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INTERPRETATION OF MULTIPLICITY DISTRIBUTIONS

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1.- Data on multiplicity distributions in proton-proton interactions at high-energies, which first become available a year or so ago, provide valuable qualitative insight into some global aspects of hadron production [1]. Further bubble chamber investigations at Serpukhov and at NAL during the past year [2,3] have added more detail on the energy (s) and multiplicity (n) dependence of the partial cross-sections $\sigma_n(s)$. At the same time, single- and two-particle inclusive momentum distributions have been obtained over the energy range 30 to 1500 GeV/c. Important analyses of the properties of selected exclusive channels are also beginning. It seems clear that proper interpretation of multiplicity spectra requires simultaneous consideration of all this other relevant information. A clear trend in this direction is visible in papers written over the past year. In some of the more interesting recent work, a serious attempt is made to integrate knowledge of multiplicity distributions, momentum spectra, and various correlations.

My charge is to report on multiplicities as such, and to leave the treatment of detailed models and of momentum spectra to others. I will concentrate primarily on pp results, since they are the most complete. In large measure, the pp data are also representative of the general picture, although interesting systematic differences are present between particle-antiparticle processes [3] (e.g. K^+p at 32 GeV/c).

2.- EARLY LESSONS. - Several important observations based on the early data have been confirmed by more recent measurements. The slow growth with s of the mean number of charged particles may be parametrized as $\langle n_{ch} \rangle \simeq a + b \log s$ or as $\langle n_{ch} \rangle \sim s^{1/3}$, (with additional "threshold" correction terms in both expansions). Coefficient b has values ranging between 1.4 and 2.0 depending upon whether threshold terms are used [4,5]. The mean spacing $\langle \Delta y \rangle$ between hadrons in rapidity space is therefore small :

$\langle \Delta y \rangle \simeq 0.3 - 0.5$. In terms of mean invariant mass of hadron pairs, this implies $\langle \Delta m \rangle \simeq 400 - 500$ MeV. Obviously, independent emission of hadrons is excluded, and one must expect important final-state interaction effects, clustering, correlations and so forth. Second, the two-prong (σ_2) and four-prong (σ_4) pp cross-sections are observed to fall continuously with s from 30 to 400 GeV/c. A crude parametrization [4] gives $\sigma \sim p_{Lab}^{-0.4}$. It is therefore by no means clear from these data that an energy-independent ("diffractive") non-zero lower bound is being approached. In pp collisions, perhaps the best way to establish the existence and magnitude of such a lower limit will be to study systematically the s dependence of selected exclusive channels (e.g. $pp \rightarrow pp \pi^+ \pi^-$). Third, the full n dependence of σ_n at large s is described well neither by a Poisson formula nor by $\sigma_n \propto n^{-2}$. Nevertheless, it is clear that a Poisson form is a much better representation of the large n ($n > \langle n \rangle$) behaviour than is $\sigma_n \sim n^{-2}$. Simple diffractive models [6] for high n are excluded. Fourth, correlation parameter $f_2 = \langle n(n-1) \rangle - \langle n \rangle^2$ grows increasingly positive as s increases. Fluctuations about the mean are significant. The s dependence of f_2 is in principle a good discriminator between models. In practice, however, data can be fitted with expressions whose leading s behaviour is $\log s$, $(\log s)^2$, $\sqrt{s}$, or s , and so we must look deeper. Fifth, a simple rule appears to describe the growth of the width $D = (\langle n^2 \rangle - \langle n \rangle^2)^{1/2}$. Data can be fitted as

$$D = (0.58 \pm 0.01) [\langle n_{ch} \rangle - 1] \quad (1)$$

This regularity was first suggested by Malhotra [7] in 1963 and later explored in more detail by Czyzewski and Rybicki (C.R) [8] and by Wroblewski [9].

3.- MORE RECENT EFFORTS. - Investigations of the past year may be placed in five categories. First,

in a number of papers, the authors seek to fit $\sigma_n(s)$ with one smooth function of n and s , with few parameters. Basically, these are modifications of probability distributions [10] $P_n = \sigma_n / \sigma$. Little or no attempt is made to justify physically or to derive these functions from models. In the second and third categories I place the Koba-Nielsen-Olesen (KNO) scaling [11] and "two-component" approaches. Fourth, interesting information is available on associated multiplicities, neutral-charged correlations, left-right hemisphere multiplicity correlations, and the like. In the final category, I collect fits to (or implications for) $\sigma_n(s)$ obtained from detailed dynamical models [12,13], in which an attempt is made to accommodate simultaneously data on $\sigma_n(s)$, momentum spectra and correlations.

Among papers dealing with one smooth function for $\sigma_n(s)$, I may mention (a) the C-R formula, now extended to neutral-charged correlations [14], (b) approximately normal distributions [15], and (c), the Buras-Koba-Weisberg formula [16]. All of these are advertized as extremely good fits, and, in most cases, they are good by any χ^2 test. However, a relevant question is raised by Kaiser [15], among others. Given the considerable structure seen for example in the inclusive proton spectrum, what right do we have to expect a smooth function $\sigma_n(s)$? If the final $\sigma_n(s)$ really is featureless, we have to explain why it should be so, in contrast to single particle momentum spectra. One speculation, investigated by the ABCLV collaboration [17], is that the charged - multiplicity distribution is smoothed out, whereas the true-multiplicity distribution has considerable structure even at relatively low energy. I find that there is little justification for supposing that one smooth function should fit, and essentially no predictive value in the results.

4.- KNO SCALING. - This heading covers one of the most hotly debated subjects of the past year. The scaling rule states that

$$P_n(s) = \frac{\sigma_n(s)}{\sigma(s)} = \frac{1}{\langle n \rangle} \psi \left(\frac{n}{\langle n \rangle} \right) . \quad (2)$$

Its original "derivation", based on the assumption of Feynman scaling for all inclusive spectra [11], can be meaningful and valid only at extraordinarily high s , if at all. One begins with the identity

$$\sigma_{\langle n(n-1) \dots (n-q+1) \rangle} = \int \dots \int dy_1 \dots dy_q \frac{d^q \sigma}{dy_1 \dots dy_q} . \quad (3)$$

If the q -particle inclusive cross-section has attained an energy independent plateau, the integral gives $C_q (\log s)^q + O[(\log s)^{q-1}]$, where C_q is a constant. Therefore, we deduce

$$R_q = \frac{\langle n^q \rangle}{\langle n \rangle^q} = C_q \{1 + O\left(\frac{1}{\langle n \rangle}\right)\} . \quad (4)$$

Correction terms of order $\langle n \rangle^{-1}$ are indicated. The ratio R_q can be expected to be represented by the right hand side of equation 4 only for $q \ll \langle n \rangle$.

If equation 4 holds for all q , then (4) implies (2).

Because an approximately s -independent plateau even for single particle spectra is not observed to set in until ISR energies, if at all, the derivation shows that only $q \leq 2$ satisfies the basic postulate. Analyses of multiplicity data [18] show, however, that R_q is roughly constant for $p_{lab} \geq 50 \text{ GeV/c}$ and $q \leq 5$. Further, a universal function $\psi(z = n/\langle n \rangle)$ as defined in equation (2) seems to fit pp data in the range $50 \leq p_{lab} \leq 300 \text{ GeV/c}$. An example [19] of such a fit is given in Fig.1.

Fig.1 - Plot of a modified KNO scaling function $\psi(z')$ vs. z' . Multiplicity data from pp interactions are shown for laboratory momenta ranging from 5.5 to 300 GeV/c. Variable $z' = (n-0.9)/(\langle n \rangle-0.9)$. This figure is taken from Ref.19, in which references to data may also be found.

In view of the fact that the required s -independent plateaux are not observed, this early onset of apparent KNO scaling clearly has absolutely nothing to do with the original derivation. Is the precocious appearance of a universal function $\psi(z)$ profound or accidental? If accidental or transitory, we may expect that as s increases further, the function $\psi(z)$ will actually change gradually before approaching

its true scaling limit $\psi_\infty(z)$, if such a ψ_∞ exists. Supporters of the idea that the early scaling is profound search for models which incorporate this feature.

The accidental/profound debate is not resolved. Data on the large n behaviour of σ_n vs n in the energy range $100 \leq p_{\text{lab}} \leq 400$ GeV/c are of limited statistical significance, so that deviations from a universal fit are easily hidden. Perhaps a more sensitive test of reliability is provided by the s dependence of the ratio $[\text{mode}/\langle n \rangle]$. As remarked by Wroblewski [9], data on this quantity show a systematic decrease with p_{lab} , whereas a constant ratio is demanded if early KNO is true.

Second, a purely heuristic derivation of early KNO scaling may be given. The distribution $P_n = \sigma_n / \sigma$ plotted versus n has unit area at all s , but its shape spreads to larger n as s increases. If the x -axis is scaled by $\langle n \rangle$ and the y axis multiplied by $\langle n \rangle$, unit area is preserved. However, the distributions at different s collapse approximately to one universal distribution provided that the ratio $D/\langle n \rangle$ is constant. (D is the "width" of the distribution, Eq.(1)). This observation reduces the apparent early onset of KNO simply to a manifestation of the Malhotra-Wroblewski rule, at least to first order. To be sure, true early KNO scaling requires that the next moment, skewness γ_3 , also be s -independent

$$\gamma_3 = \frac{\langle (n - \langle n \rangle)^3 \rangle}{\langle n \rangle^3} . \quad (5)$$

However, this quantity is relatively small.

Third, why should KNO scaling work when applied to charged multiplicity n_{ch} and not to negative multiplicity n_- ? For negatives γ_2 and γ_3 fall systematically [12] with s .

Fourth, many approaches, including the "two-component" approach fit σ_n data perfectly over the energy range 50 to 300 GeV/c. In this sense, these models provide a function $\psi(z)$ definable from their "perfect" fits in this energy range [20,21]. However, for most of these approaches the asymptotic function $\psi_\infty(z)$ is far from that deduced from present data. These fits suggest therefore that apparent KNO scaling in the present energy range is entirely transitory. The scale of energies [21] over which things change may be of order 10^4 GeV. Demonstrations of this sort may be as much against the specific models as they are against early KNO scaling, of course. However, their existence dampens enthusiasm for the empirical regularity, and surely undermines credence

in extensions of KNO fits to π^0 and K multiplicity distributions for which statistics are even less impressive [22].

Absence of a solid derivation or of strong theoretical motivation, coupled with phenomenological doubts of the type mentioned above, suggest that the real KNO scaling limit, if any, may be very different from that suggested by present analyses. Nevertheless, there has been very interesting spin-off from the efforts of the pro-KNO school. I may call attention especially to the work of Koba and of Koba and Weingarten on density correlations and normalized cumulants [23]. Models in which KNO scaling is built in from the start include several impact-parameter models, which are quite interesting in their own right [24,25].

5.- MULTI-COMPONENT APPROACH. - The physical motivation for this general view point seems especially strong. Observations of inclusive momentum distributions and of exclusive channels give tentative evidence for contributions from different reaction mechanisms: single inelastic diffraction both of low mass and of high mass states, "central" production of pions and of anti-baryons, non-diffractive peripheral mechanisms, and so forth. Each of these mechanisms may have a characteristic and different $\sigma_n(s)$. We observe the sum of all effects. It is an intriguing experimental challenge to find operational methods for separating various mechanisms.

Although the physical motivation is high, two-component fits to $\sigma_n(s)$ involve great freedom and many arbitrary assumptions. In practice, the two-component approach has meant the addition of contributions from two overly simple components [26, 27]. An approximately Poisson distribution is fitted to the high multiplicity tail, and then enough is added to the σ_n at low multiplicities to produce a perfect fit. The low-multiplicity add-on is often loosely termed "diffractive". For the high- n component, each $\sigma_n \rightarrow 0$ asymptotically, and $\langle n_{\text{high}} \rangle \sim b \log s$ with $b_{\text{ch}} \sim 2$ to 3. Even less is generally true about the low- n component; crudely, $\langle n_{\text{low}} \rangle$ grows slowly with s , if at all, and either each $\sigma_{nD} \rightarrow C_n \neq 0$ or $\sum_n \sigma_{nD} = \text{constant}$.

Several further remarks may be made. First, from the $\sigma_n(s)$ data alone, one cannot prove the need for more than one (pure-short-range correlation) component. An acceptable fit to data with $p_{\text{lab}} \geq 50$ GeV/c may be constructed in which one defines $\langle n_- \rangle, f_2^{(-)}$ to agree with data [26]. Both have leading s dependence given by logs; curvature of

$\langle n_- \rangle$ and $f_2^{(-)}$ is accommodated by non-asymptotic terms falling as $(\sqrt{s})^{-1}$. Second, if the model is defined to be one in which there are two simple components, one invariably finds $\sigma_{\text{low}} / \sigma \simeq 0.2$. This result is obtained upon forcing agreement with the Malhotra-Wroblewski regularity [28]. Third, the present two-component approach leads to an asymptotic prediction $\gamma_3 < 0$. This is qualitatively obvious inasmuch as the approach provides a low multiplicity shoulder, of smaller overall magnitude than the dominant high multiplicity component. Thus, skewness eventually becomes negative. Proponents of early KNO scaling view this feature as a possible fatal flaw of the two-component view-point [29]. Data on f_3^{ch} are roughly energy independent over the present energy interval. Fourth, a dip structure, the "Wilson-dip", may appear at high enough energies if the low and high n components separate. Its observation would be impressive support for two- or multi-component pictures, and would help nail down parameters. However, no dip in the ISR energy range can really be said to be expected from fits to lower energy data, in the sense that present parameters are too poorly determined.

Finally, any number of paralyzing objections may be made against present fits. Poisson forms for the high- n component are of doubtful justification. Correlations, clustering, and energy-momentum effects surely break any Poisson assumption. Further, obvious efforts are needed to justify assertions about the low n component. The notion of diffraction is

one based on observation of final proton momentum distributions. Thus, experimental selections to isolate operationally a diffractive subsample should provide a less ambiguous definition of a low multiplicity component [30][†]. Likewise, it would be very instructive to examine the structure of σ_n vs. n for events in which other possible mechanisms play a role (e.g. events with a π in the central region, a $\bar{B}$, a large p_T hadron, etc.). It is crucial to break-away from the idea that one must be totally inclusive. Appropriate cuts (semi-inclusive) may be very instructive.

On the theoretical front, efforts are under way to develop multi-component models with more justification and/or predictive power [12,31]. Triple-Regge expressions provide parametrizations of missing mass M and t dependence in reactions of the form $pp \rightarrow pX$. Assumptions may then be made about the dependence of multiplicity on missing mass, for each Regge exchange. Comparisons are possible with data

in selected regions of t and M^2 , as well as for the full distribution $\sigma_n(s)$. An example of results obtained from this type of approach is given in figure 2.

Fig.2 - The distribution $P_n = \sigma_n / \sigma_n(\text{max})$ is plotted versus n_{ch} . Data (Ref.1) are shown at three energies. Theoretical curves are computed from a multiperipheral two-component model, Ref.12, which also successfully describes data on single-particle and two-particle inclusive momentum spectra in the NAL and ISR energy ranges.

6. - ASSOCIATED-MULTIPLICITIES. - One example of associated multiplicity was described in the previous section. The mean charged multiplicity $\langle n(M_X) \rangle$ has been obtained from NAL data on $pp \rightarrow pX$ as a function of missing mass [30,32]. A compilation is given in figure 3.

Fig.3 - The total mean charged multiplicity observed in the reaction $pp \rightarrow pX$ is plotted as a function of mass squared of system X. Data are taken from Refs.30 and 32. Two curves are drawn for comparison. Neither is a "best-fit".

Observe that $\langle n(M_X^2) \rangle$ appears not to depend on energy s . It grows slowly with M_X^2 . Two curves are drawn on figure 3 to provide a basis for comparison. Neither curve is in any sense a best fit. I took the coefficient $b = 1.4$ in the parametrization

$$\langle n(M^2) \rangle = a_M + b \log M^2, \quad (7)$$

[†] See page C1-351

directly from my fit to the s dependence of overall pp charged multiplicity [4]

$$\langle n(s) \rangle = a_s + b \log s. \quad (8)$$

No attempt is made to reproduce threshold effects for $M^2 < 10 \text{ GeV}^2$. As will be seen, the rate of $\langle n(M^2) \rangle$ with $\log M^2$ is consistent with being the same as the rate of growth of $\langle n(s) \rangle$ versus $\log s$.

The linear curve

$$\langle n(M^2) \rangle = 0.6 M + 2 \quad (9)$$

is not an unreasonable parametrization at low M , but begins to fail for $M^2 > 50 \text{ GeV}^2$.

Theoretical interpretation of these multiplicity data is not altogether direct. The nova approach [6] is predicated on a linear increase of multiplicity with mass of a properly defined recoil cluster. In fits to low energy data [$p_{\text{lab}} \leq 30 \text{ (GeV/c)}$] with this model, the form

$$\langle n_{\text{ch}}(M) \rangle \simeq 1.4 (M - m_p), \quad (10)$$

was found appropriate (for charge multiplicity). The rather small coefficient (0.6) of the linear term found in NAL data would appear to contradict nova model parametrizations, even at low M . This objection is not as strong as it might be, however, because the missing mass in NAL experiments is not identical to recoil cluster mass of the model. Likewise, direct interpretation of the logarithmic fit [Eq.(7)] in terms of multiperipheral-like or triple-Regge models is ambiguous inasmuch as a unique or clean exchange situation is not obtained in the data unless appropriate selections are made on M^2 and t .

On a purely qualitative level, the fact that the same coefficient $b \simeq 1.4$ is found in fits $\langle n(s) \rangle \sim b \log s$ and $\langle n(M^2) \rangle \sim b \log M^2$ suggests that what is important for determining asymptotic multiplicity is the energy available (Q) in whatever system or subsystem one is dealing with. This idea cannot be pushed too far, however, in view of the large difference observed for f_2 between K^+p at 32 GeV/c.

7.- CORRELATIONS. - Inasmuch as

$$f_2 = \langle n(n-1) \rangle - \langle n \rangle^2 = \iint C(y_1, y_2) dy_1 dy_2,$$

measurements of f_2 or of inclusive correlation function $C(y_1, y_2)$ mix effects which arise from (a) charge-isospin correlations, (b) kinematic and dynamic momentum correlations, and (c) multiplicity correlations per se. It is desirable to separate these effects and to assess their distinct influences.

It is evident that a measurement of $d^2\sigma/dy_1 dy_2$ or of correlation function $C_n(y_1, y_2)$ for fixed multiplicity n would allow some separation of momentum from multiplicity correlations. Use of appropriate statistical parameters applied to individual events [33] will help to identify salient collective effects (in single events) in momentum or in rapidity space. Promising work I have done along these lines in collaboration with the Pisa-Stony Brook group is described by Foa in his plenary report. The measurement of correlation parameter $f_2^{0,0}(n_-)$ between two neutral hadrons as a function of negative multiplicity is advertised [34] as a useful tool for identifying the isospin structure of clusters of pions emitted in a primary production mechanism.

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[†] (page C1-349) A simple t cut is made by the NAL-UCLA collaboration [30]. Their analysis should be repeated over a broad range of energies to see how the diffractive and non-diffractive subsamples change with s .