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The Future of the Parton Model

(Prepared for Jim Cronin's 75th Birthday Celebration)

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I. Introduction

Today we honor Jim Cronin and his many contributions to physics. The part of his career which this talk touches comprises the early days of Fermilab, with the exquisite measurements he and his colleagues made of the spectra of particles emitted at high transverse momentum in hadron-hadron collisions. However the contact between this talk and that work will be very superficial. To do better is simply beyond my ability. While the descriptions of such spectra at higher energies and transverse momenta--namely at the CERN SPS and Tevatron colliders--are rather straightforward parton-level QCD, the situation at the Tevatron fixed-target scale turned out to be a complicated, transitional regime. To get an appropriate up-to-date story, you would have been better off to have turned to Stan Brodsky, who could have given you an update on the Constituent Interchange Model and related arcana. Even the splendid measurements of direct lepton production, with its empirical simplicity of a universal lepton/pion ratio of a part per 10^4, have turned out to be a cocktail of several contributions, no one of which possesses the simple pattern shown by the data.

So it goes. Sometimes experimental programs lead to simplicity and new deep insights. But most of the time the result is less than one's ab initio hopes, no matter how beautiful the execution of the experiment. And, alas, that is the way I see Jim's 1970's program.

Therefore I will digress in what follows. As indicated in the title, the topic will be the parton model. And the subject will be whether, after all these years, there is anything left to say. One outstanding issue, not to be pursued here, is whether one can derive the parton model from first-principles QCD. I think it has not been done in general, and that it might be an interesting problem for someone (not me!) to really clean up. Instead, I will discuss multiparton distributions. It is a subject which, to my knowledge, has not been developed far enough. There is a reason for this---it is pretty hard, at least for me, to see clear experimental consequences of looking at things from this point of view. But one thing for sure is true--it is more likely to have experimental implications than 99.9 percent of all the work on string theory done so far. So maybe there is an argument for someone taking a closer look at this approach.

II. Parton Spectra versus Multihadron Distributions

When hadrons collide at high energy, many particles are produced. The properties of the distributions of produced particles are described in the same language as the properties of partons within a hadron. The standard nomenclature for the momentum spectra of produced particles--inclusive distributions--was coined by Feynman concurrently with his introduction of similar concepts for describing the spectra of partons comprising hadrons. In fact he visualized these two concepts in very similar terms. But nowadays I perceive a distinct divergence in how most theorists view these subjects. Those who deal with partons consider almost nothing but their inclusive momentum distributions within the parent hadron. Those who venture beyond mostly consider two-particle distributions and/or their correlation functions. In fact the phrase "parton structure of hadrons" to most theorists is synonymous with "parton inclusive distributions". On the other hand there is a much wider variety of concepts used in the field of multihadron production in high energy collisions.

For example, one of the most basic measurements in high energy collisions is the multiplicity distribution of produced hadrons as a function of center of mass energy s: "What is the probability of finding n hadrons produced when the cms energy is s?" The corresponding parton-level question is "What is the multiplicity distribution of the set of partons within a proton, each of which having longitudinal momentum fraction x larger than some x_min?" An interesting corollary of this is "Is the probability of finding no more than N partons (with N a small integer like 2 or 3) greater than zero in the limit of x_min becoming vanishingly small?" Those who practice "exclusive QCD" seem to answer this question in the affirmative, while my own intuition delivers an emphatic no.

There is a great deal of other descriptive material used in the multiparticle-production community, little if any of which finds itself into the parton-model mainstream. There is no time here to go into this in detail, and I will only mention some of the buzzwords: generating functions (or functionals) of multiplicity distributions, factorial moments, cumulants, etc. etc. But for the rest of the talk I will only use one of the most familiar of these concepts--the lego plot.

III. Transverse Coordinates versus Transverse Momenta

In the parton model, one views a highly relativistic right-moving hadron as a "beam" of temporarily noninteracting constituent partons, whose transverse coordinates b_i and longitudinal momentum fractions x_i are constants of the motion during the brief period of collision with a left-moving hadron. This picture is supported by the phenomenon of relativistic time dilation--during the collision the internal clocks of the projectiles have slowed down so much that the x_i and b_i do not have time to change.

The use of transverse coordinates rather than transverse momenta is most appropriate from fundamental physics grounds. However, there is a disadvantage, because most observables have to do with transverse momenta. Nevertheless we here choose to stay with the transverse coordinates. Already there are examples of the efficacy of this language in relativistic heavy ion collisions as observed at RHIC. There a collision of two gold nuclei, as seen from the beam direction, involves the overlap of the Lorentz-contracted discs of partons comprising the incident nuclei. Those partons outside the common overlap region emerge as beams of nucleons emitted in the forward directions, and their number measures the degree of overlap ("centrality"). The parton plasma--and eventually the emitted hadrons--which expands transversely from the almond-shaped overlap region will exhibit azimuthal anisotropy. Hadrons emitted along the long axis of the almond will on average have less transverse momentum than those emitted along the short axis, in accordance with the uncertainty principle. This phenomenon ("ellipticity") turns out to be one of the most effective diagnostic tools in the interpretation of these complex collisions.

Proton-proton collisions at the LHC will involve, per event, a number of parton-parton subcollisions which begins to approach the number of nucleon-nucleon subcollisions in a RHIC gold-gold event. Therefore the RHIC language of centrality and ellipticity might even find a place in LHC phenomenology. But there is a difference as well--the proton can and should be viewed in terms of its constituent quark structure. Instead of the opaque disc of partons relevant to RHIC gold nuclei, one naively has, at Fermilab energies, three small discs of partons comprising the three constituent quarks in the proton. These discs are about a half fermi in diameter (perhaps a bit more; the exact size is no doubt negotiable), and are connected by color strings of half -fermi (or so) diameter. All this is surrounded by a more diffuse parton cloud associated with the chiral condensate (pion cloud), whose diameter is scaled by the mass of the pion, hence one to two fermis.

This naive picture of the energetic proton, seen head-on, is not the whole story, since it is often the case that one or more of the constituent quarks may shadow each other. One may expect for a variety of reasons that the quark-diquark configuration is in fact more important than the three quark configuration. In addition there is the relatively rare, but quite interesting, case of the "small-scale-configuration", when all three quarks overlap. In a given collision process there are three basic options for each projectile configuration, leading to six distinct

cases to consider. And in each of these cases one must classify the collision with respect to how many of the left-moving quarks, diquarks, or triquarks actually collide with their counterparts. I end up with 14 different collision categories.

So instead of the two parameters, centrality and collision plane (i.e.width and orientation of the "almond"), characterizing the transverse geometry of a heavy ion collision, we have in general a plethora of parameters characterizing the transverse geometry of a proton-proton collision. However, at very high energies the situation almost certainly simplifies. Most of the partons at extreme (LHC or AUGER) energies are soft gluons, and at sufficiently high energies they should by themselves form an opaque disc, perhaps in the transverse region defined by the aforementioned pion cloud. Furthermore, most of the observable manifestations of the residual constituent-quark structure will probably involve the highest-momentum hadrons emitted at small angles relative to the beam directions. Most of these particles will in fact not be detected by the LHC detectors—although they do have importance in the context of cosmic ray shower evolution.

IV. The Lego Plot Revisited

In the world of multiparticle production and for that matter multijet production, the so-called lego plot is of central importance. It is essentially an exotic representation of phase space. We assume here familiarity with the general notion, and only remind one that the y direction locates the azimuthal angle phi of a produced particle or jet, while the x-axis locates the rapidity eta, essentially the logarithm of half the polar angle theta of the particle or jet. Actually the variable eta also, to good accuracy, describes the logarithm of the longitudinal momentum of the particle, provided it is extreme-relativistic. The z-axis is usually reserved for the transverse momentum of the particle. For the parton description, we replace transverse momentum with impact parameter b of the parton, leaving the interpretation of the other two variables essentially unchanged.

If we have azimuthal symmetry of the parton population, as for a heavy ion, then the distribution of partons in the lego plot will be uniform in phi and smooth in eta. However, consider the partons in a constituent quark residing within a proton. When the transverse coordinate of the constituent quark is not near the center of the proton, it is clear that its partons will only populate a band in the lego plot centered upon the azimuthal angle of the constituent quark. Thus the three-quark configuration of a proton leads to three bands of enhanced parton density in the azumuthal variable phi. This banded structure is of course different for each of the quark configurations we have identified.

In describing a collision, we need to match the lego plot of the left-moving partons with the lego plot of the right-moving partons. This is not at all trivial, because the azimuthal band structure of the left-movers is generally not the same as the azimuthal band structure of the right movers. In putting together the left-movers' lego plot with that of the right-movers, one has to do it in a way which results in a description which is independent of the reference frame one uses. Under a longitudinal boost, the left-moving lego plot will change, as will the right-moving lego plot. The increase in length (in the rapidity variable) of one is compensated by a decrease in length of the other. How one describes the collision at the parton level may depend on the reference frame, but the outcome at the hadron-production level cannot be frame dependent. My own experience with this problem is that accomplishing a convincingly covariant description is in general hard to do, but important to achieve. In fact, this is, in the vernacular, just the problem of "the parton structure of the Pomeron".
This short talk is not the place for a general attack on this issue. But we will illustrate some of the issues involved for the case of inelastic diffraction.

V. Inelastic Diffraction at the Parton Level

Diffraction is a large component of the total proton-proton cross section, and is a close cousin of the elastic scattering process. It is, literally, a shadowy subject, defined by the absence of produced particles in a large

region of the lego plot. And it is a subject which requires a quantum description, while parton-model reasoning is strongly--but not totally--classical. This implies that the following discussion can be at most a sketch of a satisfactory description.

We consider a collision of two protons, each in a quark-diquark configuration, where none of the constituent quarks (or their color strings) collide. Nevertheless, all of the quarks and diquarks do pass through pion clouds moving in the opposite direction, and therefore excitations can occur. When we juxtapose the parton distributions of the right-moving and left-moving projectiles, as described in the previous section, into a common lego plot we encounter the awkwardness noted in the previous section. The bands of large parton density for the left-mover do not match those of the right-mover. How should we view this situation? A somehat crude and imprecise way of dealing with this is to divide all the partons into two classes: active and passive. The passive partons act as spectators, and after the collision are to be regarded as still belonging to their parent nucleon. The active partons, on the other hand, undergo collision and consequent transmutation into produced hadrons.

Now consider the band of partons associated with, say a left-moving constituent quark. It encounters the partons in the right-moving pion cloud. If there is an inelastic collision of this constiuent quark with the pion cloud, there must be active partons associated with the pion cloud. Now consider the most energetic right-moving, pion-cloud parton which is active. The location of this parton in the combined lego plot will also define the termination of the band of active partons associated with the left-moving constituent quark. And the patch of active partons so defined will define (approximately of course) the mass and longitudinal momentum of this system, as well as that of the produced hadrons. The mass of this system and its extent in the longitudinal rapidity variable will typically be much smaller than the total available, as seen in the typical non-diffractive event. So if the quark-cloud collision is all that happens, there will be large voids (rapidity gaps) in the lego plot of the produced particles.

There can also be processes where only the pion clouds excite each other. This leaves a distribution of active partons which is not dissimilar from the ion-ion example we discussed in Section III. This diffuse cloud-cloud interaction is likely to become more and more significant as cms energy increases, and eventually may evolve into collisions of opaque discs, again like the ion-ion example. If that is so, the language of centrality and ellipticity might eventually enter the domain of proton-proton collisions.

VI. Conclusions

In this talk, I have argued that there may still be room for an expanded parton-model intuition, mainly based on the tools already in place in the description of multiparticle final states in extremely high energy collisions. This line of thinking certainly overlaps the thinking of many other practitioners down through the years--starting of course with Feynman himself. I will not even try to cite those who have done, and perhaps those who are now doing, work that is in line with this point of view. Nevertheless the fact remains that this perspective is not in the mainstream of present thinking, and therefore there may be some reason to work harder along these lines. In particular, these ideas may well have their greatest impact in the valence-quark region of phase space, with implications for the physics of the production of leading particles in high energy collisions. This in turn could aid in the understanding of the propagation of cosmic-ray cascades in the atmosphere, which in turn would be of help in making Jim Cronin's present enterprise even more productive than it already is.