Hadronic Production with a Drell-Yan Trigger

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The ratio of cross sections for producing fast π^+'s and π^-'s in association with a massive dilepton should be a strongly varying function of the mass of the pair, reducing at small mass to its value in the absence of a pair. For $M_{\mu\mu}^2/s > 0.1$, the π^+/π^- ratio should fall by a factor of 1.7 in the reactions $p+\bar{p} \to \pi + (\mu^+\mu^-) + X$ and $p + \pi^- \to \pi + (\mu^+\mu^-) + X$, rise by a factor of 2.6 in $p + \pi^+ \to \pi + (\mu^+\mu^-) + X$, and fall by about 25% in $p+p \to \pi + (\mu^+\mu^-) + X$.

The production of massive dilepton pairs by the Drell-Yan mechanism[1] has long been a testing ground for parton-model ideas. In this Letter we wish to propose a new example where the Drell-Yan mechanism, by its ability to "remove" partons from hadrons, can affect the isotopic ratios of fast particle produced at small p_t. Measurement of this effect provides a new, nontrivial test of the underlying quark dynamics of hadronic fragmentation.

The parton model asserts that hadrons may be regarded in the infinite-momentum frame as collections of collinearly moving, noninteracting pointlike constituents.[2] Partons may be divided into two classes: valence partons, which carry a sizable fraction (roughly half) of the momentum as well as the net quantum numbers, of the hadron, and sea partons, whose probability distributions vary as $1/x$ at small x and vanish with some large power of $(1-x)$ at large x, where $x = 2P_{\parallel}/\sqrt{s}$. Purely hadronic interactions are mediated by the interactions between the very slow ("wee") partons of the colliding hadrons. For the purposes of this discussion, sea partons may be taken as quarks, antiquarks, or gluons interchangeably.

Now it has recently been observed that the x distributions of fast mesons produced in proton-proton collisions closely resemble the x distributions of the valence partons known from deep inelastic electron-nucleon and neutrino-nucleon scattering.[3] If these mesons were produced from the fast partons by fragmentation, just as hadrons are produced from quarks in e^+e^- annihilation, the meson spectra would fall much more steeply in x than is observed (since one would have to convolute a fragmentation function for mesons out of quarks over a probability function for finding the quark in the initial hadron). This observation has led Das and Hwa[4] to propose that fast mesons are produced in hadronic reactions by the fusion of valence and sea partons, at x_v and x_s, respectively, into mesons at $x = x_v + x_s$. Fragmentation processes $A + B \to M + X$, where the meson M is in the fragmentation region of the hadron A, measure then the combined probability for finding two quarks at once in the wave function of the hadron A, $F_{vs}{}^A(x_v, x_s)$:

$$\sigma^{-1} E d\sigma(A+B \to M+X)/d^3p = \int F_{vs}{}^A(x_v,x_s)\psi^M(x_v,x_s)\,dx_v\,dx_s, \tag{1}$$

where σ is the nondiffractive cross section of A on B. Here $\psi^M(x_v,x_s)$ is a quark-antiquark recombination function for the meson M. We can write it as a two-body piece plus a many-body piece:

$$\psi^M(x_v,x_s) = \psi_2(x_v,x_s)\delta(1 - x_v/x - x_s/x) + R(x_v,x_s).$$

Because of the difficulty of many-body recombination, the many-body component R becomes competitive only at x very near 1, where it gives rise to Regge behavior. The two quarks of the two-body component ψ_2 carry the valence quantum numbers of the meson M.

Now we turn to the production of a fast meson with a Drell-Yan trigger. One parton in the hadron A, with momentum fraction x_a, annihilates against a parton in the hadron B, with momentum fraction x_b, to produce a massive dilepton pair with mass $m_{\mu\mu}$ ($m_{\mu\mu}^2/s \equiv \tau = x_a x_b$). This is illustrated in Fig. 1. Then two partons from the hadron A fuse to form the fast meson M. Thus, this reaction measures the combined probability for finding *three* partons in the wave function of the hadron A simultaneously.

The doubly differential cross section, normalized to the Drell-Yan cross section, is

$$\frac{d\sigma}{dM\,dy}\bigg|_{y=0}^{-1} E\frac{d\sigma}{dp_{\parallel}dM\,dy}\bigg|_{y=0} = \frac{\sum_{i,a,b} Q_i^2 F_b^B(\sqrt{\tau})\int dx_v\,dx_s\,F_{vsa}^A(x_v,x_s,\sqrt{\tau})\psi_2(x_v,x_s)}{\sum_{i,a,b} Q_i^2 F_b^B(\sqrt{\tau})F_a^A(\sqrt{\tau})} = \frac{1}{\sigma_{\rm DY}}\sum_{a,b} R_{ab}^{\ v}, \tag{2}$$

where Q_i is the charge of the ith parton and a,b run over all allowed valence and sea partons. In the above formula we have required that one of the partons which fuses into the meson M be a valence parton in hadron A, an approximation which is good for fast ($x \gtrsim 0.2$) mesons. In the actual numerical calculations described below, the contribution from sea-sea recombinations is included for all values of x.

Consider next the process $p+\bar{p}\rightarrow\pi^+ + (\mu^+\mu^-)+X$. If the dilepton mass is small, dilepton production will be dominated by sea-parton annihilation. The ratio of π^+ to π^- differential cross sections should be the same as is seen in ordinary hadronic reactions: about 2, since the proton has two valence up quarks, which preferentially form π^+'s, and only one valence down quark, which forms a π^-. However, as soon as the mass of the dilepton pair becomes large ($\tau \gtrsim 0.3$), valence-valence annihilation dominates over valence-sea and sea-sea annihilations. Since (i) the coupling of the quark to the virtual photon is proportional to the charge of the quark, (ii) the quark and antiquark that annihilate must have the same flavor, and (iii) the proton (antiproton) has two up and one down valence quarks (anti-quarks) the annihilating quark is 8 times more likely to be an up than a down quark. Since partons that annihilate to form Drell-Yan pairs cannot emerge to produce mesons, the strong preference of the Drell-Yan process to proceed through $u\bar{u}$ annihilation compared to $d\bar{d}$ annihilation completely dilutes the excess of fast up quarks emerging from the collision and, as a result, the ratio of fast π^+'s over π^-'s collapses.[5]

A simple-minded estimate of the effect can be given by assuming an SU(3)-symmetric sea in the proton and antiproton. Then, evaluating the sum in Eq. (2), we find that, all $R_{ij}^{\ U}/R_{ij}^{\ D}$ being equal, $R(\pi^+/\pi^-)=2$ when sea-sea annihilation dominates, but only $\frac{9}{8}$ when valence-valence dominates the Drell-Yan process.

We now present our predictions in the context of a specific model. In order to determine without extraneous free parameters the relative magnitudes of the various terms in Eq. (3), we have written down an improved version of the well-known Kuti-Weisskopf model.[6] We write down a valence-plus-n-parton probability density

$$dP_n(x_i',i=1,2,3;x_1,\ldots,x_n) = \prod_{i=U,U,D} f_{v_1}(x_1')dx_1'\frac{1}{n!}\prod_{j=1}^{n} f_q(x_j)dx_j\,\delta(1-\sum_i x_1'-\sum_j x_j), \tag{3}$$

and then calculate the multiparton distributions by summing on n and integrating over all the unseen partons—all but one, for instance, the case of $F(x)$. Thus we automatically satisfy the normalization constraints relating $F_Q(x)$, $F_q(x)$, $F_{Qq}(x_v,x_s)$, and the three-body probabilities of Eq. (2). The $f(x)$'s are input matrix elements for the various partons: We take

$$f_U(x) \sim x^{-\alpha_0},$$

where $\alpha_0=\frac{1}{2}$ is the Regge intercept of the nonleading meson trajectories,

$$f_D(x) \sim x^{-\alpha_0}(1-x),$$

where the extra power of $1-x$ is included to ensure that

$$\lim_{x\rightarrow 1} \nu W_2^{en}(x)/\nu W_2^{ep}(x) \approx \tfrac{1}{4},$$

in agreement with observation, and

$$f_q(x) = g^2 x^{-1}(1-x)^k.$$

The structure functions are then calculated using techniques similar to those employed by Kuti and Weisskopf. We have fitted the resulting expressions for the structure functions into data on deep inelastic electron-nucleon[7] and neutrino-nucleon[8] scattering, varying g^2 and k as free parameters. With values $g^2=3.8$ and $k=2.7$, the fits are excellent. Our sea distribution vanishes as $(1-x)^7$, and our up-quark distribution vanishes as $(1-x)^{3.8}$. For pions, we proceed similarly and require that the valence distribution vanish as $(1-x)^2$. We take $\Psi_2(x_v,x_s) \sim x_v x_s/x^2$, a simple form symmetric in x_v and x_s and of short range in rapidity. Details of the calculation will be presented elsewhere.[9]

In Fig. 2 we show our prediction for the ratio of the charged-pion spectra versus x,

$$R\left(\frac{\pi^+}{\pi^-}\right) = \frac{E d\sigma(p+B \to \pi^+ + x)/d^3p}{E d\sigma(p+B \to \pi^- + x)/d^3p},$$

$$B = \pi^\pm,\ p,\ \bar{p}, \tag{4}$$

for the no-trigger case and for a Drell-Yan trigger with $\tau = 0.2$. Figure 3 shows the above ratios at fixed $x = 0.5$ as a function of $\sqrt{\tau}$. The data are for the reactions $p+p \to \pi^\pm + X$ and are from Ref. 10. The $p\bar{p}$ and $p\pi^-$ ratios fall quickly as valence-valence annihilation takes over from sea-sea and valence-sea annihilation. In pp Drell-Yan scattering, the π^+/π^- ratio falls much more gradually since there are no valence antiquarks in protons and valence-sea annihilation dominates over sea-sea annihilation only at relatively large $\sqrt{\tau}$. The π^+/π^- ratio in $p\pi^+$ scattering actually *rises* since a fast π^+ can be produced in association with $p\pi^+$ valence annihilation, but if a fast π^- is to be produced from the proton, valence-valence ($d\bar{d}$) annihilation is forbidden.

That the particle ratios change so quickly as the mass of the lepton pair increases is not an artifact of our model. Rather, it reflects the fact that the densities of valence and sea quarks cross over at quite low x ($x \approx 0.05$)—a fact which is already known from earlier fits to structure functions. That the effect happens at such a low τ is obviously a great advantage to experimentalists looking for it, since the Drell-Yan cross section falls steeply as a function of the dilepton mass.

The formalism presented in this Letter can be easily applied to the analysis of other hadronic fragmentation processes initiated by hard collisions, such as deep inelastic electron- and neutrino-nucleon scattering and, more speculatively, large-p_t hadron-hadron collisions.

In conclusion, we believe that it would be worthwhile to put a considerable experimental effort into testing the above predictions. The observation of an effect of the predicted magnitude and quantum-number systematics would provide an

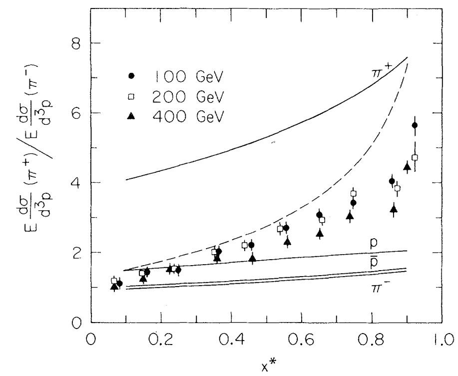

FIG. 2. $R(\pi^+/\pi^-)$ defined in Eq. (4) vs $x^* = x_\pi$ for $p+p \to \pi^\pm + X$ (dashed line and data from Ref. 9) and vs $x^* = x_\pi/(1-\tau^{1/2})$ for $p+B \to \pi^\pm + (\mu^+\mu^-) + X$ at $\tau = 0.2$ (continuous lines), with $B = p, \bar{p}, \pi^+, \pi^-$.

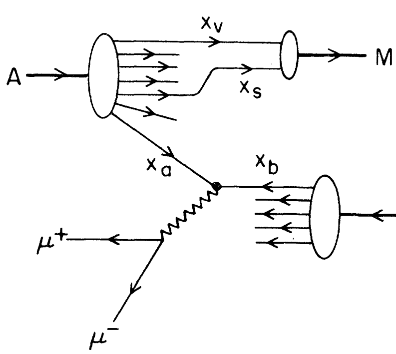

FIG. 1. Production of a fast meson M out of hadron A with an associated Drell-Yan trigger. Partons from A with momentum fractions x_v and x_s fuse to form the meson; the dilepton has $M^2 = x_a x_b s$.

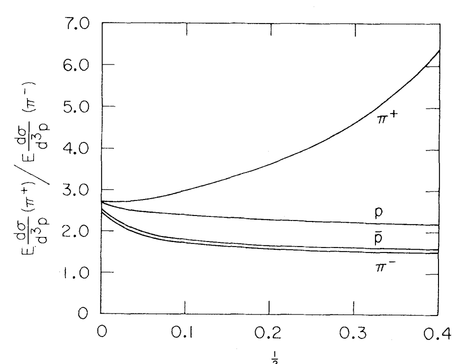

FIG. 3. $R(\pi^+/\pi^-)$ defined in Eq. (4) at $x_\pi = 0.5$ vs $\tau^{1/2} = M_{\mu^+\mu^-}/\sqrt{s}$, for the reaction $p+B \to \pi^\pm + (\mu^+\mu^-) + X$ with $B = p, \bar{p}, \pi^+, \pi^-$.

important confirmation of the parton-model ideas of how hadronic reactions are initiated and how the final-state structure of a hadron's constituents governs the spectrum and multiplicity of particles produced in hadronic reactions.

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(p,t) Reaction as a Probe for the Structure of Odd-Odd Nuclei: Levels in ^{174}Lu

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The (p,t) reaction is employed for the first time to study the structure of the deformed, rare-earth, odd-odd nucleus, ^{174}Lu. In addition to a number of levels that have been characterized in previous studies, we have seen the rotational band built on the $[\pi\frac{7}{2}^+(404), \nu\frac{7}{2}^-(514)]_{K=7}$ configuration. This band is about 6% admixed with the $[\pi\frac{7}{2}^+(404), \nu\frac{5}{2}^-(512)]_{K=6}$ band. In addition, we have observed intensity resulting from four-quasiparticle configurations related to the ground states of both ^{176}Lu and ^{174}Lu.

Odd-odd nuclei generally possess complex spectra. Not only is each valence particle capable of being independently excited, but each configuration produces several near degenerate states in the odd-odd system. In deformed systems, for example, each neutron-proton configuration leads to two distinct rotational bands where the three projections of the individual nucleons align either parallel or antiparallel to each other. Thus, for deformed nuclei, the density of intrinsic configurations in an odd-odd system will be approximately ρ times greater than that in a neighboring odd-mass system where ρ is the level density of Nilsson states that are typical for the odd-neutron or odd-proton systems.

Corrections, of course, must be applied to the simple strong-coupling picture. The Coriolis force, particle-vibrational coupling, and residual neutron-proton interactions each perturb the energy systematics and the transition probabilities predicted by the strong-coupling model. Because of the higher level density, the effect of such corrections for odd-odd nuclei should be greater than those for even-even or odd-mass nuclei.

The principal techniques for exploring the struc-