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MULTIPLICITIES IN HIGH ENERGY INTERACTIONS

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Abstract

This paper reviews the data on multiplicities in high energy interactions. Results from e^+e^- annihilation, from neutrino interactions, and from hadronic collisions, both diffractive and nondiffractive, are compared and contrasted. The energy dependence of the mean charged multiplicity, $\langle n_{ch} \rangle$, as well as the rapidity density at $Y = 0$ are presented. For hadronic collisions, the data on neutral pion production shows a strong correlation with $\langle n_{ch} \rangle$. The heavy particle fractions increase with $\sqrt{s}$ up to the highest energies. The charged particle multiplicity distributions for each type of reaction show a scaling behavior when expressed in terms of the mean. Attempts to understand this behavior, which was first predicted by Koba, Nielsen, and Olesen, are discussed. The multiplicity correlations and the energy variation of the shape of the KNO scaling distribution provide important constraints on models. Some extrapolations to the energies of the Superconducting Super Collider are made.

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Introduction

Although multiparticle production had been studied for several decades using the cosmic radiation as the incident beam, there was a revival of interest in looking at the global properties of high energy inelastic interactions when precise inclusive data became available from the CERN Intersecting Storage Rings.⁽¹⁾ A number of unifying theoretical ideas such as limiting fragmentation, and the multiperipheral model, with its prediction of short range rapidity correlations, provided a framework in which to discuss the data.⁽²⁾ The first accurate measurements of the charged particle multiplicity distributions that came from Fermilab⁽³⁾ were crucial in limiting the range of theoretical options. These data also established the validity of scaling in the multiplicity distributions, when expressed as a function of the mean, which became known as KNO scaling.⁽⁴⁾

Results from interactions such as $\bar{p}p$ annihilation and deep inelastic neutrino scattering showed narrower multiplicity distributions, which lead to the suggestion that the diffractive scattering, that is absent in such processes, was responsible for the difference with pp interactions.⁽⁵⁾ Comparisons with high energy e^+e^- data, show that this suggestion is an oversimplification.⁽⁶⁾

The first results from the CERN $\bar{p}p$ collider⁽⁷⁾ at $\sqrt{s} = 540$ GeV showed a dramatic violation of the KNO scaling observed up to the ISR energy range. This highest energy data, which shows many more events with multiplicities of three to four times the mean, stimulated a revival of interest in the subject. We are still far from a settled understanding.

In this paper, I review the results, point out similarities and differences in the data from different reactions, and comment on the models that are currently extant.

Mean Charged Multiplicity

The energy variation of the mean charged multiplicity for e^+e^- annihilation⁽⁸⁾ is shown in Fig. 1. This data includes charged particles from K^0 and Λ^0 decay, and at $\sqrt{s} = 29$ GeV such particles contribute an average 1.4 units to $\langle n_{ch} \rangle$.⁽⁹⁾ These charged particles are included in the e^+e^- data since logically, if they were to be removed, one should also remove the decay products of D and B mesons. However, these heavy particles carry a large fraction of the available energy, leaving a much lower effective energy for the hadronization of the remaining particles.

There are new quark thresholds in the 3 GeV and 9 GeV region, which, in principle, could introduce some discontinuities in the data. The systematic uncertainties in the data which are typically ~ 0.5 unit mask any such effects.

The results of Fig. 1 can be roughly represented by a power law $\langle n_{ch} \rangle = a s^{1/4}$ as originally suggested on statistical grounds by Fermi.⁽¹⁰⁾ The full line shows this variation with $a = 3.0$.

The QCD motivated variation⁽¹¹⁾ of:

$$\langle n_{ch} \rangle = a \left[\ln \frac{Q}{\Lambda} \right]^b \exp \left(c \ln \frac{Q}{\Lambda} \right)^{1/2} \quad (1)$$

also provides a reasonable representation of the data above the bottom quark threshold. Normalizing to the HRS result of $\langle n_{ch} \rangle = 13.1$ at $Q = \sqrt{s} = 29$ GeV gives $a = 0.12$ with $b = -4.92$, $c = 6.26$, and $\Lambda = 0.25$ GeV fixed by the QCD model.

A better representation of the data over the full energy range is provided by the power law expansion in lns:

$$\langle n_{ch} \rangle = a + b \ln s + c \ln^2 s \quad (2)$$

with $a = 3.33 \pm 0.11$, $b = -0.4 \pm 0.08$ and $c = 0.26 \pm 0.01$. This fit is shown by the dashed line in Fig. 1.

The pp data up to ISR energies^(3,12,13), shown in Fig. 2, can also be fit by the lns plus $\ln^2 s$ variation of Eq. (2), but with $a = 0.80 \pm 0.12$, $b = 0.47 \pm 0.05$, and $c = 0.114 \pm 0.005$ with $\sqrt{s}$ in GeV. This gives $\langle n_{ch} \rangle = 24.8$ for $\sqrt{s} = 540$ GeV in good agreement with the value of 26.8 ± 2.1 for $\bar{p}p$ interactions reported by the UA5 collaboration.⁽¹⁴⁾ The differences between pp and $\bar{p}p$ interactions at collider energies are not expected to be significant and are ignored in the subsequent discussions.⁽¹⁵⁾

Figure 3 shows the two fits of Eq. (2) together with the QCD fit of Eq. (1) (dashed-dot) over a wide energy range. The full line, which fits the data for hadronic collisions when extrapolated to $\sqrt{s} = 40$ TeV, predicts $\langle n_{ch} \rangle = 62.0$. It is possible that this may be an underestimate, since the fraction of hard collisions which populate the central rapidity region and which give much higher than average $\langle n_{ch} \rangle$ values is increasing rapidly with

energy. The hard e^+e^- processes have a much stronger variation of $\langle n_{ch} \rangle$ with $\sqrt{s}$ than does the pp data.

In the energy range from 10-30 GeV in the c.m., the pp data, if plotted at $\sqrt{s}/2$, agrees with the e^+e^- data consistent with the simple expectation that the available energy is a dominant variable⁽¹⁶⁾ and that the leading particles take half of the center of mass energy on average. This result is shown in Fig. 4. The fits to the pp and e^+e^- data of Fig. 3 indicate that this simple scaling will probably not continue at the higher energies.

Rapidity Density

The early expectation that the rapidity density would be independent of $\sqrt{s}$ and that the plateau would merely widen as the energy is increased leads to an $a + b \ln s$ variation of $\langle n_{ch} \rangle$ which is clearly not in accord with data. The rapidity density at $Y = 0$ increases with energy for both e^+e^- data and pp data⁽⁹⁾ as shown in Fig. 5. Separate, simple $a + b \ln s$ variations of $\left. \frac{1}{\sigma} \frac{d\sigma}{dY} \right|_{Y=0}$ shown by the lines represents both sets of data well. The pp bubble chamber data⁽¹⁷⁾ fits well with the collider results,⁽¹⁸⁾ although the latter measurements are made using the pseudorapidity variable η ($\eta = 1/2 \ln \tan \theta/2$), and so lie typically (10-15)% below the measurements made using the true rapidity variable Y . The ISR point⁽¹⁹⁾ is higher than the trend of the bubble chamber measurements, suggesting that perhaps the variation of the $\bar{p}p$ data is faster than is indicated in Fig. 5. The dashed line connecting the hadronic data, if extrapolated to 40 TeV, predicts a value of $\left. \frac{1}{\sigma} \frac{d\sigma}{dY} \right|_{Y=0}$ of 5.5 charged particles per unit of rapidity.

The short dashed line shows the pp data plotted at $\sqrt{s}/2$. In this case an agreement with the e^+e^- data is not obtained by such a simple scaling. This is perhaps connected with the fact that the shape of the pp and e^+e^- rapidity distributions are different.⁽⁹⁾ As seen in Fig. 6, the pp data peaks at $Y = 0$ whereas the e^+e^- data has a shallow dip in the central region. Part of this difference clearly results from the break up of the resonances containing the heavy quarks (c and b), that are responsible for almost half of the e^+e^- events and only a fraction of a percent of the hadronic interactions. The combination of the hard fragmentation and the restricted Q value of the heavy meson decays give a peak in the rapidity range $1 \lesssim Y \lesssim 2$. This is illustrated by the DELCO data⁽²⁰⁾ on b quark fragmentation shown in Fig. 7. The decay of the first rank mesons yields a distribution with a strong dip at $Y = 0$, which is only partially filled in by the higher rank fragmentation.

Neutral Pion Production

The number of neutral pions produced in pp collisions, as measured by the number of observed photons, increases proportionally to the charged multiplicity. A variation

$$\langle n_{\pi^0} \rangle = \beta + \alpha n_-$$

represents the data well and the strength of the correlation (α) increases with $\sqrt{s}$ from approximately zero in the 2- to 5-GeV range up to about 3.5 for the collider energies as seen in Fig. 8. The lower energy data⁽²¹⁾ come from the inclusive pp bubble chamber experiments; the typical ISR results shown

continue the trend of α increasing with $\sqrt{s}$.

The UA5 results can be represented by the expression $\langle n_\gamma \rangle = 8 \pm 3 + (0.9 \pm 0.08) n_{ch}$ which, assuming all γ rays come from π^0 decay, gives $\langle n_{\pi^0} \rangle = 16 \pm 6 + (3.6 \pm 0.32) n_-$.

The latter assumption may not be valid as integrating up to $|\eta| = 5$, the UA5 group measure $\langle n_\gamma \rangle = 34 \pm 2$ as compared to $\langle n_{ch} \rangle = 26.5 \pm 1$ in the same pseudorapidity range. If the charged particles are corrected for the heavy particle content, then $\langle n_{ch}^\pi \rangle = 22.5 \pm 1$ which, when compared to $\langle n_\gamma \rangle$, suggests strong π^0 production since for pions the relationship $\langle n_{ch}^\pi \rangle = 2 \langle n_\pi \rangle$ is expected to hold. An η/π^0 ratio of ~ 0.32 is required in this interpretation.

Heavy Particle Fractions

The yields of K mesons and baryons continue to increase up to the highest energies. Figure 9 shows the mean multiplicities as a function of $\sqrt{s}$ for pp collisions. The values are still increasing even at $\sqrt{s} = 540$ GeV. The average event⁽²²⁾ at this highest energy $\bar{p}p$ collision contains $2.5 K^\pm$, $2.7 (K^0, \bar{K}^0)$, $1.5 p^\pm$, $0.25 (\Sigma^\pm, \bar{\Sigma}^\pm)$, $0.5 (\Lambda, \bar{\Lambda})$ and $\sim 0.2 \Xi^\pm$ particles, with a total of 26.5 charged particles. This may be contrasted to e^+e^- annihilation⁽²⁴⁾ where at $\sqrt{s} \sim 34$ GeV, there are a total of 11.7 charged particles (removing the $K^0 \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow p\pi^-$ decay), including $10.3 \pi^\pm$, $2.0 K^\pm$, $1.6 (K^0\bar{K}^0)$, $0.8 p^\pm$, $0.28 (\Lambda, \bar{\Lambda})$ and a $0.026 \Xi^\pm$ particles. Clearly the K meson fraction is higher for e^+e^- annihilation and the baryon fraction is about the same. There is, of course, no reason to make the comparison for these particular energies

since in hadronic collisions there is a strong dependence of the particle fractions on $\sqrt{s}$.

Multiplicity Distributions

a. Comparison of e^+e^- and pp Data

The cross sections, as a function of prong number for e^+e^- annihilation at $\sqrt{s} = 29 \text{ GeV}^{(25)}$ and pp scattering at $205 \text{ GeV}/c^{(26)}$ ($\sqrt{s} = 19.6 \text{ GeV}$), are shown in Fig. 10. Even though $\langle n_{\text{ch}} \rangle = 7.68 \pm 0.07$ for the pp case, one event with 26 prongs was observed corresponding to a fractional cross section of $\sim 1.3 \cdot 10^{-4}$; a similar rate to that observed in the e^+e^- annihilation data of Fig. 10, but where $\langle n_{\text{ch}} \rangle$ is much higher ($12.62 \pm 0.03 \pm 0.5$).⁽²⁷⁾ This difference remains if the comparison is made with the nondiffractive pp data for which $\langle n_{\text{ch}} \rangle = 8.56 \pm 0.12$. It is clear that when expressed as a fraction of the mean values, the e^+e^- data is significantly narrower than the hadronic data, even after accounting for the diffractive component in the latter.

The scaling in the mean first suggested by Koba, Nielsen, and Olesen⁽⁴⁾ on the basis of Feynman scaling and a logarithmic multiplicity growth, both of which are now known to be violated, holds well for the different data sets. If $z = n_{\text{ch}} / \langle n_{\text{ch}} \rangle$, then KNO scaling says that

$$\psi(z) = \langle n_{\text{ch}} \rangle \frac{\sigma_n}{\sum \sigma_n} \quad , \quad (3)$$

where $\psi(z)$ is a universal function for a given type of reaction and σ_n is the cross section for production of the final state containing n charged particles.

Figure 11 shows a compilation of e^+e^- results.^(8,25) Similar data for a sample of nondiffractive pp interactions from Fermilab⁽²⁶⁾ and the ISR⁽¹³⁾ are shown in Fig. 12. Exact KNO scaling requires constant values for the moments of the distributions

$$C_q = \frac{\langle n_{ch}^q \rangle}{\langle n_{ch} \rangle^q} \quad (4)$$

and, in particular for $\langle n_{ch} \rangle/D$, where D is the dispersion of the distribution

$$D^2 = \langle n_{ch}^2 \rangle - \langle n_{ch} \rangle^2 \quad (5)$$

As pointed out by Breakstone et al.,⁽¹³⁾ it is only for the nondiffractive data that $\langle n_{ch} \rangle/D$ is constant, being fit by the expression

$$D = (0.439 \pm 0.007) \langle n_{ch} \rangle - (0.02 \pm 0.06) \quad (6)$$

The nondiffractive pp data of Fig. 12 is reasonably represented by the expression⁽²⁸⁾

$$\psi(z) = e^{-3.5z} (-2.72 z + 75.9 z^3 - 16.35 z^5 + 0.89 z^7) \quad (7)$$

shown by the line. The same function is also shown dashed on the e^+e^- data of Fig. 11. It is clear that the nondiffractive pp data is wider than the e^+e^- results.

Another way to exhibit the differences between the hadronic and the e^+e^- data is in terms of the $\langle n_{ch} \rangle/D$ ratios. Figure 13 shows a compilation of such results: the mean e^+e^- values are near 3, whereas the hadronic data is somewhat below 2. The $\langle n_{ch} \rangle/D$ ratios for single jet e^+e^- data shown by the crosses lie below the values for the whole event. Even though these ratios are different, the dispersion measurements themselves⁽⁸⁾ make a continuous curve as shown in Fig. 14. This remarkable result is presumably accidental.

b. Diffractive Data

We have discussed the differences between the results from the nondiffractive hadronic collisions and e^+e^- data. We now turn to a consideration of the diffractive data itself. There are several difficulties in discussing diffractive multiplicities: the definition of a diffractive event is not uniquely specified so that different groups use different selection criteria, the multiplicities are low since the effective mass of the diffractive cluster is low, and resonant N^* states (or, in the case of $\pi\pi$ interactions, the A_1 resonance) play a major role, and finally the effective c.m. energy has to be measured from the events themselves.

One of the striking early results from Fermilab⁽²⁹⁾ was the observation, shown in Fig. 15, that the multiplicity distributions in the reaction $pp \rightarrow pX$ at 205 GeV/c followed those of the inclusive $pp \rightarrow X$ reaction when compared at

the same mass of the system X. Of course, since the charge of X is different in the two cases, a comparison using n_- would not provide such good agreement. It is not clear which is the more fundamental variable.

A more detailed comparison is given in Fig. 16. The data points show the KNO scaling distributions for diffractive events from 102, 205, and 405 GeV/c pp interactions⁽³⁰⁾ is shown in Fig. 16. Although the errors are large, the data show a general accord with a scaling expectation. The line which shows the fit to the nondiffractive data (Eq. 7) indicates that the diffractive events, selected in the bubble chamber with low effective mass at the target vertex and a rapidity gap between this system and the beam proton,⁽³¹⁾ have a somewhat broader and flatter KNO distribution than do the nondiffractive inclusive data.

An extensive series of more recent measurements have been made by the Rockefeller group⁽³²⁾ using incident $\pi^\pm$, $K^\pm$ and $p^\pm$ beams of 100 GeV/c and 200 GeV/c. The recoil protons in the range $0.025 < |t| < 0.095$ (GeV/c)² were detected in a vertex spectrometer surrounding a gas target. The multiplicity of the forward system was measured by the pulse heights in two scintillation counters. The results, shown in Fig. 17, indicate that the mean multiplicity values are independent of the projectile when compared at the same values of the available energy. When expressed in the KNO form, this diffractive data is more symmetric and, as seen in Fig. 18, can be reasonably represented by the Gaussian function:

$$\frac{\sigma_n}{\Sigma \sigma_n} = \frac{2}{\sqrt{2\pi D}} e^{-\frac{(n - n_0)^2}{2D^2}} \quad (8)$$

with $n_0 = 2M^{1/2}$ and $n_0/D = 2$ or

$$n_0 \frac{\sigma_n}{\Sigma \sigma_n} = \sqrt{\frac{8}{\pi}} e^{-2(1 - n/n_0)^2} \quad (9)$$

These results, then, differ from the earlier bubble chamber data. The source of this difference could lie in the very different techniques used to define a diffractive event and to measure the multiplicity.

Goulianos⁽³³⁾ further shows that the KNO distribution for the inclusive pp system can be represented by a sum of the nondiffractive and diffractive distributions, each of which is represented by a Gaussian distribution.

(c) Neutrino Data

Multiplicity measurements in lepton-nucleon scattering have been primarily done for neutrino scattering observed in the large bubble chambers. The events are very clean but the experiments suffer from low statistics, from a low available energy, and also have some difficulty in assigning the correct energy to each event. Nevertheless, several groups have reported results from both $\bar{\nu}p$ and νp scattering. The mean charged hadron multiplicity from three $\bar{\nu}p$ experiments⁽³⁴⁾ is shown in Fig. 19. The curve represents the fit done by Wroblewski⁽²⁸⁾ to nondiffractive π^-p interactions.

The KNO distributions for the νp and $\bar{\nu}p$ data from the high statistics BEBC experiment⁽³⁵⁾ are shown in Fig. 20. Since the experiments are done with a wide band beam, the scaling can be exhibited by data from a single experiment. The $\bar{\nu}p$ distribution is broader than measured for νp . This

difference has been interpreted by Zieminska⁽³⁶⁾ to mean that one should only use the produced particles in such comparison. Since the νp ($\bar{\nu} p$) experiments lead to a final hadronic state of charge 2(0) and the total number of particles is small, this effect is strong for the neutrino data. Higher energy data, which would settle this issue will not now become available. The curves shown in Fig. 20 represent the modified Poisson distribution⁽³⁷⁾

$$\psi(z) = \frac{C^{(Cz+1)}}{\Gamma(Cz+1)} e^{-C} \quad , \quad (10)$$

with $C = 8.64 \pm 0.13$ for νp and $C = 6.25 \pm 0.18$ for $\bar{\nu} p$ interactions. These low energy neutrino distributions are sharper and narrower than either the hadronic data or the e^+e^- results of Fig. 11.

(d) Collider $\bar{p}p$ Data

As we have seen, although there are some differences in the shape of the KNO distributions for the different reactions, within a given reaction type the data scales well. The first results from $\bar{p}p$ scattering at $\sqrt{s} = 540$ GeV which showed a dramatic violation of the scaling that holds up to 62.5 GeV, the highest energy of the ISR, was unexpected. This comparison is shown in the compilation of the moments of the multiplicity distribution of Fig. 21. The higher moments C_4 and C_5 increase by about a factor of two between 60 GeV and 540 GeV.

In addition, the multiplicity distributions for selected rapidity ranges differ with the central region $|\eta| < 0.5$, showing almost an exponential fall-off with z .

Forward-Backward (F:B) Multiplicity Correlations

Another aspect of the data in which hadronic collisions and e^+e^- annihilation show different behavior is in the long range correlations that give rise to correlated multiplicities in the two hemispheres.

Figure 22, which shows e^+e^- data at $\sqrt{s} = 29 \text{ GeV}$ ⁽³⁸⁾, indicates that strong F:B multiplicity correlations are absent in such interactions. This may be contrasted with the strong correlation observed at the ISR⁽³⁹⁾ and particularly at the CERN collider⁽⁴⁰⁾. The latter can be expressed as:

$$n_F = a + b < n_B > . \quad (11)$$

The energy variation of b is given in Fig. 23.

This data has been interpreted in terms of the independent emission of clusters⁽⁴⁰⁾ consistent with the known short range rapidity correlations. However, e^+e^- data show very similar rapidity correlations but yet no F:B multiplicity correlations. The hadronic data has also been interpreted in terms of the dual model.⁽⁴¹⁾

Interpretations

What do all these results mean and, in particular, is there any simple underlying physics? The first comment is that a scaling distribution results from a tree branching process such as is indicated in Fig. 24, and which represents the underlying QCD parton level process at least for e^+e^- annihilation.⁽⁴²⁾ Such a branching process is implemented in the Monte Carlo

simulation of e^+e^- annihilation written by Webber.⁽⁴³⁾ Although such a calculation yields the distribution of partons, it is still necessary to account for the final hadronization by some reasonable prescription. There is no fundamental understanding of how to handle this nonperturbative phase of the parton-hadron transition. With this caveat, the prediction of the KNO distribution for e^+e^- annihilation, predicted by this model, is shown by the line in Fig. 11. It is a little narrower than the data, but agrees well with the overall shape of the results. Since the final hadronization in this model is done via a simple two-body decay of the color neutral clusters, it would obviously be possible to adjust the parametrization to improve the agreement. The calculation also agrees quite well with the energy variation of the yields of the stable particles π , K and p as seen in Fig. 25.

Since we do not yet have a simulation of hadronic interactions⁽⁴⁴⁾, there is no agreed explanation for the broadening of the multiplicity distribution observed at the collider. It seems that a new process may have set in and several possibilities have been discussed:⁽⁴⁵⁾ The dual parton model⁽⁴⁶⁾ provides one explanation. As the energy is increased, diagrams with additional chains, as shown in Fig. 26, start to contribute a higher multiplicity component. The results of one explicit calculation⁽⁴⁷⁾ are given in Fig. 27.

Geometrical models have also been discussed. The basic idea is that the central collisions have a different dependence of $\langle n_{ch} \rangle$ on energy than do the peripheral collisions. The physical picture is attractive and indeed, the idea of the violent collisions proceeding in a two-step process: first the production of one or more blobs of excited hadronic matter called fireballs

followed by the fireball decay goes back to the earliest days of cosmic ray studies. Such ideas are difficult to quantify and cast into a theory with predictive power. However, it is possible to explain the data a posteriori.⁽⁴⁸⁾ The broader KNO distribution observed for the central rapidity region is consistent with these ideas.

A somewhat related idea arises from the observation that the multijet events that result from hard parton-parton collisions constitute a rapidly increasing fraction of the total cross section as the energy is increased. The events with the highest multiplicities receive contributions from the high p_T jets as well as the beam fragmentations.⁽⁴⁹⁾ The striking observation that $\langle P_T \rangle$ increases with multiplicity is in accord with this idea.

Another possibility that has been discussed is that the two components are, respectively, quark and gluon initiated with the gluon multiplicity being 9/4 of the quark and the gluon/quark fraction growing with energy.⁽⁵⁰⁾

Carruthers and collaborators⁽⁵¹⁾ have discussed a different approach. They point out that KNO scaling is a rather general result in physics ranging from photoelectron emission in quantum optics to the distribution of the number of galaxies in clusters. They speculate that the differences in the KNO distributions may reflect different underlying mechanisms. A generalization of the Bose-Einstein distribution results from emission by k identical sources. ,

$$P_n^k = \frac{(n+k-1)!}{n! (k-1)!} \left[\frac{\langle n \rangle / k}{1 + \frac{\langle n \rangle}{k}} \right]^n \frac{1}{\left(1 + \frac{\langle n \rangle}{k}\right)^k} . \quad (12)$$

For n and $\langle n \rangle$, large compared to k , this reduces to

$$\psi(Z) = \frac{k^k}{(k-1)!} Z^{k-1} e^{-kZ} \quad , \quad (12)$$

which fits the hadronic KNO distributions well if $k \sim 3-4$. However, to obtain a narrower distribution k must be increased which is difficult to understand intuitively. However, the single jet e^+e^- distributions are broader than those measured for complete event as seen from the $\langle n_{ch} \rangle/D$ ratios plotted in Fig. 13. The whole e^+e^- event is then a super position of two independent but equal quark emitters.

Conclusions

Although much beautiful data exists on multiplicities and related subjects, no one has illuminated the real underlying physics. The subject is very active and more detailed information will become available both at current energies, as well as from higher energy e^+e^- and $p\bar{p}$ collisions.

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Figure Captions

1. Center of mass energy variation of mean charged multiplicity $\langle n_{ch} \rangle$ for e^+e^- annihilation. The full line shows the power law $\langle n_{ch} \rangle = 3.0 s^{1/4}$; the dashed line a $\ln s$ plus $\ln^2 s$ variation.
2. Center of mass energy variation of mean charged multiplicity $\langle n_{ch} \rangle$ for pp interactions. The full line represents the fit $\langle n_{ch} \rangle = 0.80 + 0.47 \ln s + 0.114 \ln^2 s$.
3. Extrapolation of $\langle n_{ch} \rangle$ for e^+e^- annihilation and pp interactions to SSC energies. The full line represents the pp data of Fig. 2; the dashed line the e^+e^- data of Fig. 1. The dashed-dotted line is the QCD fit to the e^+e^- data.
4. Comparison of $\langle n_{ch} \rangle$ for e^+e^- and pp data.
5. Energy variation of the rapidity density for e^+e^- and pp data.
6. Rapidity distributions for e^+e^- and pp data. (a) HRS data at $\sqrt{s} = 29$ GeV, (b) comparison of HRS two-jet data with pp interactions at similar $\sqrt{s}$ values.
7. Rapidity distribution for $e^+e^- \rightarrow b\bar{b}$ events at $\sqrt{s} = 29$ GeV as measured by DELCO. The dashed-dotted line shows the Y distribution expected from the B meson decay products and the dashed line the remaining hadrons.
8. Energy variation of neutral pion: charged particle multiplicity correlations.
9. Energy variation of the heavy particle fractions for pp collisions.
10. Cross sections for charged particle production in (a) e^+e^- annihilation at $\sqrt{s} = 29$ GeV ($\bullet$ scale on right) and (b) pp collisions at $\sqrt{s} = 19.6$ GeV (scale on left).

11. KNO scaling distribution for e^+e^- annihilation. The full line shows the prediction of the Webber model and the dashed line the fit to nondiffractive pp data.
12. KNO scaling distribution for nondiffractive pp scattering observed in the Fermilab bubble chamber (19.6 GeV) and at the ISR, 30.4 GeV and $\sqrt{s}$ 62.2 GeV.
13. $\langle n_{ch} \rangle/D$ ratios for e^+e^- annihilation and pp interactions. The data points (x) between the two lines show the single jet $e^+e^- \langle n_{ch} \rangle/D$ ratios.
14. Energy variation of the dispersion D for e^+e^- annihilation and pp inelastic scattering.
15. Multiplicity distribution for $pp \rightarrow pX$ (x) compared to $pp \rightarrow X$ (•) for different selections of the mass (M) of the system X. (a) $0 < M^2 < 5 \text{ GeV}^2$, (b) $5 < M^2 < 10 \text{ GeV}^2$ and $p_{lab} = 5.5 \text{ GeV}/c$, (c) $0 < M^2 < 25 \text{ GeV}^2$ and $p_{lab} = 13 \text{ GeV}/c$, (d) $25 < M^2 < 50 \text{ GeV}^2$ and $p_{lab} = 26 \text{ GeV}/c$, (e) $50 < M^2 < 100 \text{ GeV}^2$ and $p_{lab} = 50 \text{ GeV}$ and (f) $100 < M^2 < 150 \text{ GeV}^2$ and $p_{lab} = 69 \text{ GeV}/c$.
16. KNO scaling distribution for diffractive pp scattering observed in the Fermilab bubble chamber.
17. Variation of $\langle n_{ch} \rangle$ and $\langle n_{ch} \rangle/D$ with available energy for (a) πp , (b) Kp , and (c) pp collisions.
18. Comparison of diffractive KNO distribution with gaussian curve.
19. Energy variation of the mean charged multiplicity for $\bar{\nu}p$ scattering.
20. KNO scaling distributions for νp and $\bar{\nu}p$ scattering as measured in BEBC.

21. Energy variation of the moments of the KNO distribution for pp scattering.
22. Forward (F):backward (B) multiplicity correlations for e^+e^- annihilation.
23. Energy variation of F:B multiplicity correlations in pp scattering.
24. Tree branching process.
25. Energy variation of particle yields in e^+e^- annihilation as fit by Webber model.
26. Dual model diagrams.
27. Dual model calculation compared to KNO distribution at $\sqrt{s} = 540$ GeV.

Fig. 1

Fig. 2

Fig. 3

Fig. 6

Fig. 7

3-85

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Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 15

Fig. 16

Fig. 17

4-85

5081A20

Fig. 18

Fig. 20

JET - JET MULTIPLICITY CORRELATIONS

Fig. 22

Fig. 23

Fig. 24

Fig. 25

Fig. 26

Fig. 27

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