A MEASUREMENT OF THE TRANSVERSE MOMENTA OF PARTONS,
AND OF JET FRAGMENTATION AS A FUNCTION OF $\sqrt{s}$ in p-p COLLISIONS

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(Submitted to Physics Letters)

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ABSTRACT

A large solid-angle apparatus consisting of a superconducting solenoid magnet, cylindrical drift chambers and two arrays of lead-glass counters was used to examine particles associated with a high transverse momentum trigger in p-p collisions with three $\sqrt{s}$ values at the CERN ISR.

The trigger was given by energy deposition in lead-glass arrays centred at 90° . The trigger transverse momentum range covered was $3 < p_{T \text{ trig}} < 11 \text{ GeV/c}$. Results are given for p_{out} for both individual charged particles, and also for the sum of charged particle momenta in the hemisphere opposite to the trigger. Mean values are then deduced for the parton transverse momentum k_T , and for the jet fragmentation momentum j_T .

The CCOR Collaboration is engaged in a general study of high transverse momentum processes arising from p-p collisions at the CERN Intersecting Storage Rings (ISR)¹⁻⁴⁾. This letter reports a study of the charged particles on the opposite side to that of a high momentum trigger particle. This is the first experiment capable of momentum analysis of charged particles over the full azimuth. Thus the measurement of particle momenta out of the trigger plane p_{out} does not need acceptance corrections.

The apparatus (Fig. 1) consists of two arrays of lead-glass Čerenkov counters to provide a high-energy trigger⁵⁾, and an inner detector to momentum-analyse charged particles. The lead-glass arrays were located outside a thin-walled superconducting solenoid, one on either side of the intersection region. The apparatus was triggered by energy deposition exceeding a given threshold in either array. Subsequent analysis accepted events with energy clusters of 3×3 counters. The pulse heights in the scintillation counters (B) were used to correct each cluster for the energy lost in the magnet coil and cryostat (1.0 radiation length of aluminium). The clusters were assumed to be due to π^0 's, and the energy correction was typically 300 MeV. This correction has been discussed in more detail elsewhere^{1,4)}. The final result is a transverse momentum measurement with an r.m.s. resolution of $\Delta p/p = \Delta E/E = 0.004 + 0.043/\sqrt{E}$ (E in GeV) for each lead-glass counter, a 5% r.m.s. counter-to-counter variation, and a systematic scale uncertainty of 5%. The clusters were located in azimuth with an r.m.s. uncertainty of $\Delta\phi \approx 20$ mrad.

The momentum of charged particles was determined from measurements of the trajectories of the particles in the magnetic field. The solenoid produced a 1.4 T field uniform to $\pm 1.5\%$ in a cylindrical volume 170 cm long with a radius of 70 cm. A cylindrical hodoscope (A), used to measure the event time, and four cylindrical drift chamber modules (DCM1-DCM4) located inside the solenoid, surrounded the ISR beam pipe. Each drift chamber module consisted of two gaps equipped with delay line read-out for each of the sense wires⁶⁾. The track-finding efficiency is estimated to be $75 \pm 10\%$, and the spatial resolution is 350 μm . This

together with the number of measurements and multiple Coulomb scattering gives an r.m.s. momentum resolution $\Delta p_T/p_T = \sqrt{(0.07/p_T)^2 + 0.02^2}$ (p_T in GeV/c). The r.m.s. azimuthal resolution for tracks is $\Delta\phi = 10$ mrad.

Data have been taken with the ISR operating at $\sqrt{s} = 62, 45$, and 31 GeV, and at luminosities of up to $4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. They were divided into nine different sets according to their $p_{T \text{ trig}}$ and $\sqrt{s}$ values (Table 1), where $p_{T \text{ trig}}$ is the transverse momentum of the trigger particle calculated in the p-p centre-of-mass system. The quoted number of events is the number of events after all cuts described below.

Tracks were reconstructed and vertices fitted for all events. Those tracks not pointing to the vertex were rejected. The momentum of each particle was transformed to the p-p centre of mass assuming that the particle was a pion. The pseudo-rapidity $\{\eta = -\ln [\tan (\theta/2)]\}$ was calculated for each particle. The trigger particle was defined as the neutral particle forming the energy cluster with the highest p_T . The two lead-glass arrays were denoted 'inside' and 'outside'. Each charged particle was required to have $p_T > 300$ MeV/c. Those in the hemisphere opposite to the outside array were required to have $|\eta| < 0.7$, and those in the hemisphere opposite to the inside array were required to have $|\eta| < 0.9$. These cuts ensured a uniform ϕ acceptance for the charged particles within each hemisphere. An estimate of some of the possible systematic errors involved was made by a comparison of the results of the two sides. The results agreed within the errors quoted.

For each charged track, p_{out} is the component of momentum out of the plane formed by the two beams and the trigger particle, and $x_E = -\vec{p}_{T \text{ track}} \cdot \vec{p}_{T \text{ trig}} / |p_{T \text{ trig}}|^2$. Corrections were applied to $\langle |p_{\text{out}}|^2 \rangle$ for charged particle momentum resolution and ϕ_{trig} resolution. These corrections, which are bigger at higher x_E^2 , always decrease the value of $\langle |p_{\text{out}}|^2 \rangle$, but are always less than 20%.

In parton models, finite values of p_{out} are believed to be produced by two effects: the transverse momentum (k_T) of the partons that enter the hard scattering process, and the transverse momentum relative to the jet axis (j_T) given to

a particle during the fragmentation of its parent parton after scattering. In this picture the parameters of the model may be obtained from the approximate relationship⁷⁾:

$$\langle |p_{\text{out}}| \rangle^2 = 2 \langle |k_{\text{Ty}}| \rangle^2 x_E^2 + \langle |j_{\text{Ty}}| \rangle^2 (1 + x_E^2), \quad (1)$$

where $\langle |k_{\text{Ty}}| \rangle$ and $\langle |j_{\text{Ty}}| \rangle$ are the average values of the components of k_T and j_T out of the scattering plane. Figure 2 shows $\langle |p_{\text{out}}| \rangle^2$ plotted versus x_E^2 for the nine data sets listed in Table 1. It is clear that the data do not satisfy Eq. (1) for the complete range of x_E^2 . At low x_E^2 a departure from linearity is expected because j_{Ty} is kinematically constrained to be small when track momenta are small. If only those points are used which correspond to $p_{\text{T track}} > 1.4 \text{ GeV/c}$, for which the kinematic constraint is small, reasonable $\chi^2/\text{d.o.f.}$ may be obtained for straight line fits. Even in this region, the model's assumption that x_E is equivalent to the jet fragmentation variable z can influence the numerical results of $\langle |k_{\text{Ty}}| \rangle$. However, the trends in the data should not be sensitive to any errors introduced by this assumption.

Figure 3 shows $\langle |j_{\text{Ty}}| \rangle$ as a function of $p_{\text{T trig}}$ (Fig. 3a) and $\sqrt{s}$ (Fig. 3b). For Fig. 3a, $\langle |j_{\text{Ty}}| \rangle$ was constrained to be the same value for all $\sqrt{s}$ values, but was allowed to vary with $p_{\text{T trig}}$. There is no apparent variation of $\langle |j_{\text{Ty}}| \rangle$ with $p_{\text{T trig}}$. Similarly, for Fig. 3b $\langle |j_{\text{Ty}}| \rangle$ was constrained to be the same for all $p_{\text{T trig}}$ values but was allowed to vary with $\sqrt{s}$. There is no indication that $\langle |j_{\text{Ty}}| \rangle$ is a function of $\sqrt{s}$. Thus it is reasonable to constrain $\langle |j_{\text{Ty}}| \rangle$ to one value for all nine data samples, and fit for $\langle |k_{\text{Ty}}| \rangle$ and $\langle |j_{\text{Ty}}| \rangle$. This yields a χ^2 of 62 for 50 degrees of freedom, and the $\langle |j_{\text{Ty}}| \rangle$ found is $0.393 \pm 0.007 \text{ GeV/c}$. The values of $\langle |k_{\text{Ty}}| \rangle$ (Fig. 4a) show an increase with both $p_{\text{T trig}}$ and $\sqrt{s}$, rising to $\langle |k_{\text{Ty}}| \rangle \sim 0.8 \text{ GeV/c}$ at the highest $\sqrt{s}$ and $p_{\text{T trig}}$.

From the vector sum of the away-side charged particles another measurement of $\langle |k_{\text{Ty}}| \rangle$ may be obtained which has different systematic uncertainties but requires no extra physics assumptions. If one selects events where the sum of the charged particle transverse momenta in the hemisphere opposite to the trigger

balances the trigger transverse momentum, i.e. $\Sigma x_E \sim 1$, then the same model predicts

$$\langle |\Sigma p_{out}| \rangle = \sqrt{2 \langle |k_{Ty}| \rangle^2 + \langle |j_{Ty}| \rangle^2} . \quad (2)$$

Using the value of $\langle |j_{Ty}| \rangle$ found above, $\langle |k_{Ty}| \rangle$ may be determined. The model does not require corrections for 'jet' containment or track efficiency. In addition, corrections to $\langle |\Sigma p_{out}| \rangle$ due to momentum resolution and ϕ_{trig} resolution were found to be negligible. Events were selected with $0.9 < \Sigma x_E < 1.1$, and a small correction was applied to allow for the fact that Σx_E in this region is not exactly 1. The results for $\langle |k_{Ty}| \rangle$ thus obtained are shown in Fig. 4b.

These values are equal, within statistical errors, to the values obtained from single particles, with the exception of the $\sqrt{s} = 31$ GeV, $p_{Ttrig} = 3$ GeV/c point, which is higher. It is thought that formula (1) is least reliable when $k_{Ty} \sim j_{Ty}$, and thus the low threshold values in Fig. 4a have large systematic errors.

It should be noted that $\langle |k_{Ty}| \rangle$ is the average value of the component out of the scattering plane of a parton's transverse momentum. If one assumes a Gaussian distribution in k_{Ty} , then $\sqrt{\langle k_{Ty}^2 \rangle} = \langle |k_{Ty}| \rangle \times \sqrt{\pi/2}$. If one assumes, in addition, that the two components of k_T are equal, $\sqrt{\langle k_T^2 \rangle} = \sqrt{\langle k_{Ty}^2 \rangle} \times \sqrt{2}$, and these values can be read using the right-hand scale of Fig. 4. Similarly high values of k_T have previously been reported at the ISR^{2,8,9}). A calorimeter experiment¹⁰) has measured k_T in the scattering plane as a function of p_{Ttrig} and $\sqrt{s}$, and found the same trends as this experiment.

The value of $\langle |j_{Ty}| \rangle$ of 0.393 ± 0.007 GeV/c, gives $\sqrt{\langle j_{Ty}^2 \rangle}$ of 0.493 ± 0.009 GeV/c assuming a Gaussian, and $\sqrt{\langle j_T^2 \rangle}$ of 0.697 ± 0.013 GeV/c taking the two components to be equal²⁾. This value refers only to fragments with $p_T > 1.4$ GeV/c and should not be directly compared with results obtained by integrating over all jet fragments. It is in reasonable agreement with the value obtained by another ISR group (0.62 ± 0.06 GeV/c)⁹⁾, but somewhat higher than results for e^+e^- data

$(\sim 0.55 \text{ GeV/c})^{11})$ obtained including only high-momentum hadrons. It should be stressed that the error quoted is statistical only.

Conclusions

The p_{out} of charged particles in the hemisphere opposite to a high- p_T trigger has been studied. Using an approximate parton model, values for the parton transverse momentum k_T and fragmentation transverse momentum j_T have been deduced. The following conclusions were reached:

- i) k_T increases with $p_{T \text{ trig}}$ and $\sqrt{s}$ to a value of $\langle |k_{Ty}| \rangle \sim 0.8 \text{ GeV/c}$ for $p_{T \text{ trig}} > 9 \text{ GeV/c}$ and $\sqrt{s} = 62 \text{ GeV}$.
- ii) The value of $\langle |j_{Ty}| \rangle$ obtained for fragments with $p_T > 1.4 \text{ GeV/c}$ is $\sim 0.4 \text{ GeV/c}$ independent of $p_{T \text{ trig}}$ and $\sqrt{s}$.

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Table 1

$p_{T \text{ trig}}$ range (GeV/c)	$\sqrt{s}$ (GeV)	$\sim$ No. of events
3-5	62	11,700
5-7	62	11,000
7-9	62	22,900
9-11	62	1,700
3-5	45	5,300
5-7	45	8,700
7-9	45	2,300
3-5	31	2,300
5-7	31	1,000

Figure captions

- Fig. 1 : A view of the apparatus normal to the solenoid axis.
- Fig. 2 : $\langle |p_{\text{out}}| \rangle^2$ versus x_E^2 for the nine different data samples. The crosses are those points used in the fit. The straight lines are obtained keeping the intercept the same for all nine data samples.
- Fig. 3 : a) $\langle |j_{Ty}| \rangle$ and $\sqrt{\langle j_T^2 \rangle}$ as a function of $p_{T\text{trig}}$.
b) $\langle |j_{Ty}| \rangle$ and $\sqrt{\langle j_T^2 \rangle}$ as a function of $\sqrt{s}$.
- Fig. 4 : a) $\langle |k_{Ty}| \rangle$ and $\sqrt{\langle k_T^2 \rangle}$ as a function of $p_{T\text{trig}}$ for three different $\sqrt{s}$ values, obtained from single-particle correlations.
b) The same for multiple-particle correlations.

Fig. 1

Fig. 2

Fig. 3

Fig. 4