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Hadron Production in e^+e^- Annihilation at High Energies

by

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I. INTRODUCTION

The real subject of this meeting is detectors, not theory expectations of what will happen in them at PETRA or PEP. We all know that this is the proper order of things. Nevertheless, I have been asked to talk about hadron production at PETRA/PEP, and there are some reasons for believing that this may not be a senseless assignment. The first reason lies in the ability of the quark model and the (quark) parton model to tie together an extraordinary amount of data in a coherent fashion. Maybe this is a grossly incomplete picture - it certainly isn't a theory - but if we want to speculate, it is the logical place to start. The second reason is the existence of intuitive pictures for e^+e^- based on field theory.(1) These can offer hints about where to look for new effects. The last is not a reason, but a question: why is the energy gap between the psions and the light mesons so much greater than the level spacing of either light mesons or psions? A new mass scale seems to have appeared, and PETRA/PEP will allow us to explore mass range $\gtrsim 10$ times this spacing. Perhaps new heavy vector mesons and other new physics will turn up.

Part of this talk is a catalog of quark model expectations assuming the existence of "light" quarks u,d,s and the first generation heavy charmed quark c.(2) When discussing new possibilities (some of which may even be relevant at current energies), I simply add a very heavy quark Q (or quarks Q_1, Q_2 ...). New psions ψ_s are built of $Q_i\bar{Q}_i$; $Q\bar{q}$ or Qq $(q = u,d,s,c)$ composites are labelled S (generically, all these are "supers"). Of course, much of this does not depend on the detailed picture - supers may exist and have nothing to do with quarks - but it provides us with a nice framework. It is useful to have a simple picture to help in exploring options.

Of course, we really do not know what will happen at PETRA/PEP. The timelike physics of one-photon e^+e^- annihilation is likely to get more rather than less surprising as we explore still shorter distances and higher energies and energy densities.

II. $R = \sigma_{HAD}/\sigma^{QED}_{\mu^+\mu^-}$

The history of $e^+e^- \to 1\gamma \to$ hadrons is resonances (Fig.1). Of those seen so far with $\Delta R \geq 10$ only one (the ρ^0) is really very broad.

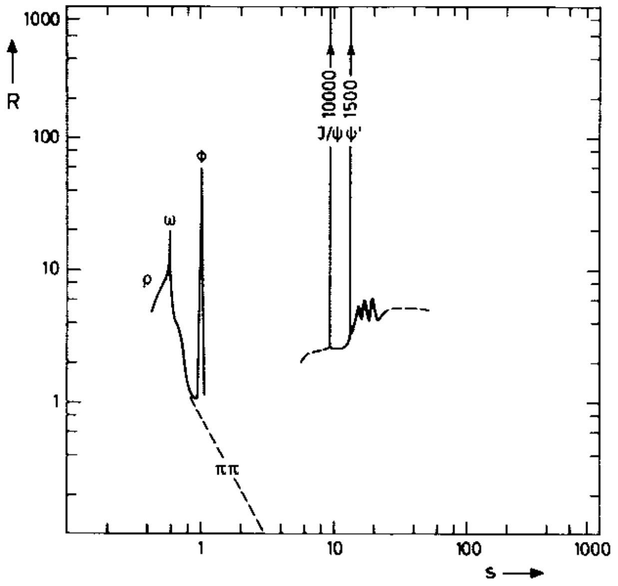


FIG.1

Exploration at large $\sqrt{s} = 2E_{beam}$ may turn up more new narrow hadronic resonances. These supers (ψ_s) might be the $Q\bar{Q}$ composites already mentioned, color or other excitations of $q\bar{q}$, or something really new. Experiences with ρ^0, ω, ϕ, J/ψ, ψ' leads us to expect $\Gamma(\psi_s \to e^+e^-) \gtrsim 1$ KeV. Fig.2 shows $\int \sigma_{Had}\, d\sqrt{s}$ for $\Gamma_{e^+e^-} = 1$ KeV, $\Gamma_{Had}/\Gamma = 1$. At M_{ψ_s} = 20 GeV, $(\Delta R)_{res} \sim 5$ for CM machine energy spread $\Delta\sqrt{s}$ = 40 MeV and $\Gamma(\psi_s) \ll$ 40 MeV. Recall that for ψ, $\int \sigma_{Had}\, d\sqrt{s} \sim 10^4$ nb.-MeV. Conclusion: new heavies may not show up as dramatically as did the ψ.

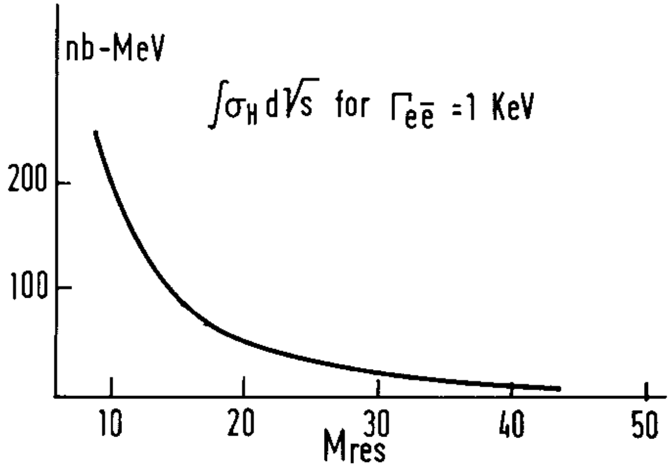


FIG.2

We expand on this guess of $\Gamma(\psi_s \to e^+e^-)$, and on the level spacing of new supers $M_{\psi_s'} - M_{\psi_s}$. Two semiempirical inputs to this end:

(i) If J/ψ (3.1) is really $c\bar{c}$ $e_Q = 2/3$ then the (experimental) relation$^{(3)}$

$$\frac{\Gamma_{e^+e^-}(\psi)}{\Gamma_{e^+e^-}(\phi)} = 4 \times (0.94) \approx \left(\frac{2/3}{-1/3}\right)^2 \qquad (1)$$

indicates (but doesn't prove) that $\Gamma_{e^+e^-}$ is independent of M (the resonance mass), at least in first approximation.

(ii) Empirically, if the $(\Delta R)_{res}$ of a resonance is averaged over the level spacing, this roughly reproduces the step $(\Delta R)_\infty$ above threshold where there is no longer any resonance structure (this works roughly for ρ^0, ω, ϕ and for J/ψ, ψ').$^{(4)}$ In the parton model $(\Delta R)_\infty = 3e_Q^2$, where the 3 comes from assuming that all quarks come in 3 colors, and e_Q is the quark charge in proton charge units. Then for our supers this leads to

$$3 e_Q^2 \sim 9\pi \frac{M_{\psi_s}^2}{\Delta M_{\psi_s}^2} \frac{\Gamma_{e^+e^-}(\psi_s)}{\alpha^2 M_{\psi_s}} \frac{\Gamma_{had}}{\Gamma} \qquad (2)$$

and if $\Gamma_{e^+e^-} \propto e_Q^2$, the spacing of the lowest levels is roughly the same for all mesons(5)

$$(M_{\psi_s'} - M_{\psi_s}) \sim (M_{\psi'} - M_{\psi}) \sim (M_{\rho'} - M_{\rho}) \qquad (3)$$

The most plausible guess: level spacings as for $J/\psi - \psi'$, γ ray transition energies to C = + states likewise.

If we apply asymptotic freedom estimates (invented for J/ψ(6)) to this case (for ψ_s below $S\bar{S}$ threshold), we get another most plausible guess that $\Gamma_{e^+e^-}/\Gamma \sim$ 5-15 % for these new supers and such a small direct decay that much of Γ_{HAD} comes from $\psi_s \to 3\gamma \to$ hadrons. These estimates should not be trusted much, but Γ probably should be small anyhow. It seems plausible that matrix elements connecting light hadron states and $Q\bar{Q}$ vanish as $M_{Q\bar{Q}} \longrightarrow \infty$ (very massive states are irrelevant to the light hadron world), and this in turn argues for small $\Gamma(\psi_s)$. Of course, if the ground state ψ_s is above the $S\bar{S}$ threshold it will be broad (remember the ϕ?); there will surely be structure above threshold in any case.

How will a narrow ψ_s decay?

(i) Two back-to-back jets from $\psi_s \to 3\gamma \longrightarrow$ hadrons?

(ii) Two (three? (6)) jets from the direct decay? Two jets is most plausible if ψ_s mixes substantially with $c\bar{c}$ states (one charmed particle per jet).

If there are no new narrow hadrons, light Z^0 or other new particles to provide excitement, one can still ask

(i) Is $R = 3\sum e_i^2 + c/(\ln s/\mu^2)$ (asymptotic freedom(7))?

(ii) Does R approach an unintelligible constant (e.g. $3\pi/2$ Oscillate? Rise or fall indefinitely?(8) These options do not seem too attractive to me.

III. PARTICLE DISTRIBUTIONS AND SPECIES

A) A NAIVE MODEL

The evidence at $\sqrt{s} \lesssim 7.4$ GeV is that $s\, d\sigma/dx$ (the inclusive single hadron distribution) scales at not too small $x = 2p/\sqrt{s}$, $\langle n_{ch} \rangle$ rises slowly, and there are jets.(9) A simple jet model(10) allows us to guess what the single particle inclusive spectrum will look like at PETRA/PEP, using present data as input. Of course, this assumes that nothing new happens. Assume:

(i) one particle and jet type,

(ii) a simple scaling jet fragmentation function $f(x) \exp(-p_T^2/\langle p_T^2 \rangle)$

where $p_T = y\,p$ is the momentum ⊥ to the jet axis.(11) Averaging over all angles of the jet and integrating over the directions of the particles we get a simple factorized formula

$$\left.\frac{x\,d\sigma}{\sigma_{\mu^+\mu^-}dx}\right|_{\sqrt{s}\ \mathrm{now}} = \left\{ v\, \frac{p^2}{\langle p_T^2 \rangle} \int_0^1 \frac{dy^2}{(1-y^2)^{1/2}}\, e^{-p^2y^2/\langle p_T^2 \rangle} \right\} \left.\frac{x\,d\sigma}{\sigma_{\mu^+\mu^-}dx}\right|_{\sqrt{s}=\infty} \qquad (4)$$

This delivers an asymptotic estimate for $x\,d\sigma/\sigma_{\mu^+\mu^-}dx$ from present data assuming

(i) all particles are pions (not a critical assumption),

(ii) $\langle p_T^2 \rangle = 0.2\ \mathrm{GeV}^2$ at all x (Fig.3 (12))

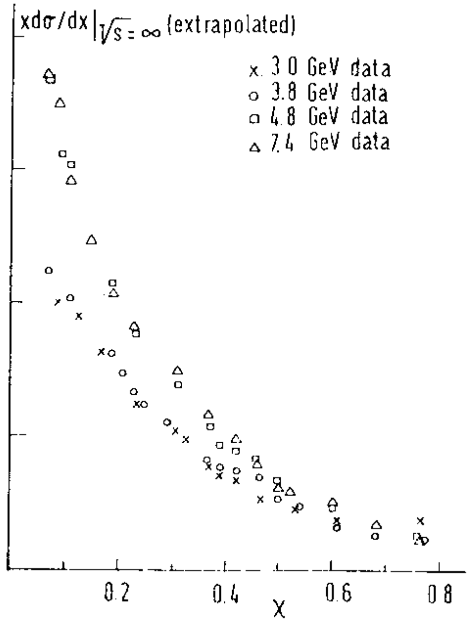


Fig. 3

Comments:

(i) The turnover of $x\,d\sigma/dx$ seen in present data is always near $p \sim .5$ GeV ($x \sim .03$ for $\sqrt{s} = 30$ GeV). Moreover in this simple model

$$\left.\frac{x\,d\sigma}{\sigma_{\mu^+\mu^-}\,dx}\right|_{\sqrt{s}=\infty} \sim 1.5 \left.\frac{x\,d\sigma}{\sigma_{\mu^+\mu^-}\,dx}\right|_{\sqrt{s}=30\,\mathrm{GeV}} \quad (x=.03) \qquad (5)$$

Scaling is a long way off at small x !

(ii) Half of $\langle n_{ch}\rangle \sim 6\text{-}8$ comes from $x \lesssim .1$ ($p \lesssim 1.5$ GeV)

(iii) Roughly every event has at least one charged particle with $x \gtrsim .3$ (i.e. has a definable jet axis). One in 3-5 events has at least one charged hadron with $x \gtrsim .5$. Without correlations perhaps one event in 10-30 might have two $x \gtrsim .5$ hadrons.

(iv) The rise in R around 4 GeV seems associated with inclusives of $x \lesssim .5$. We will use this later, assuming the rise to be due to charm production and decay. Part of the rise in R may be due to production and decay of a pair of heavy leptons.(28)

The naive model represents a "dullest case". We use it for a starter.

B) PARTICLE SPECIES

e^+e^- is a good $K\bar{K}$ source (40-50% of the events have a $K\bar{K}$ at low energy versus $\sim$10% for $p\bar{p} \rightarrow$ mesons near threshold) (13); η and baryon production are probably big, too. e^+e^- is the ideal place to make new species (charmed D mesons, cqq, ccq, ccc charmed baryons, supers carrying a new quantum number ...). What might particle distributions look like? Point (iv) above is a hint. Let's use it to construct a (speculative) physics schema:

(i) u,d,s quarks (and heavy leptons?) fragment in a one stage process to light mesons. These children populate all x .

(ii) charm quarks fragment in a two stage process: first to D + light mesons, then via a weak decay D → light mesons (plus perhaps $\ell\bar{\nu}_\ell$). The children at each stage have lower momentum than the parent and are more numerous. This populates $x \lesssim .5$.

(iii) superheavy quarks can follow the same pattern as (ii) with D replaced by S , or they can fragment as Q → S + light mesons followed by the (weak?) decay S → D + light mesons (+ $\ell\bar{\nu}_\ell$?), followed in turn by the weak decay D → light mesons (+ $\ell\bar{\nu}_\ell$). This populates very small x and produces large $\langle N_{had}\rangle$. Precedent for this chain decay scheme is the charm prediction that D → K + pions or D → K + pions + $\ell\bar{\nu}_\ell$ followed by K → pions or K → $\ell\bar{\nu}_\ell$ + pions.

This picture is the basis of what follows. It seems to me to be yet another most plausible guess, and it can be tested (see later).

B1) OLD PHYSICS AT $x > .5$

If (i) and (ii) are at least good approximations, particles with $x > .5$ come from light quarks (u,d,s; a possible heavy lepton contribution may have to be subtracted in practice). Now if this is really so, for $x > .5$

(i) U-spin gives $d\sigma(\pi^+) = d\sigma(K^+)$. Experimentally, $K/\pi = .22 \pm .08$ for $\sqrt{s} = 4.8$ GeV, $p \geq 1.1$ GeV.(14) This is not surprising, considering the large K/π mass ratio: it is probably due to SU_3 breaking. But what about PETRA/PEP energies?

(ii) SU_3 or the u,d,s quark parton model gives(8)

$$3\,d\sigma(\eta) = 2\,d\sigma(K_s) + d\sigma(K^+) \qquad (6)$$

and the parton model gives inequalities

$$2 \geq \frac{d\sigma(K_s)}{d\sigma(K^+)} \geq 2/5 \qquad 5/3 \geq \frac{d\sigma(\eta)}{d\sigma(K^+)} \geq 3/5 \qquad (7)$$

The small $\eta - K$ mass difference makes these look more promising (SU_3 breaking may be at the $\approx$ 20% level). Relations (6), (7) could still be wrong if pseudoscalars at high x are children of leading ρ, ω, ϕ, K^* (η''s are rare). We still do not know how large resonance production in e^+e^- is.

(iii) For baryons, Gribov and Lipatov(15) would lead us to expect for "direct" production related to the deep inelastic νW_2 :

$$d\sigma(n)/d\sigma(p) = \nu W_2^n(x=1/\omega)/\nu W_2^p(x=1/\omega) \qquad (8)$$

Sequential $e^+e^- \to \Lambda / \Sigma / \Xi + \cdots \to n / p + \cdots$ messes this up. For what it is worth these spoilers satisfy

$$2\,d\sigma(\Sigma^0) = d\sigma(\Sigma^+) + d\sigma(\Sigma^-) \quad \text{(isospin)}$$

$$3\,d\sigma(\Lambda) = d\sigma(\Sigma^0) + 2\,d\sigma(n) \tag{9}$$

$$4 \geq \frac{d\sigma(n)}{d\sigma(p)} \sim \frac{d\sigma(\Sigma^-)}{d\sigma(n)} \geq 1/4 \qquad 3/2\ ?\ \frac{d\sigma(\Lambda)}{d\sigma(n)} \geq 5/6$$

Again, the inputs are SU_3 and the parton model.

The moral? Particle ratios in e^+e^- jets at large x may be much less model dependent than, e.g., for large p_T jets in hadron reactions. Studies in e^+e^- may be a prelude to understanding particle ratios in high p_T jets, and are interesting for their own sake.

B2) DIRECT PHOTONS

Maybe jets contain directly produced photons not from π^0, η or η' decay. We present a simple guide. One source: in the parton model, direct photons can come from internal bremsstrahlung off a parton (Fig.4a). The background is from (4b) and is large even at $\theta_\gamma = 90^0$

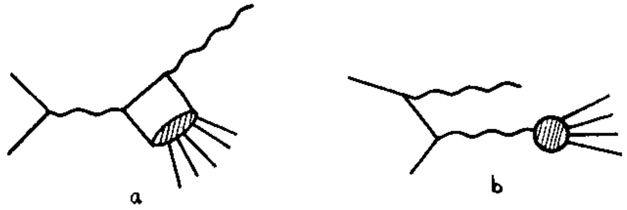


FIG.4

for $x_\gamma \geq .9$. Fig.5 shows the direct γ/π^0 ratio at $\theta_\gamma = 90^0$ for integer charge partons and $x\,d\sigma(\pi^0)/5\sigma_{\mu^+\mu^-}\,dx \approx (1-x)^2$. If this predicted large direct γ/π^0 ratio were found, it would offer still more support to the idea of pointlike constituents.

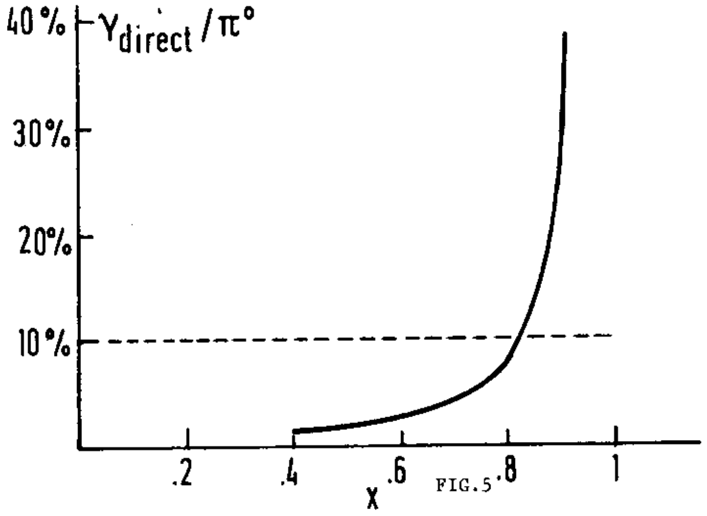


FIG.5

other sources might be copious ω ($\to \pi^0\gamma$) production, production and radiative decay of new supers, etc. All these probably populate small and intermediate x with photons.

Once D's are found, it would be interesting to know their inclusive distribution. This is relevant to understanding lepton distributions from charm in e^+e^-. Not too far above threshold we might have $E\,d\sigma/d^3p \propto \exp(-E/kT)$ (it works roughly for π, K, p). Asymptotically, the parton model would lead us to the Ansatz

$$\frac{x\,d\sigma(D)}{5\sigma_{\mu^+\mu^-}\,dx} \propto x\,D_a^D(x) \propto x^a(1-x)^b \tag{10}$$

b = 1 is favored by quark power counting, b = 2 if you appeal to $e^+e^- \to h^\pm + x$ data. Common sense tells us that the fraction of events with $2(D\bar{D}) + \ldots$ must be very small, and a = 1 ensures that $\langle n_D \rangle$ is constant. Some people might like to relate the power a to the intercept of a charmed meson Regge trajectory, but such a change won't affect the following remarks much.

Notice that the inclusive spectrum of children will fall much more steeply than that of the parent D, which is itself not very small for ≥.5 .

B4) INCLUSIVE LEPTONS

We can guess at the spectrum of leptons at high $\sqrt{s}$ from $e^+e^- \to D + \ldots \to \ell^\pm \nu_\ell + \ldots$ using the parent-child relation (16) and a few necessarily rough assumptions: (i) the D distribution is given by (10) with $a = 1$, $b = 2$, (ii) the semileptonic branching ratio is the same (15 %) as the leptonic branching ratio for a heavy lepton of the same mass, (iii) the inclusive rest frame decay spectrum is approximately the same as that of its constituent quark, $c \to s\,\ell\,\nu$ ($m_c = 1.5$ GeV, $m_s = .5$ GeV, V-A assumed). In fig. 6 we compare $e^+e^- \to D + \ldots \to \ell\,\nu + \ldots$ to the heavy lepton distribution. Of course, this is only good for illustration.

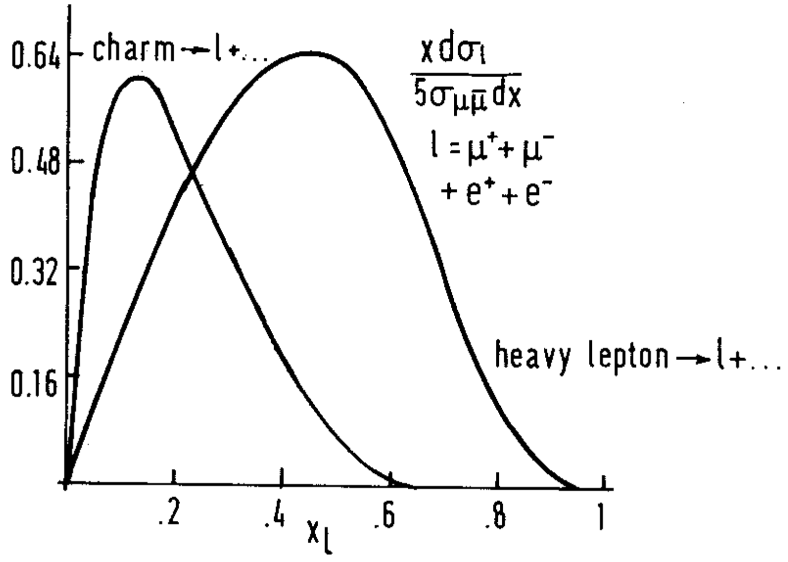


FIG.6

Note that $x d\sigma^\ell/dx$ scales and is small beyond $x = .5$ (consistent with the behavior in fig. 4 where it appears that nothing new happens for $x > .5$. In the charm scheme at least one kaon accompanies this lepton in the same jet.

B5) SUPERS

What might the effects of supers be like at PETRA/PEP? Near threshold we expect $e^+e^- \to S^+S^-$ or S^oS^o ($S^{++}\,S^{--}$?) and at higher energies $e^+e^- \to S^+S^-$ + light hadrons, S^+S^o + light hadrons, and so forth. Of course, if a new quantum number conserved by electromagnetism is involved we would not expect single production or, e.g., $e^+e^- \to S^+S^+$ + light hadrons. The two "most plausible" options (mentioned earlier) might deliver a new component to the final state hadron distributions - after the supers have decayed - like the sketch (fig. 7) (17).

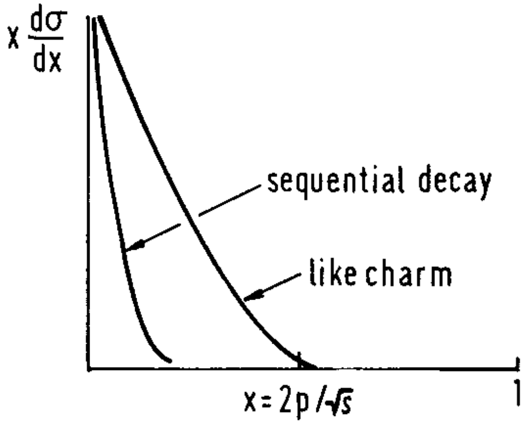


FIG.7

From experience with charm, it may be hard to find $S^\pm$, S^o in mass plots. Perhaps neutral + charged mass plots would yield something. The sequential decay case $S \to D$ + light hadrons → still more light hadrons (+ leptons?) has the striking feature that events with supers may have large multiplicity and occasionally several charged leptons per jet. Sequential decays can even lead to events with same sign leptons - in the same or opposite jets depending on the parent quark charge and the form of the weak current. Lepton distributions may be a promising way to study new quark contributions to e^+e^-. For example, correlations between strangeness, baryon number (or charm) and the sign of the lepton charge will be important.

If some super decays via a weak neutral current there is the happy possibility of finding a narrow spike in an $\ell^+\ell^-$ + charged hadrons mass plot. Then we might also find production of S in neutral current neutrino interactions $\nu_\mu N \to \nu_\mu S + \ldots$.

Still another possibility: $S^\pm$ or S^o may be long-lived (say $\tau \geq 10^{-10}$ sec). Decay inside a detector would be quite spectacular (e.g. very near threshold). If $\tau \geq 10^{-8}$ sec, seeing S^+ presents no essential problem (at least near threshold); an S^o might have to be detected by interaction or perhaps via missing energy/momentum. For S^o produced via one photon annihilation we expect that the momentum it carries off averaged over many events is roughly isotropically distributed (unlike the missing momentum arising from 2 γ processes). Looking for an S^o this way requires a measurement of the visible energy and three momentum (of course, K_L, neutrons and neutrinos then create a problem.$^{(18)}$

Still more surprising things can happen: supers might carry baryon number or, better yet, lepton number. This includes the option that these particles are integer-charged quarks. One spectacular signature here would be a narrow lepton-hadron resonance, if an unstable S has nonzero lepton number.

IV. JETS AND CORRELATIONS

A) OPTIONS

A great success of the parton model was its prediction of jets in e^+e^- annihilation $^{(8)}$ - a prediction which now appears confirmed. This prediction is closely tied to the cutoff in momentum transverse to the parton-antiparton axis and to $R = \sum e_i^2$. Perhaps it now needs emphasis that other things might happen at PETRA/PEP, quite aside from the possible existence of supers. Some options:

(i) Multiple jets (fig. 8)

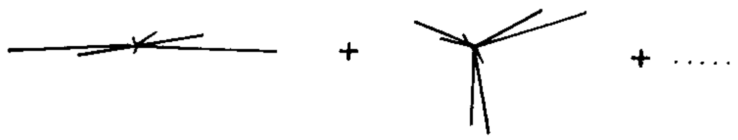


FIG.8

This sort of things was predicted six years ago by Polyakov $^{(19)}$ from a model which does not in general deliver $R = \sum e_i^2$. Perhaps the rate of multiple jet events is related to the deviation of R from its parton model value. Recently it has been shown that asymptotically $R = \sum e_i^2$ in so-called asymptotically free field theories, and a natural question is what happens to jets in such theories. Maybe the hadron final state shows multiple jet structure à la Polyakov $^{(20)}$. Maybe the "low-energy" jets simply broaden and become diffuse (see the next point). Maybe nothing at all new happens. But it will be exciting to look for qualitatively new things.

(ii) Fat jets. We know what fixed $\langle p_T^2 \rangle \sim .2$ GeV^2 jets will look like at PETRA/PEP. If it turns out that instead of $\langle p_T^2 \rangle$ being bounded $\langle \theta^2 \rangle$ is $^{(21)}$ (θ the angle of a particle relative to the "jet" axis), the events will look quite different. Fig. 9 contrasts two cases for $\alpha(p,s)$ in $d\sigma/d\Omega \propto 1 + \alpha(p,s)\cos^2\theta$ (p is the particle momentum): $\alpha = \alpha(p)$ (e.g. parton jets) and $\alpha = \alpha(x)$ (natural for fixed $\langle \theta^2 \rangle$ jets). For this case $\langle p_T^2 \rangle$ could be ~ 2 - 5 GeV^2 at PETRA/PEP.

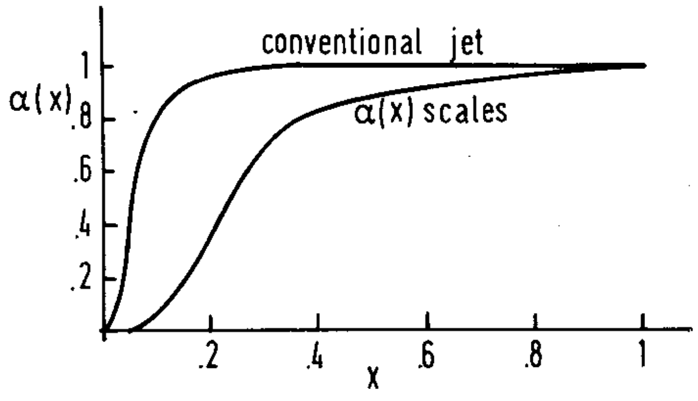


FIG.9

(iii) Unsymmetrical or finite-mass jets. The naive parton model expectation is that there will be a plateau in rapidity $y = \frac{1}{2} \ln(E + p_\parallel)/(E - p_\parallel)$ measured relative to the jet axis. Two other options (theoretically not popular) for the rapidity distribution for an event (assuming bounded p_T) are sketched in fig. 10(a) $^{(21)}$, (b). 10(b) is disfavored by SLAC-LBL data showing that jets contain few light hadron resonances (9). It also leads to $\langle N\rangle \to \text{const}$ as $s \to \infty$ and the data do not indicate this.

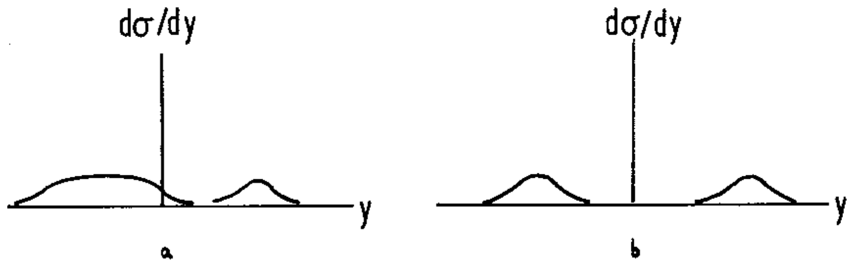


FIG.10

Where tests of these ideas involve having a plateau in y it ought to be noted that the x-distribution of fig. 3 (i.e. the low energy data extrapolated for fixed $\langle p_T^2\rangle$) converted to $d\sigma/dy$ at $\sqrt{s} = 30$ GeV looks like fig. 11 - no sign of a plateau.

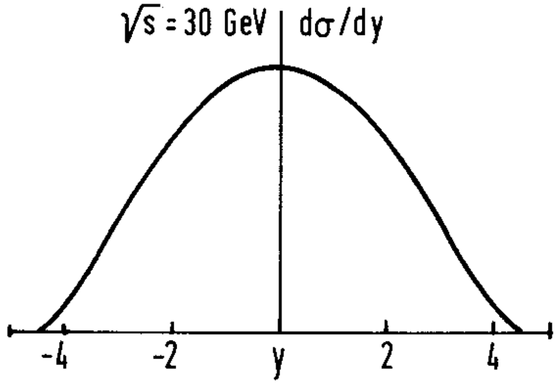


FIG. 11

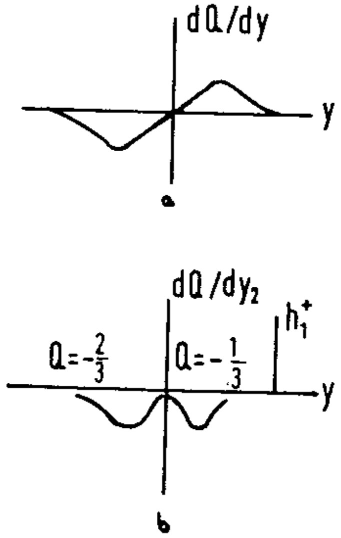
In field theories behaviors (i) or (ii) are usually connected to a scaling violation in $s\, d\sigma/dx$. (The distribution shifts to smaller x as s increases). (19) Simple jet model kinematics produces a similar effect even for bounded $\langle p_T^2\rangle$, but it dies out rapidly at high energies.(10)

(iv) No jets. Again the argument that jets and $R = \sum e_i^2$ are connected is persuasive. But it is still possible that some events which look like explosions may occur (few particles, uncorrelated in angle), or that some events may involve many low-momentum particles (a fireball). This is a theoretically least plausible option.

B) OLD PHYSICS JETS

Suppose nothing new happens. e^+e^- should still be replete with striking and important long-range correlation effects. We have the option of chasing light quark quantum numbers by triggering on a particle of $x \geq .5$ (if the earlier discussion is right (23)). There is accumulating evidence that quark quantum numbers do show up (24) (partially screened, it is true (25)) in deep inelastic processes. How can we try to exploit this? (26)

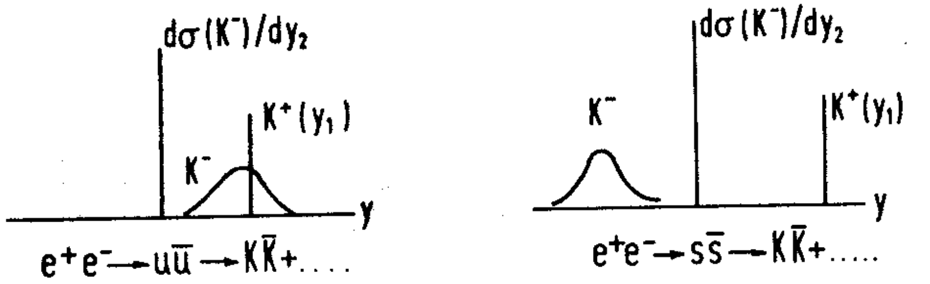
(i) Via jet charges. Suppose, as illustration, that quark charges do emerge on the average, and in the region $|y - Y_{max}| \leq 2$ with the "plateau" neutral. Globally we expect one jet to be predominantly positive, the other negative. Given enough Y_{max} the charge distribution might look like fig. 12a.



Of course, one can select that class of events with at least one particle of $x \geq .5$, if desired. Fig. 12b shows the corresponding result when there is one positive of large x. The "other side" quark has $e = -2/3$ and the remaining "same side" quark (after emission of h^+) $e = -1/3$.

These jet charges may turn out to be quite useful when looking for EM-weak interaction interference effects in $e^+e^- \to$ hadrons (e.g. via forward-backward asymmetries of the negative jet - which may, of course, come from a quark or antiquark). Unfortunately, we can't yet say how seriously the jet charges will be smeared. Fig. 11 might inspire pessimism.

(ii) Strangeness or baryon-number correlation. We expect that $K\bar{K}$ from $e^+e^- \to s\bar{s} \to K\bar{K} + \ldots$ are located in opposite jets (a long-range correlation in y); by contrast, $K\bar{K}$, from $e^+e^- \to u\bar{u} \to K\bar{K} + \ldots$ should be in the same jet or in the plateau and nearby in y. A sketch of the $K\bar{K}$ case is given in fig. 13 (particle 2 is a K^- at y_2 and particle 1 a K^+ of fixed y).



(Short range correlation)

(Long range correlation)

FIG.13

Similar correlations involving $B\bar{B}$ may occur and are of special interest. The presence of three quarks in a baryon could change the correlation picture entirely. Certainly the frequent occurrence of events with $B\bar{B}$ widely spaced in rapidity would be astounding and important (possible evidence for quark baryon number).

These are only the most striking correlation effects. The quark parton model produces a profusion of similar long-range correlations involving particles of different species $^{(27)}$. The moral here is that in order to find evidence for quark quantum numbers, one needs particle identification.

C) NEW PHYSICS JETS

So far we have assumed that the jets under study come from u,d,s quarks. Jets containing charmed particles or supers are even more interesting. Such jets may have $\langle p_T^2 \rangle$ different from light quark jets (if charm or super decays contain high-momentum particles). This can be checked by its effect on $\alpha(p,s)$ or by studying $\langle p_T^2 \rangle$ for events with <u>no</u> particle of $x > .5$ versus $\langle p_T^2 \rangle$ for events with a particle of $x > 1/2$. More spectacular: multiple jet events.

It will be very interesting to put conditions on one jet so as to ensure that the other comes from fragmentation of a selected object. For example:

(i) If heavy ($M \geq 2$ GeV) leptons exist and have no neutral current decays a heavy lepton jet constrained to have one charged lepton contains nothing else visible. If neutral current decays can go, look for cases where one jet has 3 leptons and nothing else $(L \to (Z^0 \to e^+e^-) + e^-)$.

(ii) A jet containing a direct charged lepton plus additional hadrons comes from charm (below threshold for any supers)[*]. Then the other jet arises from charmed quark fragments (see fig. 14; dashed line indicates u,d,s fragments)

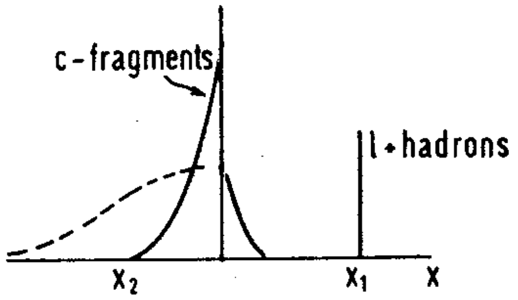


FIG.14

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[*] Ignoring possible neutral current heavy lepton decays.

(iii) If supers exist, one can try the same, demanding e.g. a jet with two leptons, or a lepton and some combination of hadrons. On the other side we expect fragments of the new heavy quarks, anno 1984.

CONCLUSION

My aim has not been to make predictions for what will happen at PETRA/PEP - that would be witless. The object of this talk was simply to illustrate new sorts of things that can happen in hadron final states. Equally striking new effects can appear from the production of new non hadrons - one need only to think about the decay modes of a 10 - 15 GeV heavy lepton to see this.
One thing we all confidently expect: e^+e^- physics at PETRA and PEP will not be dull.

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REFERENCES

1) A.M. Polyakov, JETP 32 (1971) 296; 33 (1971) 850.

2) Y. Hara, Phys. Rev. 134 (1964) B 701.
J.D. Bjorken and S.L. Glashow, Phys. Lett. 11 (1964) 255.
S.L. Glashow, J. Illiopoulos and L. Majani, Phys. Rev. D2 (1970) 1285.
Of course, much more than just charm production may be going on at present energies.

3) D. Yennie, Phys. Rev. Lett. 34 (1975) 239.

4) E.g. D. Schildknecht and F. Steiner, Phys. Lett. 56B (1975) 36 and references there.

5) This regularity has also been noticed by F. Close (private communication).

6) T. Appelquist and H.D. Politzer, Phys. Rev. Lett. 34 (1975) 43.

7) T. Appelquist and H. Georgi, Phys. Rev. D8 (1973) 4000.
A. Zee, Phys. Rev. D8 (1973) 4039.

8) J.D. Bjorken, talk at the Bonn Conference (1973).
New interactions: See the talk of J. Ellis at the London Conference (1974).

9) R. Schwitters, talk at the Stanford Lepton-Photon Conference (1975).

10) M. Gronau et al., Nucl. Phys. B104 (1975) 307 and references there.

11) H. Satz and coworkers would presumably object to the assumption of early scaling made here.

12) K. Koller and T.F. Walsh (unpublished).

13) For e^+e^- I have used twice the fraction of events with a K^- of momentum $p \gtrsim 0.7$ GeV (usually quoted as ~ 20 %); this probably underestimates the fraction of events with $K\bar{K}$. For $p\bar{p} \to$ mesons I used the data in "$N\bar{N}$ and $\bar{N}D$ Interactions - A Compilation" LBL-58 (May 1972).

14) T.L. Atwood et al., Phys. Rev. Lett. 35 (1975) 704.

15) V. Gribov and Lipatov, Sov. J. Nucl. Phys. 15 (1972) 675.

16) J.D. Bjorken and G. Farrar, Phys. Rev. D9 (1974) 1449.

17) For the "direct" decay option there is the possibility of copious production of supers in $\nu_\mu N$ or $\bar{\nu}_\mu N$ reactions (off valence quarks). For the "sequential" mode, production via neutrinos is probably small (e.g. off the $c\bar{c}$ sea).

18) I want to thank H. Meyer for a discussion on the subject of long-lived supers.

19) See ref. (1) and, e.g. J. Kogut and L. Susskind, Phys. Rev. D9 (1974) 697.

20) For a concrete proposal along these lines, see J. Ellis et al., CERN preprint.

21) G. Sterman, Illinois preprint ILL(Th)-75-32 (Dec. 1975).

22) Fig. 9(a) can arise in a chain-decay model where the heavy photon decays to a light meson or resonance and a heavy system which decays further in the same fashion. Without a p_T cutoff, this model gives multiple jets at high energy if an approximate two-jet structure occurs at low energy. Each of these multiple jets carries quantum numbers.
The model is described in:
N.S. Craigie and K.D. Rothe, Nucl. Phys.
N.S. Craigie and T.F. Walsh, Ann. Phys. 92 (1975) 340.

23) The idea can be tested (say for $\sqrt{s} \sim 7$ GeV) as follows. The spectrum of particles recoiling in the jet opposite to a hadron of $x > 0.5$ should be the same as the unfolded 3.0 and 3.8 GeV data on fig. 3 and not the same as the total single particle spectrum (the unfolded 4.8 - 7.4 GeV data). The difference should be striking.

24) R.P. Feynman, Photon-Hadron Reactions, Benjamin (1972).

25) G. Farrar and J. Rosner, Phys. Rev. D7 (1973) 2747.

26) For some data, see
F.W. Brasse, Bonn Conference (1973).
F.J. Sciulli, Caltech preprint CALT 68-520 (Oct. 1975).

27) T.F. Walsh and P. Zerwas, Nucl. Phys. B77 (1974) 494.
M. Chaichian et al., Nucl. Phys. B24 (1974) 111.

28) See, e.g. H. Harari, Stanford Lepton-Photon Conference (1975).