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

s = 45 GeV and 9.2 X 10^{37} at s = 62.4 GeV. A trigger of this type selects events in which not only the momentum transfer but the parton c.m. energy for the scattering process may be estimated. From this additional information the full functional dependence of the scattering cross section will be found.

In the previous section it was mentioned that the quark scattering models require assuming a large initial average parton transverse momentum in order to fit the observed P_t^{-8} behavior at low P_t. In view of these calculations it is not unlikely that any form of constituent scattering would show a similar distortion in the single arm inclusive cross section if the constituents had a non-negligible initial P_t. In the single arm trigger there is a tendency to bias the event selection such that the initial state was moving in the direction of the trigger. By triggering symmetrically this bias is greatly reduced and the true cross section (hopefully) more directly measured.

Before proceeding with a complicated discussion of how to arrive at this goal it is best to see what the event distributions look like. A trigger of this type has almost no contamination from the backgrounds affecting the inclusive analysis. Backgrounds to this trigger are limited mainly to cosmic rays and air showers. Beam related backgrounds have difficulty satisfying the trigger requirements in both arms simultaneously. The cosmic ray and air shower backgrounds can easily be rejected by requiring the presence of a vertex in the interaction region.

In considering the spectrum from such a trigger there are several resonable choices of variables for its description. A two particle system requires six variables to be fully described (ignoring spins). As these are basically high P_t events variables reflecting this might seem the most reasonable. Such a procedure is not practical as it is difficult to really define things clearly.

Another choice would be the mass of the two particle state and its transverse momentum. Figures 52 and 53 show the mass spectra (dN/dM) for the two c.m. energies (62.4,45 GeV). Figure 54 shows the mean value of the transverse momentum of the two pion state as a function of mass (P_t). It is through use of the variables used to describe a decay process that an invariant method of describing the scattering in a model independent manner will be achieved.

4.8 CHARGED CORRELATIONS AND SIMILARITIES TO THE SINGLE ARM TRIGGER

The first thing to establish is the relationship between the events selected by the symmetric trigger and those of the more general single arm trigger. The similarities should be investigated to know with what confidence the conclusions drawn can be extrapolated to the more general phenomena. To study these similarities each symmetrically triggered event was treated as two individual single arm triggers. Distributions similar to those of the previous section could be made in a well defined manner. More specifically for every event, the two pions of the massive pair were treated in succession as if they were the triggering particles of a single arm trigger. Azimuthal distributions (with respect to one "trigger", then the other) of charged particles as a function of $P_{t\ ch}$ are made and the characteristic two peak structure is observed (Figure 55). In this case the two peaks are of the same height unlike the case in the single arm trigger. Binning the events in P_t "$_{trig}$" and constructing for each of the two "triggers" a centered same side region of +/-60 in azimuth, distributions in $P_{t\ ch}$ were made for the particles in those solid angles (Figures 56 through 63). These distributions can be directly compared to the same side distributions made with the single arm trigger. The distributions were only made including the overlapping particles. These distributions are very similar to the corresponding distributions observed in single arm triggers. They appear to have the same shape as the distributions from the single arm triggers, but a normalization which drops slightly with P"$_{t\ trig}$". The similarity can also be studied by investigating the "trigger" dependence of $\langle Z_{trig}\rangle$ (as defined in equation (4.2) see Fig. 64 and 65). The deviation from a scaling behavior, (as reflected in the P_t dependence of $\langle Z_{trig}\rangle$) is again apparent. The point that should be stressed is the large value. The difference between the values found with the single arm and symmetric triggers is an important effect and more will be said of that in the last chapter.

The issue of X_t dependence is not properly addressed as the effect of the mass requirements for the two data samples is difficult to understand and was not made in a scaling manner in any case. As these values were computed including conversion electrons and the contribution from minimum bias particles the true values are even higher. The values with an estimate of these contributions subtracted are shown in Figures 66 and 67.

Scaling behavior is still observed on the recoil side. Again using one of the two triggering clusters as a singles trigger and the other as a recoiling secondary, the dN/dX_e were made in bins of P_t "trig". The two clusters then exchange roles and another value of X_e and P_t "trig" are computed and histogrammed (see Figures 68 and 69). Due to the solid angle effects the normalizations are different depending on which side (inside or outside) is treated as the recoil. The slopes for the two sides are the same and found independent of P_t "trig" though not quite as steep as the same distributions made for charged particles with the singles trigger. In all the two particle correlations exhibit many of the same characteristics that described the single arm triggered events. With this assurance, the events selected by the symmetric trigger, in which both jets are required to be in the apparatus, will be used to measure the parton interaction.

4.9 INVARIANTS AND THE SCATTERING CROSS SECTION

The large trigger bias observed, as measured by the high value of $\langle Z_{trig} \rangle$, indicates that in the symmetrically triggered events the two trigger particles make an excellent approximation of the scattered constituents just by themselves. This approximation is even more accurate in the directions than in the magnitude of the momenta in view of the small values observed for P_{out} and P_{out} , and this can easily be taken advantage of.

The problem of studying correlated quantities in high P_t interactions is that it is difficult to define things in a sufficiently precise manner such that unambiguous, quantitative results can be found. All the correlations presented would change to varying degrees if different solid angle conventions had been used for example. To avoid this it would have been necessary to correct all quantities through modelled calculations hoping to arrive at some convergence. The difficulty with this approach is that if the model has nothing to do with the real physics the results and conclusions could be very wrong.

In view of these difficulties, to arrive at quantitative results, the quantities being studied must be extremely well defined. This is most easily accomplished by maintaining simplicity. In this case that would mean using no more than two particles, as the number of necessary variables needed to specify the final state is three times the number of particles involved (and the one particle case has already been dealt with). For two particles this means six variables and is clearly a non-trivial problem.

Though these are high P_t events, the angular correlations make the use of variables like the linear difference and sum of the transverse momenta of the two trigger particles awkward as the geometrical features of the apparatus do not factor out neatly. This does happen in the case of using variables of a decay process, so this approach will be used. The six variables needed to specify the final state if described as a two particle decay would be the mass, three variables describing the motion of the massive state, and two angles specifying the decay defined in the massive "parents'" rest frame. Normally these angles would be defined with respect to the direction of motion of the massive state. If instead they were defined with respect to the incident beam direction, one could be chosen to be the scattering angle. This is how the connection to the basic scattering nature of the process will be made.

The description of a differential cross section is frequently made in terms of the mandlestam variables S, T, and U. For an elastic two body scattering process these variables can be written in the center of mass as

$$S = (P_a + P_b)^2$$

$$T = -0.5*S*(1-\cos\ )$$

$$U = -0.5*S*(1+\cos\ )$$

where is the (polar) scattering angle. Due to this, and dimensional requirements, if there are no other inherent energy scales any cross section that can be written as a polynomial in the mandelstam variables can be factorized to be written as the product of a power law in S and a function of cos :

$$Ed^3 /dP^3 = F(S,T,U) = f(S)*g(\cos\ )$$

$$f(S) = A*S^n$$

The cross section will be parameterized in terms of its angular dependence (in bins of mass to verify the factorization) and its mass dependence. Due to the symmetry of the final state what is actually measured is the magnitude of cos , its sign being indeterminate.

As what is actually sought is the angular distribution in the parton c.m. (which is not necessarily the c.m.) an ambiguity arises. The large observed mean transverse momentum of the "parent" state (Figure 54) could easily have a considerable contribution from inequalities of the values in Z_{trig} for the two sides. This possibility prompted two decisions: to require that the events be cut to having the smallest value of P_t that statistics would allow and not to use the pion pair c.m. as the frame where the scattering angle was evaluated. The "scattering angle" was chosen to be defined in the frame where the massive state had no momentum along the beam axis. The transverse momentum of the pair was left unaffected as the transformation was only along the beam direction (Z). As the polar angles of the two pions were unequal if P_t = 0 the definition for cos *' was chosen as the average of the cosines:

$$\cos\ ^{*\prime} = 0.5*(|P_{z1}{}^{*\prime}/P_1{}^{*\prime}| + |P_{z2}{}^{*\prime}/P_2{}^{*\prime}|)$$
$$= 0.5*(|\cos\ _1| + |\cos\ _2|)$$

It was hoped that this definition might be a little less sensitive to the fragmentation issue. As P_t was required to be small (P_t < 1 GeV/c for m < 12 GeV/c^2) any error caused by this choice of definition should also be small. This was verified by a simple monte carlo calculation that will be described later.

There still remain six variables per event which are far too many to deal with in a reasonable way. What is wanted is the distributions in two (S or mass, and cos *) in a well defined form. Integrating over the others is done by defining the acceptance (these two operations being really the same thing). A correct choice of variables will make this task rather simple. The variables used were:

M being the mass of the pion pair

P_t being the transverse momentum of the massive pair

Y being the rapidity of the massive pair

cos $^{*\prime}$ which was already defined as the cosine of the scattering angle

* being the azimuthal angle of the plane of the decay

By using rapidity (instead of the Z momentum for example) the acceptance defined by integrating over P_t and become independent of mass and only a function of Y and cos $^{*\prime}$. This is clear in the limit of P_t = 0 as then

$$Y = 0.5*\ln((1+\ )/(1-\ ))$$
$$=P\ \ /M\ \ =v/c$$

and is explicitly independent of mass.

To calculate the acceptance, a monte carlo generated massive "states" within a 1 GeV mass bin with a slope within the bin similar to that seen in the 62.4 GeV data ($e^{-.7M}$). This mass was generated flat in Y (|Y| < 1) and with the P_t distribution observed in the data requiring that P_t be less than 1 or 2 GeV/c (acceptance maps were made separately for each cut). The direction of the transverse momentum was generated flat in . This is a physics assumption in that the direction of the transverse momentum could be correlated to the plane of the decay but it is the only model dependence in the entire calculation. As long as P_t is small this assumption has little effect. The rest frame of the massive state is found and the decay is generated flat in and cos , where the angles are defined with respect to the Z axis (beam axis) in the true c.m. In the "PP" c.m. the value of cos $^{*\prime}$ is calculated transforming only along Z. A table was made in Y vs cos $^{*\prime}$ in small bins (Y = cos $^{*\prime}$ = 0.05) of the number of generated events in each bin. The two decay products are then transformed to the "lab" frame and if they enter the fiducial area of the lead glass arrays (10 X

12 blocks) entered in a similar table of "accepted" events. The bin by bin ratios are found and this is the acceptance map in Y vs cos $^{*\prime}$ for that mass bin. These maps were found to be independent of mass to within the statistical accuracy of the monte carlo in the region finally used for the analysis (|Y | < 0.35, cos $^{*\prime}$ < 0.5). For the higher values of mass increasing the maximum allowed transverse momentum of the parent from 1 to 2 GeV/c had a negligible effect on the acceptance. As the maps were all identical the final acceptance corrections were calculated using all the generated and accepted events (satisfying the maximum transverse momentum requirement). Approximately two million events were generated in the monte carlo. The final acceptance correction map is shown in Figure 70.

Similar tables were made in 1 GeV mass bins using data again requiring that P_t be less than some upper limit determined by statistics as outlined in the following table.

sqrt(s) = 45 GeV		sqrt(s) = 62.4	
mass	P_{tmax}	mass	P_{tmax}
6.25-7.25	1	8-9	1
7.25-8.25	1	9-10	1
8.25-9.25	1	10-11	1
9.25-10.25	1	11-12	1
10.25-11.25	2	12-13	2
11.25-12.25	2	13-14	2
12.25-14	3	>14	3

The 6-7 GeV bin suffered from threshold problems and was ignored in general. The first bin of the 62.4 GeV data (8-9) may also have suffered from threshold problems due to the processing, but was used anyway as the data was not very badly affected.

The tables were made in bins of Y = cos $^{*\prime}$ = 0.05 as was the acceptance correction table. The tables from data (example Figures 71 and 72) were then corrected bin by bin and the distributions in cos $^{*\prime}$ found for bins of mass integrated over the region of reasonably flat acceptance (|Y | < 0.35). These distributions are shown in Figures 73 through 76 for the two c.m. energies and constitute a well defined measurement of g(cos).

As the acceptance was independent of mass the true mass distributions could be found in a similarly well defined way. This was done by requiring that the events have P_t less than 1 GeV/c (no increasing cut this time), |Y | < 0.35, and cos $^{*\prime}$ < 0.4. Each event was weighted by the acceptance correction found for its value of Y and cos $^{*\prime}$. The mass cross sections are shown in Figure 77. By this method f(S) and g(cos) were found in a manner independent of models and apparatus.

4.10 THE SYMMETRIC TRIGGER WITHIN A PARTON MODEL

An analysis of this form is motivated by the belief that the distributions found in cos $^{*\prime}$ and mass for the two trigger particles will be almost identical to those of the parent partons. Of the two distributions the easier to compare with a model and test the accuracy of the two patricle approximation is the cos $*'$ distribution.

The test is made by making a simple parton model calculation as outlined diagramatically in Figure 2. Pragmatically what is done is two partons are generated by monte carlo, each with gaussian transverse momenta (= 800 MeV/c for each component) and flat X distributions, weighted according to $(1-X)^3$ (X = P_z/31 GeV). These partons are scattered through a polar angle determined in the parton parton c.m. with respect to the parton parton axis. The events are generated flat in cos and weighted according to the differential cross section (f(S)*g(cos)) being tested. The scattered partons are then fragmented into leading particles each with gaussian transverse momenta (= 500 MeV/c for each component) with respect to the scattered partons' direction. The longitudinal momentum fraction, Z, was generated flat and weighted according to a $(1-Z)^2$ distribution from Z_{min} = 0.5 to 1. The lower cuttoff increased the efficiency by 4 with little bias as less than 1% of the weighted events had either of the values of Z < 0.5. The momenta of the leading particles were transformed to the PP c.m. and distributions in cos $*'$ found.

The events were then required to satisfy the same cuts as the data (|Y| < 0.35, P_t < 1 GeV/c) and the angular distributions were fit to the form

$$1/(1-\cos\ *')^n + 1/(1+\cos\ *')^n$$

$$\sim(s/2)^n*(1/t^n + 1/u^n)$$

To see what distortion the event requirements put on the parton angular distributions, the true (generated) cos distributions were also fit for the "good" events. The reason for this was that the P_t cut could have distorted the distributions. This is because the range in $|Z_1 - Z_2|$ which satisfies this cut increases as the scattering becomes more forward (cos large) steepening the cross section.

Two differential cross sections were used to test the effects of the analysis method within the context of this modeled calculation. The range in cos $^{*\prime}$ was again 0. to 0.5. The two forms used were:

$$(1/s)^4 * (1/(1-\cos\ )^2 + 1/(1+\cos\ )^2)$$

and

$$(1/s)^3 * (1/(1-\cos\ )^3 + 1/(1+\cos\ )^3)$$

Then the angular distributions of the leading particles in cos $^{*\prime}$ were fit to the form

$$1/(1-\cos\ ^{*\prime})^n + 1/(1+\cos\ ^{*\prime})^n$$

The fits yielded 2 and 3 to within 2% for the four 1 GeV mass bins from 8 to 12 GeV. This would indicate an excellent resolution of this method for finding the differential cross section even when all the transverse momenta of the partons and the fragmentation process are considered.

4.11 FITS FOR f(S) AND g(cos *')

The functional form chosen for fitting the mass and angular distributions is motivated by the expected parton nature of the process. This would lead to a scaling behavior for the cross section.

$$d^3\ /dmdydcos\ \ = \ A*F(m,cos\ \ )*H(X)$$

which should factorize as

$$A*f(m)*g(cos\ \ )*H(X)$$

The anticipated factorization of the cross section is apparent on inspection of the angular distributions (Figures 73 through 76). The degree of factorization can be made quantitative by fitting these distributions to some functional form. The form chosen for the complete fit is similar to the form used in the inclusive analysis.

$$A*(1/S)^{p}*((1/T)^{n} + (1/U)^{n})*e^{-bX}$$

$$A'*/m^{2*(p+n)}*(1/(1-cos\ \ )^{n} + 1/(1+cos\ \ )^{n})*e^{-bX}$$

with the scaling variable, X, defined as m/ s or m^2/s. Noting that in a parton model

$$m^2 = s*X_1*X_2$$

$$\text{if } Y=0 \qquad m^2 \sim s*X^2 \qquad X = m/\ s =$$

The form chosen for the polynomial in S, T, and U was made by the notion that the scattering could be described as some poynomial in T and then symmetrized by the final state. There has been little theoretical work done concerning a symmetric trigger and none (to the authors knowledge) along the lines of this analysis.

Taking the angular distributions and fitting to the form

$$1/(1-\cos\ ^{*\prime})^n + 1/(1+\cos\ ^{*\prime})^n$$

the power "n" was found to be reasonably independent of mass and c.m. energy as outlined in the following table

sqrt(s) = 45 Gev		sqrt(s) = 62.4 GeV	
mass	n	mass	n
7.25-8.25	3.3 +/- .11	8-9	2.8 +/- .06
8.25-9.25	3.35 +/- .2	9-10	3.02 +/- .1
9.25-10.25	2.88 +/- .21	10-11	3.05 +/- .15
10.25-11.25	2.86 +/- .34	11-12	2.84 +/- .13
11.25-12.25	3.29 +/- .4	12-13	2.99 +/- .19
12.25-14	3.4 +/- .52	13-14	3.15 +/- .22

The for the fits are all acceptable but considering the small number of degrees of freedom this is not surprising. A global fit to all the angular distributions yields a value for the power "n" of

n = 2.94 +/- 0.03 stat +/- .2 syst

chisq = 124/116

Only the 6.25-7.25 GeV bin was ignored. If the first bin of the 62.4 GeV data was ignored as well the power "n" increased by ~ 0.07 with an increase in the statistical error of .02. The quality of the fit emphasizes the factorization of the cross section. If the angular distributions were fit to limited range in cos *, the fits were not significantly changed.

As the cross section factorizes it seems reasonable to continue the approach and find the dependence on the mass. To do this spectra at two energies are required to specify the scaling dependence. The mass cross sections are calculated as

(d /dmdydcos)dcos = N /(m* Y*L)

where N is the number of events in a mass bin (m = .25 GeV/c^2) each weighted by the acceptance correction for its value of Y and cos *, (as stated previously). The events were required to have P_t < 1. GeV/c throughout the spectrum (unlike the cos *, distributions where the upper limit was increased with mass when statistics required), |Y | < .35 and cos *, < 0.4. These mass distributions constitute a well defined cross section independent of the apparatus.

The cross sections at the two energies were fit to the form

$$A/m^n * e^{-bX}$$

The parameters A, n, and b are listed below for the two definitions of X, both have excellent for the fits.

	X = M/ s	X = M^2/s
A	28.1 +/- 6 X 10^{-28}	11.6 +/- 2.8 X 10^{-28}
n	6.4 +/- .13	6.55 +/- .13

b	14.2 +/- .7	38.9 +/- 1.8
chisq	77/73	83/73

The errors stated are statistical. For the purposes of these fits, the data were kept in bins of 0.25 GeV/c^2 and not in the wider bins presented in Table VI which were determined by statistical requirements. The systematic error on the parameter "n" is 0.5 in both fits.

The systematic effects considered included overall and relative scale and luminosity uncertainties. The systematic errors in the angular fits are primarily due to possible systematic variations in the calibration across the glass (cos *') which are estimated to be less than 3%. The effect of the contribution of other mesons, and K_s, is to raise the power of both the angular and mass fits (the acceptance of the cluster algorithm changes slightly with cos *'). The power "n" for the fits of the angular distributions is increased negligibly however, the mass fits are changed by ~.5 in the power law if the corrections in Figure 18 are used.

Combining the results of the fits to the angular and mass distributions the cross section can be written in the form

$$(1/m)^{2*(p+n)}*(1/(1-\cos\ )^n + 1/(1+\cos\ )^n)$$

or

$$(1/S)^p*((1/T)^n + (1/U)^n)$$

with

$p = .25 \pm .07$ statistical $\pm .25$ systematic

$n = 2.94 \pm .03$ statistical $\pm .2$ systematic

5. SUMMARY OF RESULTS

The results presented are reviewed in the short discussion that follows.

The inclusive cross section (Fig. 16) for production does not exhibit a continuation of the scaling observed in the previous experiments when extended over a much larger range in transverse momenta. The data from these experiments had allowed a global parameterization of the form

$$A*F(X)/P_t^n$$

with n = 8. The deviation from this is illustrated in Figure 19 where the power n is found for selected regions in the scaling variable X_t and is observed to drop from a value of ~ 8 to one of ~ 5.5 as P_t increases above 9 GeV/c ($X_t > 0.3$).

The results of the study of the associated event are indicative of the underlying constituent scattering nature of high P_t phenomena. An isolated system is observed recoiling from the trigger particle in an otherwise typical (average, i.e. minimum bias) PP interaction. The constituents of the recoiling system are observed to be produced in a manner that scales with the trigger momenta (Fig 34a through 36a). They can individually have large (~ 1 GeV/c) momentum components transverse to the plane defined by the trigger and the beams (P_{out} see Figure 20 for definition Figures 26 through 29) but are much more tightly grouped to each other than these values alone would indicate (see section 4.6 and Figure 51). These properties of the recoiling particles tend to suggest their description as a jet-like structure. This data represents the clearest evidence for such a structure (similar to that seen in e^+e^- anihilation) in hadronic interactions. These observations strongly support the conjecture that high P_t phenomena are the product of a constituent scattering process and the large acoplanarity suggests a large initial state motion of the constituents.

The particles produced on the same side as the triggering high P_t meson indicate a strong correlation both in additional yield (Figures 31a and d through 33a and d), from that expected for minimum bias and location (Fig 23 through 25). The simple interpretation afforded by the jetlike structure of the recoiling particles is however not reached. Though a significant increase of additional particles is observed, it does not represent a large additional average total momentum. If a jetlike structure is involved (and the additional particles are not just the result of secondaries from resonances) the jet can be approximated to extremely good accuracy ($\langle Z_{trig} \rangle \sim 90\%$ Fig. 37 through 40) by just the trigger particle (when binned in the transverse momentum of the trigger). Description of the correlated secondaries in this roundabout manner ($\langle Z_{trig} \rangle$), does restore a scale invariance, typical of parton processes, the value being just a function of X_t (Fig. 39). When a hard recoiling secondary is also required, as in the case of the symmetric trigger (see chapter 3) the amount of momentum accompanying the trigger is found to increase substantially (Figures 64 through 67). The issue of whether the correlated particles are just due to resonances (ex   etc.) can probably be decided most conclusively by the excess of low P_t secondaries ($P_{t\ ch}$ < 1 to 1.5 GeV/c for example). The added yield (in excess of minimum bias) of such particles is almost 1 per event while the fraction of phase space that produces such asymmetric decays (for $P_{t\ trig}$ = 7 GeV/c for example) is small. The author however chooses to leave this calculation to some concerned theorist for the time being.

The analysis of the massive meson pair data (symmetric trigger) leads to a far more detailed understanding of the basic interaction. By being able to approximate with good accuracy both scattered partons by the two trigger particles (the conclusion reached from the large observed value of $\langle Z_{trig} \rangle$) the limitations of the apparatus can be taken out of the measurement in a model independent manner (see section 4.9 and Figures 70 and 72). The interaction measured by this method is observed to factorize into a product of an angular function and a power law in mass (Figures 73 through 77), section 4.11). The angular distributions are observed to be independent of mass and c.m. energy. Within the context of a parton model the method proved extremely accurate even when the effects which severely distort the inclusive cross section are considered (section 4.10). The conclusion of the analysis is that the differential scattering cross section can be parameterized approximately as

$$1/T^3 + 1/U^3$$

6. REVIEW OF THEORETICAL SITUATION AND IMPLICATIONS OF THIS DATA

The phenomenology of high P_t meson production presents an extremely tempting field for testing the constituent nature of hadronic matter. The distance scales probed by the large momentum transfers extend down to as small as ~10^{-15} cm. On time and distance scales of this order of magnitude the possibility of reliably using the impulse approximation in calculations has been conjectured for almost a decade. The recent work on gauge theories of strong interactions has added impetus to these conjectures. With the renormalization effects on the coupling constant in the standard SU(3) color gauge symmetry, implying a coupling strength of ~0.2,

$${}_s = 12\ /(33-2n_f)\log(Q^2/\ {}^2)$$

the realm of high P_t phenomena becomes one of the only purely hadronic phenomena which has any hope of being reliably calculable in the near future.

The underlying assumption in all the scattering models (not just the "QCD" model) is that the process can be described in a factorized manner.

$$\frac{Ed^3}{dP^3} \sim F(X_1)*F(X_2)*\frac{d}{dt}*G(Z)dX_1dX_2dZ$$

This is essentially what is meant by the impulse approximation as within that framework the initial (incident) and final (scattered) states can be described independently of the rest of the hadronic field. What follows is a discussion of some theoretical concepts and calculations within this framework by various authors in light of the presented data. This discussion is again divided into three parts as was the analysis.

6.1 THE INCLUSIVE CROSS SECTION

The deviations from the P_t^{-8} scaling description of the inclusive cross section can be accommodated by all the scattering models (CIM, Quark Fusion, and the phenomenological QCD model). The scattering of the fundamental fields leads to a P_t^{-4} behavior and an asymptotic approach to this is somewhat inevitable in theoretical calculations of this nature. The comparison of the scattering models on the basis of the inclusive cross section deals with the steeper (P_t^{-8}) behavior.

The models involving the more complicated constituents (CIM and Quark Fusion) arrive at the higher power naturally through the Brodsky, Farrar[66, 67] counting laws, predicting a scattering behavior of the form

$$\frac{Ed^3}{dP^3} \sim S^{(2 - n_a)} F(\ )^{n_p}$$

n_a = number of active fields

n_p = number of passive fields

= M^2/S where M^2 is the square of the missing mass for the inclusive process

$\sim (1. - X_t)$

The power law in S comes from the Brodsky, Farrar counting rules and the scaling form from phase space considerations of the undetected particles. In both the CIM and Quark Fusion models the number of active fields is six, two basic quark lines (2) + two di-quark (meson) lines (4). The number of passive fields are ten (quark lines) in the CIM and twelve in the quark fusion (adding the initial and final state lines). The normalization is a free parameter in these models. A P_t^{-4} component is added by simply including a naive parton (i.e. exact scaling) contribution (scattering the fundamental fields) with an unknown normalization. Such a double power law fit has intrinsically six free parameters to fit for and can accommodate almost any data.

The recent calculations based on the gauge theory of the quark parton model[44, 45, 46, 47, 48, 49] have indicated that many of the features inherent in such a theory will produce a steeper behavior (at low P_t) than P_t^{-4} as required for pointlike particles. As has been previously mentioned, in parton models with gauge field interactions exact scaling is not possible. The effect is to soften the distributions as the momentum transfer of the probe is increased. Experiments measuring the nucleon structure functions have observed precisely this effect. In high P_t phenomena the effect of this is to lower the probability at fixed X_t as s (or $P_{t\ trig}$) is increased. This will raise the power "n" in a local fit. The running coupling constant

$$_{s} = 12\ /(33-2*n_f)\ln(Q^2/\ ^2)$$

where Q^2 is the square of the momentum transfer

decreases with increasing transverse momenta. As all diagrams (see Figure 7a) lead to terms proportional to $s^2(Q^2)$ there is a $\ln^{-2}$ dependence in the calculated cross section. The inclusion of the gluon diagrams (Fig. 7b) has two effects. Mainly they just boost the cross section at low X (X_t) as these diagrams involve the softer gluon distribution functions ($\sim(1.-X)^5$). They also tend to raise the local power as the scaling violations in the gluon distributions were found to be much larger than those of the valence quarks[68, 69, 45]. More will be said of this in the last section of this chapter. These effects lead to reasonable agreement between data and theory above a transverse momenta of ~5 GeV/c[45, 47, 48].

The accuracy of the calculation is significantly improved if a large initial state motion is postulated, in which case

$$F(X) \qquad F'(X,Q^2) \qquad F''(X,Q^2,K_t)$$

The K_t dependence is usually taken to factorize into some exponential or gaussian form (the choice seems to be irrelevant) times the already discussed non-scaling structure functions

$$F''(X,Q^2,K_t) \qquad F'(X,Q^2)*G(K_t)$$

Introducing this initial transverse momentum of the partons can significantly increase the cross section at low values of P_t (P_t < 5 GV/c[44, 46]) but requires postulating an initial mean value of 0.5 to 0.85 GeV/c for each parton. By postulating a transverse momentum the size of that seen in massive lepton pair production (Fig. 78) the effective local power "n" is increased by 1.5 to 2. The improvement of the accuracy in the calculation is not the only consequence of introducing this "primordial" transverse motion. It also results in a large acoplanarity of the two jet structure when evaluated in the P P c.m. This acoplanarity is easily observed in the two particle correlations through the variable P_{out}. In the two jet model with a fragmentation process having a limited transverse momentum to the jet axis (p_{tj}), the mean value of P_{out}^2 should be something like

$$P_{out}^2 \sim p_{tj}^2 + (p_{tj}^2 + K_t^2)*z^2 \qquad (6.1)$$

where p_{tj} is the mean transverse momentum to the jet axis and K_t is the partons' average initial transverse momentum. The $p_{tj}^2*z^2$ term arises because P_{out} is measured with respect to the trigger particle which also has a momentum p_{tj} (on average) transverse to its jet axis. In the constituent interchange model this term would be missing but the equation would be about the same.

6.2 CORRELATION DATA

The most important conclusion that can be drawn from the correlation analysis is the existence of a recoiling jet structure superimposed on a typical hadronic interaction. This observation has two phenomenological consequences: that high P_t meson production is associated with constituent scattering, and that there is a remarkable connection between the recoiling constituent and the process of hadron production in e^+e^- anihilation. The similarities between the hadrons recoiling from the trigger particle and those produced at electron storage rings consist of the characteristics which for the basis of thee parton jet concept. Both systems produce hadrons in scaling distributions, which take an exponential form (~ e^{-6*Z}) with a limited momentum (~ 300 MeV/c) transverse to a central axis[33, 34]. The dramatic scaling violations reported by a previous ISR experiment are simply not observed[64]. Calculations of the degree of scale violation in the X_e distributions that might be expected in the context of the gauge theory[70, 71] lead to deviations too small to be observed reliably by this experiment.

The clear evidence of a recoiling jet does not prefentially select either the phenomenological QCD model or the Constituent Interchange model of Brodsky et al. It does pose problems for the Quark Fusion model. This model rather naturally predicts a (smeared) function behavior in the X_e distributions. It is quite clear that this is not a major contribution to the observed spectrum.

The distribution of secondaries produced on the same side as the trigger are far more difficult to understand. While observing a scaling distribution might be esthetically easy to believe, there is really little reason to believe that the usual jet model can be reliably applied to this extremely biased fragmentation. The average total additional momentum that is unaccountd for by the minimum bias contribution is only ~ 400 MeV/c. How this low average is accounted for in terms of a detailed spectrum would undoubtedly prove extremely difficult to calculate. That the observed distribution is (within errors) independent of trigger transverse momentum is certainly curious. The effect of resonance decays should be calculated and the author will certainly attempt such a calculation in the near future. The author is unaware of any published calculations concerning this distribution. The independence from $P_{t\ trig}$ of this distribution seems to the author to exclude the resonance explanation as complete considering the phase space of decays (assume for example / = 1 and independent or slowly varying with P_t).

While the exact distribution of secondaries cannot easily be calculated the mean value of Z_{trig} lends itself trivially to calculation within the context of the parton model. According to Figure 2 the invariant cross section is proportional to

$$\frac{Ed^3}{dP^3} \sim F(X_1)*F(X_2)*\frac{d}{dt}*G(Z)dX_1dX_2dZ$$

and clearly

$$\langle Z_{trig}\rangle_{P_t} = \frac{F(X_1)*F(X_2)*\frac{d}{dt}*Z*G(Z)dX_1dX_2dZ}{F(X_1)*F(X_2)*\frac{d}{dt}*G(Z)dX_1dX_2dZ} \qquad (6.2)$$

To do this calculation in a manner that could be reliably compared with the data care should be taken to include the effect of the lower limit in $P_{t\ ch}$ (300 MeV/c) which the magnet introduced.

The only published prediction of this quantity within the framework of the quark scattering models, of which the author is aware, is by the Cal Tech group of Feynman, Field, and Fox. Unfortunately the prediction was made while this group was using an ansatz scattering cross section of 2300mb/st^3 and exact scaling functions. However it is believed the predictions are not changed greatly in the phenomenological QCD form[72]. The prediction was that this number should be a function of X_t and rise slowly (see Fig. 79). This dependence on X_t is also discussed by Jacob and Landshoff[52]. The observed behavior is in remarkable agreement, considering the ad hoc nature of the calculation. Within the framework of equation (6.2) the accuracy of the data presented improves as $P_{t\ trig}$ is increased, as the magnetic cutoff decreases to lower values of Z. A concerted effort to do this calculation including all scaling violations would be worthwhile, for it is a number that can experimentally be easily and accurately measured (though there is a question about the "minimum bias" contribution).

The prediction of the Constituent Interchange model would be 1., barring resonances. At low values of $P_{t\ trig}$ where this mechanism might have a large contribution (where the effective power "n" is still large) the deviation from unity is perhaps slightly larger than this mechanism might suggest but not by an extraordinary amount.

The quark parton model would suggest that $\langle Z_{trig} \rangle$ would decrease if a high momentum particle was required on the recoiling side[52, 73]. This seems to be what is observed when this quantity is computed with the symmetrically triggered events. This effect cannot be accounted for in the CIM calculations.

Within a jet model (even if only for the recoil system) the acoplanarity of the events measured by the variable P_{out} leads to an estimate of the transverse momenta of the initial constituents. Using equation (6.1), assuming $Z = X_e$ and that the values of P_{out} and P_{out} give the parameter p_{tj} ($\sim$ 300 MeV/c), then a value of K_t of $\sim$.7 to 1. GeV/c is found by using the value of P_{out} at $X_e \sim 1$. This large value is quite independent of the nature of the constituents if the recoiling one leads to a jet. The work cited in references 44 and 46 was mostly done before the large values of P_{out} (at large $X_e \sim 1$) were published[74] and can therefore be taken as predictions, though there had been earlier indications of this[75].

If the result of the "QCD" calculations can be inverted, it would seem likely that a large initial state transverse momentum would lead to an increase of the effective power found from the inclusive cross section. Thus if a P_t^{-8} cross section was the "true" scattering law (as in the CIM) after the smearing of the initial state an effective power as high as 10 might be produced. What the data would indicate is that a large initial state motion must be included in theoretical calculations as it seems to be observed. In view of this conjecture and the way in which all the features of the data presented are "naturally" accommodated by the phenomenological QCD model the author sees no need to postulate more complicated mechanisms than the interactions of the fundamental fields to explain high P_t phenomena.

6.3 THE SYMMETRIC TRIGGER AND QCD

The remainder of this chapter will be devoted to the symmetric trigger data. The only previous work done with a symmetric trigger consists (to the authors knowledge) of one experimental[75] and two theoretical papers[76, 73]. These papers deal with the spectrum in the variable $P_{t\ ave} = 0.5*(|P_{t1}| + |P_{t2}|)$ evaluated at $P_{t1} \sim P_{t2}$, with both at ~ 90 . This is a double differential cross section and quite different from what the author has done. The experimental result was stated in a similar form to that used for the inclusive cross section. The data were fit to the form $A*F(X)/P_{t\ ave}^{n}$, yielding a value of n = 8.2 reminiscent of the inclusive cross section. The theoretical calculation mentioned extrapolates the results from Fermilab energies to the ISR but cannot be easily compared to the measurement defined here. The dimensions of the double differential cross section would be P_t^{-6} while the mass cross section as defined has dimensions M^{-3}. These dimensional requirements yield the power laws expected for the naive quark parton model. The "QCD" model would then raise these powers through the effects already described. The $m^{-6.5}$ power law when evaluated at 90 becomes $P_{t\ ave}^{-6.5}$; this however is hardly informative. A calculation similar in nature to those performed for the inclusive cross section should be made for the mass cross sections.

The angular distributions however present an even bleaker situation. The author can only present his own attempts at calculating the "QCD" predictions concerning them as this constitutes the only work (to the authors knowledge again) of this nature. The procedure tried is rather straightforward and involves only combining the results of a few publications.

The parton monte carlo mentioned earlier indicated that the angular distributions as determined by the two leading particles described the fundamental distributions of the parton scattering to phenomenal accuracy. Placing unreasonable faith in this result the author will compare the parameterization of the data

$$1/(1 + \cos\ )^{2.94} + 1/(1 - \cos\ )^{2.94} \qquad (6.3)$$

with the corresponding distributions calculated from the scattering diagrams of the assorted QCD processes. It should be noted that the power 2.94 is found including the lowest mass bin at 62.4 GeV. If this bin had not been used (as it was slightly affected by offline thresholds) the power would be 3.01 with a negligible increase in the statistical error. No consideration of fragmentation need be made if the result of the monte carlo is correct. The diagrams shown in Fig. 7b have been calculated by several authors[47, 48] and their results used extensively[44, 45, 46, 49]. The results are shown in Figure 7a and were taken from Ref 48. The diagrams all can be written in the form

$$\frac{{}_s^{2}(Q^2)*sig(\cos\ )}{S^2} \qquad (6.4)$$

by use of the identities

$$T = -\frac{S}{2}(1. - \cos\ ) \qquad (6.5)$$

$$U = -\frac{S}{2}(1. + \cos\ )$$

Due to the symmetry of the final state all the diagrams must be symmetrized (the angular distributions are really f(|cos |)). This is done by exchanging U and T throughout and averaging, thus for example

$q_i q_j$ to $q_i q_j$

$$\sim \left(\frac{S^2 + U^2}{T^2}\right)$$

$$\left[\left(\frac{S^2 + U^2}{T^2}\right) + \left(\frac{S^2 + T^2}{U^2}\right)\right]$$

A note of caution is interjected here: in doing this symmetrizing it was assumed that Q^2 was invariant under an interchange of U and T. This is by no means obvious and given the lengthy discussions which are devoted to the definition of Q^2 some thought is in order. The exact definition of Q^2 enters the calculation in two ways: first through the coupling constant, and through the non scaling structure functions. This second effect is important as the structure functions determined through deep inelastic lepton scattering data determine how much to weight each diagram. If Q^2 is a function of cos (which is certainly reasonable) then the relative contributions of the diagrams can change with cos as well.

The uncertainty in the definition of Q^2 presents some problems. The most "natural" choice would be to use the square of the four momentum of the propagator for each diagram. The scattering of identical quarks would become

$$q_i q_i \quad \text{to} \quad q_i q_i$$

$$Q^2 \quad -T \qquad\qquad Q^2 \quad -U$$

This sum however is not a gauge invariant[48] result due to the difference in $_s(Q^2)$ for the two parts. The problem is that the only graphs in which the choice of Q^2 is uniquely "well defined" (not that these definitions are correct for the renormalization scheme) are the diagrams that have only one part: the scattering of dissimilar quarks and the anihilation of a pair of one flavor to a pair of different flavor. If the "natural" definition were used Q^2 would be defined as -T and S for the two diagrams respectively. Considering the difficulty of the problem and the all too apparent incompetence of the author in dealing with the question, what was done was to choose a definition for Q^2 and use it for all the diagrams and structure functions (remembering to always symmetrize the calculation in U and T). The three definitions of Q^2 used were, -T (which went to -U in the symmetrization), T*U/S (= $P_t{}^2$ and clearly symmetric), and S. The last of these has the property of leading to none of the variations with cos that arise with other more "normal" (ie..commonly used in the literature) definitions. This also exhibits just the basic shape of the diagrams.

The last uncertainty that must be addressed is the value of the constant   which is normally found from moment analysis of the structure functions. As there is some uncertainty in the exact value (ranging from 0.3 to as high as 1.1), the author used two values in the calculation, 0.3 and 0.5 (these being more commonly quoted values).

The valence quark structure functions were extracted from the lepton scattering data by Buras and Gaemers[68, 69]. They parameterized them as

$$XF_V(X,Q^2) = \frac{3}{B[\ _1(s), 1+\ _2(s)]} X\ ^{\ _1(s)} (1-X)\ ^{\ _2(s)}$$

$$XD_V(X,Q^2) = \frac{1}{B[\ _3(s), 1+\ _4(s)]} X\ ^{\ _3(s)} (1-X)\ ^{\ _4(s)}$$

$$XU_V(X,Q^2) = XF_V(X,Q^2) - XD_V(X,Q^2)$$

where B is the euler beta function

$$_1(s) = 0.7 - 0.176*s$$

$$_2(s) = 2.6 + 0.8*s$$

$$_3(s) = 0.85 - 0.24*s$$

$$_4(s) = 3.35 - 0.816*s$$

$$s = \ln \frac{\ln(Q^2/\ ^2)}{\ln(Q_0{}^2/\ ^2)}$$

$$Q_0{}^2 = \text{reference momentum} = 1.8\ \text{GeV}^2$$

$$= 0.3\ \text{GeV}$$

The gluon and sea quark distributions were found by Owens, Gluck, and Reya[45] who gave the parameterizations

$$XF_g(X,Q^2) = (2.41 + 3.592*s + 0.764*s^2) *(1-X)^{5 + 7.201*s + 3.87*s^2}$$

$$XF_s(X,Q^2) = 1/6(1.21 + 0.613*s + 0.764s^2) *(1-X)^{10 + 1.652*s + 3.33*s^2}$$

the factor of 1/6 comes from the assumption of an SU(3) symmetric sea. The final U and D quark structure functions then come from adding the valence and sea contributions

$$XD(X,Q^2) = XD_v(X,Q^2) + XF_s(X,Q^2)$$

$$XU(X,Q^2) = XU_v(X,Q^2) + XF_s(X,Q^2)$$

Finally the calculation of the angular distributions is made as follows

$$f(\cos\ ) = \frac{2.}{g(0)} g(\cos\ ) \qquad (6.6)$$

$$\begin{aligned} g(\cos\ ) = \; & F_i(X,Q^2(U,T))*F_j(X,Q^2(U,T))*\ _s{}^2(Q^2(U,T)) \\ & *sig_{ij}(U,T) \\ + \; & F_i(X,Q^2(T,U))*F_j(X,Q^2(T,U))*\ _s{}^2(Q^2(T,U)) \\ & *sig_{ij}(T,U) \end{aligned}$$

The value of equation (6.3) evaluated at cos = 0 is 2 and sets the normalization. The quantity $sig_{ij}(U,T)$ is defined by (6.4) the subscripts i,j denote parton type. The arguments U and T relate to cos by the previous identities (6.5)

The results of these calculations are shown in Figures 80 through 86. Independent of the uncertainties in the definition of Q^2 some very interesting conclusions can be drawn from the angular dependence of the cross section. If all the diagrams outlined in Figure 7 are added in accordance with (6.6), at low X (~ .125 corresponding to m = 8 GeV/c^2 at s = 62.4 GeV) the sum is dominated by the gluon diagrams, particularly

qg to qg

and

gg to gg

There has been considerable conjecture that the gluon fragmentation function is considerably "softer" (lower mean value of Z). In view of this conjecture, the clear disagreement between the "theoretical prediction", and the data (as parameterized by (6.3)) and the strong mass dependence indicated by the calculation (see Figure 82 and 86), the author simply suppressed the diagrams with gluons in the final state (qq to gg, qg to qg, and gg to gg). This was done by simply not including these terms in the sum of (6.6). The effect was to significantly improve the agreement between "theory" and data. If this is taken seriously the conclusion that must be drawn is that the gluon final states must be heavily suppressed from contributing to the symmetric high P_t final state.

One of these diagrams (qg to qg) was needed to fit the inclusive data but the outgoing gluon contributed mainly by being on the recoil side and not producing the triggering particle. This was due to the gluons being assigned a much softer fragmentation function. The angular distributions would seem to support this idea. This could be cross checked independently by calculating the mass cross sections as defined in this thesis. If all the parton fragmentation functions were identical the three gluon final state diagrams would contribute ~ 90% of the cross section at a value of X of 0.125 ($m = 8$ GeV/c^2). By a value of X of 0.2 ($m = 12$ GeV/c^2) this contribution has dropped to ~ 50%. (This is based on the structure functions used of course.) The inclusion or suppression of these diagrams would change the computed cross section by almost an order of magnitude (at $m = 8$ GeV/c^2, $s = 62.4$ GeV) which would be easily distinguished even by as crude a calculation as done here.

Thus clear conclusions can be drawn on the basis of the angular distributions concerning the SU(3) gauge theory of strong interactions as applied through the parton model. In order to achieve any degree of success in describing the shape and the mass dependence of the observed distributions, the diagrams leading to gluon final states must be heavily suppressed. The inclusion of the gluon final state diagrams at $m = 8$ GeV/c^2 ($X = .125$) with = 0.5 GeV and $Q^2 = -T$ (or TU/S) could be written in the form of equation (6.3), but with a power of 2.5 instead of 2.94. This in turn would have to be accounted for as a systematic variation in the calibration of the lead glass blocks of 10% from the center of the array to both sides, in both arrays! Such a miscalibration is completely excluded by a large number of measurements. These are the width and mass of reconstructed low momentum (see Appendix I), the observed mass of the (9.5 GeV/c^2) resonance[77], and even the order of magnitude of the inclusive pion cross section where it has been measured by many experiments (P_t < 5 GeV/c). The systematic error of +/- 0.2 in the description of the angular dependence corresponds to the largest possible error within these constraints (~ +/- 5% see Appendix I). Thus the systematic error as stated does not represent but the authors' estimate of its largest value. Systematics other than this miscalibration have a comparatively small effect.

It would appear that "QCD" can be made to describe the data reasonably well. This is rather striking as the basic diagrams by themselves are not nearly steep enough but the scaling violations and the running coupling constant seem to be able to bring about some success. To do this certain subprocesses must be heavily suppressed. This is the first experimental evidence that actually supports the idea that the gluon fragmentation function is in fact softer than that of quarks. Even so, the systematic errors must be taken at least in full to achieve agreement (the statistical errors can be considered zero). Quite independent of these arguments what seems to be true is that the distributions arrived at by this method of analysis comprise an accurate measurement of the sum of the underlying proceeses, whatever they may be. It would be preferable to do this measurement with charged particles as particle identification would be possible (and consequently quantum number correlations) and the uncertainty of the cluster source (and the uncertainty of the number of particles that causes) eliminated. Considering that in the near future there will be two experiments with these added abilities, (E605 at Fermilab, and R807 at the CERN ISR) which can corroborate this data the matter will be left to the theorists until that time.

THE FUCKING END!!!!!!!

(except for the bloody appendices)

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