interest is the observed enhancement in the azimuthal distributions, and it is the structure of the enhancements that will guide the requirements.

The azimuthal size of the away side region (squared) would indicate roughly the solid angle needed to contain a jet. Given the rapidity interval, $|Y| < 0.7$ of the chambers, some care is necessary in order to insure containment. This is made even more difficult if this is a parton phenomena as the c.m. of the scattering system could be moving with large momentum parallel to the beam axis. This could cause the recoiling jet to miss the apparatus altogether. This would seem to occur as at 3 GeV/c $P_{t\ trig}$ 25% of the time no charged particles are observed at all in the away side region (Figures 47 and 48).

While the azimuthal solid angle of the away side region for the tracks can be rotated to be opposite the trigger (the chambers cover the full azimuth) the same cannot be said of the glass in the non-triggering array. In addition the efficiency of neutral particles to satisfy the cluster algorithm, coupled with the effects of the coil make detection of low P_t neutrals (below ~ 2 GeV/c) a hopeless endevor. In view of these two difficulties the neutral particles were ignored altogether in order to simplify the analysis and not rely on a heavily model dependent monte carlo. Monte carlo calculated corrections would depend heavily on the particle density assumed and as this is exactly what is supposed to be studied, such corrected measurements could be extremely wrong and misleading. (Authors note: this same problem carries over even into momentum resolution corrections for any of the charged particle results described so far. This is because the momentum resolution, as determined from cosmic ray data, varied from 4% to 7% P_t for the tracks depending on the configuration of planes which detected the track. As the efficiencies were clearly spatial density dependent it was decided by the author not to correct any of the spectra involving charged particles for momentum resolution. They were corrected for the average efficiencies found in each of the three regions (different due to densities). The correlation results are all really qualitative anyway and calculations of the corrections indicated they were never larger than 10% (the largest effect was to reduce the values of P_{out} at very large $P_{t\ ch}$). An effect of this size seemed small enough to be ignored.)

In view of these difficulties the vector sum constructed consists of all charged particles in the away side region with $P_{t\ ch}$ > 300 MeV/c. In an attempt to achieve some level of containment, the vector sum was required to satisfy the condition

$$|P_{z\ jet}/P_{t\ jet}| < 0.3$$

or

$$|\ _{jet}| = |\ln(\tan(\ /2))| < 0.296$$

Thereby leaving a minimum of ~0.4 units of pseudo rapidity to the limits of the detector. The problem of the spectators still remains in that a single 300 MeV/c (P_t) particle in the middle of the apparatus satisfies this definition of a jet, while not being within the qualitative concept. To insure that the particles recoiling from the trigger included those expected from a jet structure, if it existed, a minimum transverse momentum of the vector sum was also required. As this analysis would have at best, on average, only 2/3 of the recoiling momentum, (no neutrals or charged track efficiency corrections are used) and to minimize the effect of the spectators, only the high threshold data were used. Consequently requiring 3 GeV/c P_t for the vector sum was not unreasonable. This cut was motivated by the spectrum of the vector sum P_t for centered vector sums (Figure 49). 3 GeV is about the lowest value where the spectrum no longer has the characteristics typical of threshold effects. The author reasoned that if jets existed the sample of events selected by these cuts would surely contain them.

One other point should be kept in mind which illustrates how the models influence the analysis. In the quark scattering models a necessary input for fitting the inclusive cross section is to assume a large (.8 to 1 GeV/c) average initial transverse momentum of the partons. This has the effect of biasing the events selected by the trigger such that the initial state would have a net momentum in its direction (of order 1 to 2 GeV/c). Consequently, for example, a 7 GeV trigger could be caused by two 6 GeV partons with an initial combined P_t of 1.5 GeV in the trigger direction. This in turn produces a recoiling parton of ~4.5 GeV P_t in the PP c.m. (and therefore ~3 GeV P_t in charged particles recoiling). This theoretically motivated possibility was partially responsible for the "low" value of 3 GeV required of the sum less than half the required trigger P_t of 7 GeV. (There was also a slight statistical consideration.)

As the entire issue of the evidence for a jetlike structure (or the lack thereof) is a qualitative one, the questions of confidence in what is determined become very simple to deal with. A trivial monte carlo calculation will demonstrate that the recoiling particles are in fact, more correlated to the vector sum than acceptance and their individual correlations to the trigger would require. The calculation is performed by generating events with particle distributions as similar to the data as possible, with only the secondary to secondary correlations removed. This is easily done by being able to generate random numbers according to an input distribution. The CERN histogram program (HBOOK) has exactly such a procedure and requires only a very finely binned histogram in order to generate a "smooth" distribution. (Note: this is really not a complicated procedure to write in any case.) The distributions used were:

1. The distribution of trigger P_t
   a. needed to select the distribution in $P_{t\ ch}$ due to the strong dependence of these distributions on $P_{t\ trig}$
2. The charged multiplicity distribution in the away side region (Figure 46)
3. The distributions in $P_{t\ ch}$
   a. dependent on which value of $P_{t\ trig}$ was generated, one histogram for each GeV in $P_{t\ trig}$
   b. each histogram was 100 bins ranging from 0 to 7.5 GeV
   c. just for overkill distributions 1. and 3. were done seperately for inside and outside triggers

According to the multiplicity generated from 2 a certain number of particles would be generated according to 3 (dependent on the generated value from distribution 1). The particles were generated flat in rapidity ($|Y| < 0.7$) and either flat in azimuth or according to the observed azimuthal distributions (Figure 25b). (The distribution used depended on the generated value of $P_{t\ ch.}$ for each particle) The value of was required to be in the 120 of the away side region (or another value was generated). After an event was generated the same event cuts and analysis were performed (exactly the same Fortran code was executed). The values of P_{out} and P_{out} are shown in Figures 51a and 51b for the data and the monte carlos. (The values of P_{out} were the same using either method of generating the azimuthal distributions.) The separation between the observed and generated values is obvious, even when the independent azimuthal correlations to the trigger are included, demonstrating the core struture. Also apparent is the azimuthal symmetry about the jet axis. These results and their implications will be discussed in greater detail in a later chapter (Theoretical Interpretation).

4.7 ANALYSIS OF THE SYMMETRIC TRIGGER

In the course of the experiment a unique data sample was accumulated. The symmetric trigger collected a subset of high P_t events in which very high P_t particles were present on both sides. The data sample accumulated represented ~0.75 million events written to the final DSTs and the integrated luminosities stated of 1.7×10^{37} at