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RECENT DEVELOPMENTS IN THE THEORY OF LARGE TRANSVERSE MOMENTUM PROCESSES*

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One of the most important questions in hadron dynamics is the understanding of the underlying mechanisms for the production of large transverse momentum particles. The emerging features of the associated particles accompanying a high p_T trigger (jet structure, coplanarity, angular correlations, scaling laws) lend support to an underlying two-body hard scattering mechanism, as outlined by Berman, Bjorken, and Kogut[1] and Bjorken.[2] Although it was natural to hope that the basic large p_T mechanism could be related to elementary quark-quark scattering, the new Chicago-Princeton (CP)[3] proton target data at FNAL appear to rule this out. We will briefly review the evidence for this and present a comparison with the predictions of the constituent interchange model (CIM)[4] which postulates that the important subprocesses involve quark-hadron scattering.

If the parton distribution functions scale, then the large p_T power-law scaling behavior of the inclusive cross section $Ed\sigma/d^3p(A + B \rightarrow C + X) \rightarrow p_T^{-n} f(x_T, \theta_{c.m.})$ directly determines the fixed $\theta_{c.m.}$ scaling of the underlying hard scattering subprocess $- d\sigma/dt(a + b \rightarrow c + d) \rightarrow s^{-n} f(\theta_{c.m.})$. The new Chicago-Princeton data for $pp \rightarrow \pi^+ X$ at 200, 300, 400 GeV/c at $\theta_{c.m.} \sim 90^o$ reported at Tbilisi by Shochet,[3] which shows that $n \cong 8.5$ for $0.3 < x_T < 0.7$, greatly extends the scaling behavior ($n \cong 8$) observed at the ISR for $0.1 < x_T < 0.4$, $\sqrt{s} < 57$ GeV.[1] Although the natural scaling behavior predicted for point-like quarks with a scale-invariant interaction is $p_\perp^{-4}$, several authors have proposed scale-breaking modifications to account for the observed behavior.[5] Such modifications of course should also affect the standard parton scaling laws (e.g., for $pp \rightarrow \mu^+\mu^- X$ and dimensional counting predictions for form factors). This idea now seems intractable in view of the CP data for $pp \rightarrow pX$ which scales as $Ed\sigma/d^3p \propto p_T^{-11.7}(1 - x_T)^{6.8}$. The change in p_T power from $n \sim 8$ for meson to $n \sim 12$ for baryon production contradicts the idea of a fixed form for the subprocess. Further, using $qq \to qq$ for $pp \to pX$ requires three powers of the proton structure function $\sim (1-x)^3$, which, together with two convolution integrations, yields a minimum threshold dependence $\sim (1-x_T)^{11}$, in contrast to the $\sim (1-x_T)^7$ dependence observed.

The $qq \to qq$ description of large p_T reactions also appears to lead to a difficulty with the scaling behavior of the system on the away side of a 90^o high p_T pion trigger as measured at the ISR. The quark-fragmentation distribution $\sim (1-x)^m/x$ ($m = 1$ to 2 from SPEAR $e^+e^- \to \pi + X$ data) implies that the p_T of each of the outgoing quarks is 30 to 50% higher than the p_T of the trigger.[6] The observed scaling behavior of the away side system, however, indicates that the recoil jet has an excess of only $\sim 10\%$ of the trigger momentum. This is related to the fact that few additional hadrons are seen along the trigger particle direction, the same side jet often consists of the trigger hadron alone.[1] Even more significantly, the charged particle multiplicity on the towards side is $\langle n_{ch} \rangle \sim .85 \pm .15$, independent of the trigger particle p_T ($2 < p_T < 6$ GeV). In contrast, in the $qq \to qq$ model one predicts an increase of $\Delta n_{ch} = .4$ (for $m = 1$) over the range $2 < p_T < 6$ GeV. A still more sensitive test is possible: in the $qq \to qq$ model, the toward side associated multiplicity is predicted to change significantly as a function of the event-by-event location of the opposite side jet.[7] Such changes are absent in the CIM subprocesses in which the trigger side system is dominated by single particle and resonance production.

In the CIM, one predicts that the leading quark-hadron subprocess for $pp \to \pi X$ is $Mq \to \pi q$ (where M represents a limited-mass $q\bar{q}$ state fragmented from one of the nucleons). A $p_\perp^{-8}$ scaling behavior is predicted by the model essentially because of the additional factors $\sim t^{-2}$ from $F_M^2(t)$. The predictions of the CIM are systematized using the dimensional counting rules[8]

$$E\frac{d\sigma}{d^3p} = \sum_{abcd} \frac{f(\epsilon, \theta_{c.m.})}{(p_T^2+m^2)^{n_{active}-2}}$$

where n_{active} is the total number of elementary fields (q, ℓ, γ) in the hard subprocess $a + b \to c + d$, and m^2 ($\lesssim 1\ GeV^2$) represents a typical parton mass scale. At the exclusive limit, where $\epsilon \equiv 1 - \sqrt{x_T^2 + x_L^2} \to 0$, $f(\epsilon, \theta_{c.m.}) \to f(\theta_{c.m.})\epsilon^F$; $F = 2n_{spect}-1$ increases as the number of "spectator" or "passive" quarks in the hadrons A, B, C increases.[9] These rules are based on Born graphs in renormalizable (scale-invariant) theories and finite Bethe-Salpeter hadronic wave functions. Derivations and discussions of spin and kinematic effects are given in Refs. 4, 8, and 9. The quark model requires $n_{active}=4, 6, 8, \ldots$ and hence predicts the series $p_\perp^{-4}$, $p_\perp^{-8}$, $p_\perp^{-12}$, ... at fixed x_T and $\theta_{c.m.}$.

The leading CIM contribution ($Mq \to \pi q$, $n_{active} = 6$, $n_{spec} = 5$) for $pp \to \pi^\pm, K^+X$ leads to the asymptotic prediction $p_\perp^{-8}(1-x_T)^9$. This can be compared to the fits to the CP measurements, $p_\perp^{-8.5}(1-x_T)^{8.8}$ for $pp \to \pi^+X$, $p_\perp^{-8.9}(1-x_T)^{9.7}$ for $pp \to \pi^-X$, and $p_\perp^{-8.4}(1-x_T)^{8.8}$ for $pp \to K^+X$. (See Table I.) The observed fixed p_T ratio $\pi^-/\pi^+ \sim (1-x_T)$ could be related to the down-to-up quark ratio in the proton structure function or to the effects of resonance decay. The subprocesses $M\bar{q} \to K^-q$ and $q\bar{q} \to K^+K^-$ for K^- production predict the fixed p_T ratio $K^-/K^+ \sim (1-x_T)^4$ and $(1-x_T)^2$, respectively. The CP result for $pp \to K^-X$ is $p_T^{-8.9}(1-x_T)^{11.7}$ or $K^-/K^+ \sim (1-x_T)^3$ at fixed p_T.

The leading subprocesses for proton production $q + qq \to M + p$ and $qB \to qp$ give the predictions $p_\perp^{-12}(1-x_T)^5$ and $p_\perp^{-12}(1-x_T)^7$, respectively, compared to the CP measurement $p_\perp^{-11.7}(1-x_T)^{6.8}$. The $p_\perp^{-8}$ subprocess $q + q \to B + \bar{q}$

(which like $qq \to qq$ requires "double color neutralization" - see below) is ruled out by the data.

The leading CIM subprocess for $\bar{p}$ production[4] with $n_{active} = 6$ is $qM \to qM$ [where the $\bar{p}$ fragments from a large p_T meson state], giving the prediction $p_T^{-8}(1-x_T)^{15}$. The leading $n_{active} = 8$ subprocesses give $p_T^{-12}(1-x_T)^{11}$. The new CP fit[3] is $p_T^{-8.8}(1-x_T)^{14.2}$, indicating that the predicted $n_{active} = 6$ subprocesses give a good representation of the $\bar{p}$ data.

Thus the CIM seems to account for many of the features of the large p_T data - naturally accounting for the meson/baryon power change. Note that all s-wave $q\bar{q}$ resonances contribute roughly equally in $Mq \to M'q$ and one may thus expect appreciable same side associated multiplicity and correlations; multiparticle resonances are required to account for the $\pi^-\pi^-$ same side correlations. The predicted angular distribution, $d\sigma/dt \sim u^{-1}t^{-3}$, for $qM \to qM$ apparently leads to a reasonable angular correlation for the away side system.[7] (See also R. Baier et al., Ref. 5.)

Many theoretical reasons have been advanced for the suppression of $qq \to qq$. Recent suggestions include (a) the effects of the trigger bias[6] - a $\delta(1-x)$ term gives 20-60 more events than a $(1-x)^m/x$ ($m = 1$ to 2) distribution of the decay jet; (b) small coupling constants and asymptotic freedom effects;[10] (c) the fact that double neutralization of color[11] is required for $qq \to qq$ or $qq \to B\bar{q}$ (and thus double hadron multiplicity[7]); in contrast, the standard parton model lepton processes and the CIM subprocesses all involve single neutralization.

The prediction for $\pi p \to \pi X$ in the CIM has asymptotic terms of the form $p_T^{-8}(1-x_T)^5$, $p_T^{-8}(1-x_T)^7$, and $p_T^{-12}(1-x_T)^3$ for $q\bar{q} \to \pi\bar{M}$, $Mq \to \pi q$, and $q + qq \to \pi + B$, respectively. The "leading-particle" diagram where the incoming meson scatters directly on a quark of the target proton is normalized by the factor $[d\sigma/dt\ (\pi p \to \pi p)]/[d\sigma/dt\ (ep \to ep)]$ to the deep inelastic electron scattering cross section, and is found to be negligible until $x_T \gtrsim 0.7$ at FNAL energies. The recent FNAL data of Donaldson et al.[12] at $p_{lab} = 100,\ 200$ GeV/c when $x_T < .6$ was fit to the form $(1-x_T)^{5.5\pm0.3}/(p_T^2 + m^2)^{5.0\pm1.1}$ with $m^2 = 1.8$ GeV^2. The CIM predicts the ratio $\sigma(pp \to \pi X)/\sigma(\pi p \to \pi X) \sim (1-x_T)^2$ if p_T^{-12} terms dominate both reactions in this low energy regime or $(1-x_T)^2$ to $(1-x_T)^4$ depending on which p_T^{-8} terms dominate. The measurements indicate the ratio at fixed p_T is $\sim (1-x_T)^{1.6\pm0.3}$. A much more dramatic effect is predicted for the ratio $\sigma(pp \to \bar{p}X)/\sigma(\pi p \to \bar{p}X) \sim (1-x_T)^6$ since the contributing fusion reaction $q\bar{q} \to B\bar{p}$ is highly sensitive to the projectile antiquark contribution. To summarize, the current pion beam data appear to be consistent with the dominance of the simplest possible subprocesses.

The CIM can predict in detail quantum number flow, correlations of particles associated with large p_T events. Many more experimental tests of the model are required at higher p_T and x_T, including the use of different beams (especially photons). Measurements of quantum number correlations, the distribution of charge, and detailed comparisons with the final states in $e^+e^- \to$ hadrons, $pp \to \mu^+\mu^- X$ are also important.

Jet structure is the underlying link between lepton and hadron processes. Different types of single or multiquark jets (all with total 3 or $\bar{3}$ SU(3) color quantum numbers) are expected in $e^+e^- \to X$ (q and $\bar{q}$ jets), $\ell p \to \ell X$ (q and qq jets), $pp \to \mu^+\mu^- X$ (qq and $qqqq$ jets) and $pp \to \pi X$ (q and qq jets for the $qM \to \pi q$ subprocess). Assuming that the multiplicity in the central region is due to the virtual separation of color, the multiplicity can be related in each case to the $e^+e^- \to X$ multiplicity.[7] On the other hand, valence effects can be unraveled by observing the quantum number flow and using the spectator counting rule $dN/dx \sim (1-x)^{2n_{spec}-1}$ in the jet fragmentation region. The form of the forward inclusive cross section and fragmentation probabilities can be predicted for both gluon- and quark-exchange models.[7]

Recent work on dimensional counting includes a field theoretic derivation of the form factor rule[13] $F(t) \sim t^{1-n}$(modulo anomalous dimension corrections) by Goldberger, Guth, and Soper,[14] and the fixed angle scattering rule[13] $d\sigma/dt \sim s^{2-n}f(t/s)$ by Polyakov.[15] Infinite order modifications in an Abelian gluon model have been recently discussed by Efremov and Radyushkin.[16]

There has also been recent work applying dimensional counting to nuclear systems.[11,17,18]

In the case of the deuteron form factor, one expects on general grounds that $F_D(q^2)$ will fall faster than $F_N^2(q^2/4)$ since each nucleon must change momentum by $\sim q/2$. The underlying six quark structure then predicts[11,17,18] that the reduced form factor $f_D(t) = F_D(t)/F_N^2(t/4)$ will fall like $(1/t)$. This prediction is confirmed by the new measurement at SLAC by B. Chertok's group.[18] The scaling result for $f_D(t)$ reflects an underlying scale-invariant form for the nuclear force once the effects of nucleon structure are removed.[17]

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TABLE I

Scaling Predictions for $E\, d\sigma/d^3p = C\, p_T^{-n}(1-x_T)^F$

Large p_T Process	Leading CIM Subprocess	Predicted	Observed (CP)[3]
		n//F	n//F
$pp \rightarrow \pi^+X$	$qM \rightarrow q\pi^+$	8//9	8.5//8.8
π^-	$qM \rightarrow q\pi^-$	8//9	8.9//9.7
K^+	$qM \rightarrow qK^+$	8//9	8.4//8.8
K^-	$qM \rightarrow qK^-$	8//13	8.9//11.7
	$q\bar{q} \rightarrow K^+K^-$	8//11	
$pp \rightarrow pX$	$q(qq) \rightarrow Mp$	12//5	11.7//6.8
	$qB \rightarrow qp$	12//7	
$pp \rightarrow \bar{p}X$	$q\bar{q} \rightarrow B\bar{p}$	12//11	8.8//14.2
	$qM \rightarrow qM$	8//15	
$\pi p \rightarrow \pi X$	$q\bar{q} \rightarrow M\pi$	8//5	
	$qM \rightarrow q\pi$	8//7	
	$q(qq) \rightarrow B\pi$	12//3	
	$\pi q \rightarrow \pi q$	8//3	