Implications of the Chou-Yang model for $e^+e^- \to h\bar{h}$

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Analyses of $P_\perp$ and x,z distributions of inclusive $e^+e^- \to h\bar{h}$ from experiments at the SLAC storage ring PEP at 29 GeV confirm that there is only one temperature $T = 196 \pm 7$ MeV of e^+e^- annihilation for various hadrons, as predicted by Chou and Yang. It is found that $T \propto E^{1/4}$ according to the TASSO data; its relationship with the impact parameter b sets a lower limit (for $b=0$) $T_0 \sim 106$ MeV related to the effective light-quark mass $m_q = 3, T_0 \simeq 318$ MeV. Hadron multiplicities from PEP experiments, covering ~ 3 orders of magnitude, are accounted for by a semiempirical formula derived from the Boltzmann factor with quark contents and a unique temperature $T = 196$ MeV for all hadrons under investigation.

I. INTRODUCTION

In formulating the concept of the partition temperature T_p (Ref. 1), Chou, Yang, and Yen predict that there is only one temperature T_p and only one impact parameter b for two-jet events of e^+e^- annihilation:[2]

$$e^+e^- \to \gamma^* \to q\bar{q} \to h\bar{h} \ . \tag{1}$$

Clearly, there is a correlation between T_p and b, since they depend only on $E_{\rm c.m.}$, abstraction being made of the hadron mass. An attempt is therefore made to investigate this point, together with the following question: How do we account for multiplicities of various hadrons of (1) covering almost 3 orders of magnitude as shown in Fig. 4 below, and assuming only one temperature as predicted by Chou and Yang?[2]

We notice that this important property of "only one temperature for e^+e^- annihilation" holds also for the conventional temperature T (Ref. 3), using the transverse momentum $P_\perp$ instead of the longitudinal momentum $P_\parallel$ as in the case of the partition temperature, and that the appropriate Boltzmann factor for our purpose is

$$f \sim e^{-(E - bP_\parallel)/T} , \tag{2}$$

which was introduced by Fermi to describe the angular distribution of secondaries of cosmic-ray jets.[4]

In this paper, we present results of a further analysis[5] of experiments at the SLAC e^+e^- storage ring PEP at $E_{\rm c.m.} = 29$ GeV (Refs. 6–8). We estimate the temperature T (Sec. II) and the impact parameter b (Sec. III) for $\pi, K, \ldots$ and Ω, using distributions of $P_\perp$ and x,z, respectively. We then discuss the equipartition property in the fireball (FB) system, its velocity being determined by b (Sec. IV), see the Appendix. For the charged multiplicities of hadrons of (1), we will use a semiempirical formula [Eq. (12)] derived from the Boltzmann factor (2), including quark contents of the hadron and assuming a unique T (Sec. V). The energy dependence of T and b will be investigated by using the π data of the TASSO Collaboration[9] (Sec. VI). We find $T \sim E_{\rm c.m.}^{1/4}$, suggesting that the hadrons from e^+e^- annihilation (1) behave like an ideal gas (Sec. VI). Furthermore, a simple expression [Eq. (14)] is found to relate b to T [see Fig. 5(b)]; it has a constant which sets a minimum temperature $T_0 \sim 106$ MeV, corresponding to $b=0$, i.e., FB at rest (Sec. VII), it reflects the mass of light quarks $m_q = 3T_0 \sim 318$ MeV, constituent of hadrons. Remarks will be made on the properties of T, unique independent parameter of e^+e^- annihilation (1) as well as conservation of strange number in the Ξ and Ω production by e^+e^- annihilation (Sec. VIII).

II. TEMPERATURE ESTIMATION

Consider first the $P_\perp$ distribution according to the Boltzmann factor (2). As $P_\perp$ is invariant, we may use the fireball (FB) system, characterized by an isotropic angular distribution, i.e., $b=0$ (see the Appendix), to get

$$\frac{d\sigma}{dP_\perp^2} \sim \int_0^\infty e^{-E/T} dP_\parallel = m_\perp K_1(m_\perp/T) \sim \sqrt{m_\perp} E^{-m_\perp/T} , \tag{3}$$

where $m_\perp = (P_\perp^2 + m^2)^{1/2}$ and the Bessel function $K_1(x)$ has been approximated by $\sqrt{2/\pi x}\, e^{-x}$. Note that the integral is taken over a three-dimensional phase space as is required by the flux conservation of particles under consideration.[10] The validity of this $P_\perp$ distribution (3) has been tested for various hadrons of e^+e^- annihilation[11(a)] as well as other hadron collisions.[11(c)]

We have analyzed $P_\perp$ distributions of inclusive $e^+e^- \to h\bar{h}$ at 29 GeV of the Mark II Collaboration[6] and the TPC Collaboration[7] using (3) for $P_\perp \le 2$ GeV/c corresponding to $\sim 3\langle P_\perp \rangle$ of baryons of these experiments. The details of our analysis have been reported elsewhere;[5(b)] we recall that, for π's, we have to assume $m_\pi \ne 0$ so that the cross section derived from (3) remains finite as is required by the multiplicity formula, Eq. (12) (Sec. V).

The estimates of T are shown in Fig. 1. The dotted straight line represents the average T, excluding Ξ for reasons discussed in a previous paper:[5(b)]

$$\bar{T} = 196 \pm 7 \text{ MeV} .$$

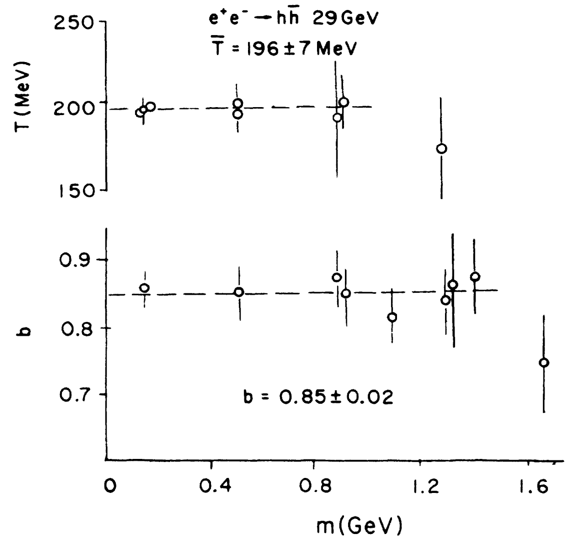

FIG. 1. Plots of temperature T (MeV) and impact parameter b, in units of effective radius, see text, according to $P_\perp$ and z distribution of $e^+e^- \to h\bar{h}$ at 29 GeV, using data of the Mark II, TPC, and HRS Collaborations, Refs. 6–8.

Note that all the measured temperatures deviate very little from the average, which is essentially the temperature of π, indicating that there is only one temperature for e^+e^- annihilation as predicted by Chou, Yang, and Yen[1] We shall discuss its important properties, such as energy dependence and relationship with b in Secs. VI and VII.

III. THE IMPACT PARAMETER

With regards to the parameter b of the Boltzmann factor (2), it has the important property that the angular distribution depends only on b [Appendix, Eq. (A5)]. Furthermore, there is resemblance between the angular distribution of $e^+e^- \to h\bar{h}$ of the TASSO data,[9(b)] Fig. 6 below, and that of inclusive $pp \to \pi^-$ of a previous analysis.[12(b)] Therefore, just as in the pp case, we regard b as an impact-parameter expressed in terms of the effective radius $R=\sqrt{\sigma/\pi}$, where for reaction (I) $\sigma=\sum Q_i^2(4\pi\alpha^2/3s)$, Q_i being the quark charge and $\alpha=e^2/hc=\frac{1}{137}$.

Because of lack of data of angular distributions of identified $\pi, K, \ldots$ of (1), we have to use the x or z distribution to estimate b. Noting that in the c.m. system (c.m.s.), $P_\parallel \gg m$, we may neglect m and get

$$\frac{d\sigma}{dP_\parallel} \sim \int_0^\infty f\, dP_\perp^2 = T^2\left[1+\frac{P_\parallel}{T}\right]e^{-(1-b)P_\parallel/T} \qquad (4)$$

and, in terms of the scaling variable $x \equiv 2P_\parallel/\sqrt{s}$,

$$a \equiv (1-b)\sqrt{s}\,/2T \qquad (5)$$

so that

$$\frac{d\sigma}{dx} = Axe^{-ax}\ . \qquad (6)$$

Likewise, for the radial scaling variable $z=2E/\sqrt{s}$,

$$\frac{d\sigma}{dz} = \frac{d\sigma}{dx}\frac{E}{P_\parallel}\ , \qquad (7)$$

so that the Jacobian $E/P_\parallel$ is only important for heavy particles near the origin (cf. below).

We now proceed to analyze the $e^+e^- \to \pi^+\pi^-$ data of the Mark II Collaboration,[6(d)] reproduced in Fig. 2; they represent mostly pions including some decay particles of K and Λ. We have to divide the data into two parts in order to separate the fragmentation jet from the central region as described in a previous work.[5(a)] The fit for $x \geq 0.2$ yields $a=10.3\pm0.39$, and $A=(1.115\pm0.280)\times10^5$. For $x<0.2$ we subtract the data from the extrapolation of the previous fit and fit again the remainder with (6); we get $a'=36.7\pm1.4$ and $A'=(3.48\pm0.67)\times10^6$. The result is shown in Fig. 2.

We have analyzed other hadron data of PEP experiments[6–8] by setting $x,z \geq 0.2$. As illustrations, the fits for Λ, Ξ, and Ω of the Mark II Collaboration[6(b)] are shown in Fig. 3.

Knowing a, we deduce the impact-parameter b by (5) assuming $T=196$ MeV. The results thus obtained, in terms of the effective radius R as mentioned above, are presented in Fig. 1. The average, excluding Ω, is shown by the dotted line:

$$\bar{b}=0.85\pm0.02\ .$$

Here too, we find only one impact parameter for all hadrons of e^+e^- annihilation as expected from the prediction by Chou and Yang.[2]

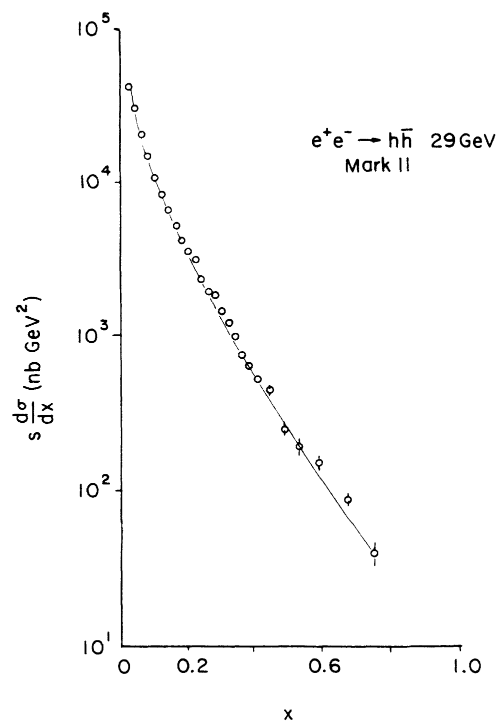

FIG. 2. x distribution of $e^+e^- \to h\bar{h}$ at 29 GeV, Mark II data, Ref. 6(d). The curve is the result of two fits with Eq. (6) for $x<0.2$ and $x \geq 0.2$, see text.

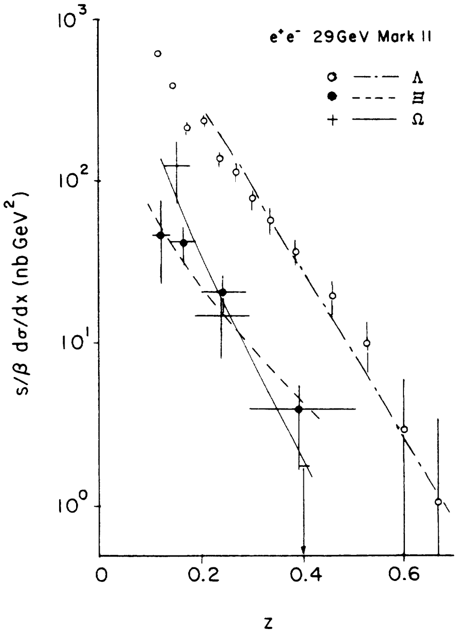

FIG. 3. z distributions of Λ, Ξ, and Ω from e^+e^- annihilation at 29 GeV. Mark II data, Ref. 6(b). The curves are fits with Eq. (7).

IV. EQUIPARTITION IN THE FIREBALL SYSTEM

We now investigate the properties of kinematics of (1) in the fireball (FB) system, namely, *rest frame* of hadrons of the same hemisphere, e.g., $x>0$, moving along the jet axis with a velocity β (in units of $c=1$) with respect to the c.m.s. If we transform the energy E of a hadron of mass m to the FB system, $E^*=\gamma(E-\beta P_\parallel)$, and assume that the temperature transforms as $T^*=\gamma T$, we then get[12]

$$\frac{E-\beta P_\parallel}{T}=\frac{E^*}{T^*} \tag{8}$$

so that (2) represents the covariant Boltzmann factor by substituting

$$b \to \beta \tag{9}$$

indicating that the angular distribution of hadrons in c.m.s. and the FB velocity are related. Note that in the FB system, $b=0$ and $\gamma=1$, the Boltzmann factor becomes $e^{-E^*/T}$ with this characteristic feature of isotropic angular distribution, whereas the temperature determined by $P_\perp$ remains as invariant. We note, in passing, that the same Lorentz transformation of T mentioned above has recently been used by Li and Young in their application of the partition-temperature model[1] to hadron-nucleus reactions.[13] Thus, the property of one temperature T and one impact parameter b for hadrons of e^+e^- annihilation (1) implies, in turn, equipartition of energy in the FB system defined by (9); namely, a hadron of mass m acquires, in average, an energy according to (3):

$$E^*=3T+mK_1(m/T)/K_2(m/T) . \tag{10}$$

As a check of this property, consider in particular the $d\sigma/dz$ distributions of Ξ and Ω in Fig. 3. Note that here, the minimum of z corresponding to the lower edge of the first bin is not an experimental bias, since the corresponding decay mean free path $l=\tau cP/m$ exceeds the cutoff 15 mm for the vertex reconstruction of the Mark II detector,[6(c)] cf. l presented in Table I. As for Λ, we must use the average $z_{\min}$ of three PEP experiments by the Mark II, Time Projection Chamber (TPC), and High Resolution Spectrometer (HRS) Collaborations.[14] The values of l and $z_{\min}$ are summarized in Table I, effects due to decay Λ from Σ, Ξ, and Ω being negligible.

We turn now to the kinematics of hyperons listed in Table I. We find that their velocities in the FB system $\beta^*=P^*/E^*$ computed according to (10) are less than the FB velocity $\beta=0.85$. Consequently, their momentum in the c.m.s. is always positive, the minimum being

$$P_{\min}=\gamma(\beta E^*-P^*) . \tag{11}$$

We may neglect $P_\perp$ and approximate $P_\parallel \equiv P^*$, and compute the corresponding $z_{\min}=2_x\, E_{\min}/E_{\text{c.m.}}$; the results are listed in Table I for comparison with the experimental values in the same table. We find good agreement; this justifies *a posteriori* our parametrization of the temperature T and the impact parameter b using the Boltzmann factor (2).

V. HADRON MULTIPLICITIES

As another crucial test of our estimation of T and b, we propose to analyze the multiplicities of various hadrons observed in e^+e^- annihilation,[15] by considering especially $\pi, K, p, \ldots, \Omega$ of light quarks. For this purpose we use a semiempirical formula based on the Boltzmann factor (2) with quark contents as follows:

TABLE I. Characteristics of the $z=2E/E_{\text{c.m.}}$ distributions of Λ, Ξ, and Ω in Fig. 3. β^* is the hyperon velocity in the FB system, see text. Mark II data, Ref. 6(b).

Particle	β^*	Decay mean free path c.m.	$z_{\min}$ Experimental	$z_{\min}$ Computed
Λ	0.65	5.7	0.09[a]	0.09
Ξ	0.61	3.2	0.11	0.11
Ω	0.53	2.5	0.13	0.13

[a]Average of PEP experiments, see text.

$$n = \frac{C_2}{1-b} \frac{e^{\Gamma/T}}{(2I+1)(2J+1)} T^3 \left[\frac{m}{T}\right]^2 K_2 \left[\frac{m}{T}\right] u^\lambda s^\mu \ , \tag{12}$$

where λ and μ are numbers of u/d and s quarks of the hadron of mass m, the factors involving T and b as well as the spin J and the isospin I are from (2), the exponential factor containing the decay width Γ is due to the resonance enhancement;[16] $\Gamma=0$ for stable particles, and the coefficient C_2 refers to particle-antiparticle (albeit charged multiplicity) such as $\pi^+\pi^-, p\bar{p}$, etc., so that $C_2 \to C_2/2$ for K^+K^-, $K^{0*}\bar{K}^{0*}, \ldots$ to account for their associated production and likewise for self-charge conjugate particles such as $\phi = s\bar{s}$, etc. A detailed discussion of this simple formula has been reported elsewhere.[5(b)] Here, we note that $n=\infty$ for $m=0$, so that we have to keep $m_\pi \neq 0$ as mentioned above (Sec. II).

For the charged multiplicity of PEP experiments at 29 GeV, we recall that

$$T=0.196 \text{ GeV}, \quad b=0.85$$

and that we have chosen, as reported before,[5(b)]

$$u=0.55, \quad s=u/2, \quad C_2=1.16\times 103 \text{ GeV}^{-3} \ .$$

The values of n thus computed for $\pi, K, \ldots, \Omega$ are shown in Fig. 4.

A comparison with the charged multiplicities of Mark II (Ref. 6), TPC (Ref. 7), and HRS (Ref. 8), experiments plotted in the same figure indicates that except for Ω, the agreement is very satisfactory, covering a range of ~ 3 orders of magnitude. This gives strong feeling that indeed "there is only one temperature for e^+e^- annihilation" as predicted by Chou and Yang.[2]

Finally, we mention in passing that an attempt has been made to extend this semiempirical formula (12) to charmed particles as has been reported previously.[5(b)]

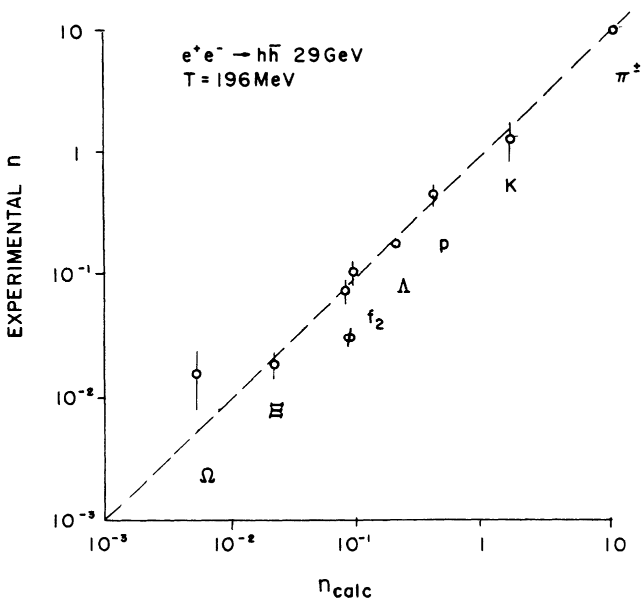

FIG. 4. Hadron multiplicities of $e^+e^- \to h\bar{h}$ at 29 GeV, data of PEP experiments, Refs. 6–8, plotted against computed multiplicities using a semiempirical formula Eq. (12) based on the Boltzmann factor (2) with quark content of h and assuming $T=196$ MeV for all hadrons, see text.

VI. ENERGY DEPENDENCE OF T AND b

We now investigate the energy dependence of the parameters T and b. We have seen that their estimates depend mainly on the π data (Fig. 1). Therefore, we have to consider only the case of $e^+e^- \to \pi^+\pi^-$ at 14, 22, and 34 GeV of the TASSO Collaboration.[17] We use the same criteria as for the PEP data, namely, $m_\pi = 140$ MeV and cutoff $P_\perp \leq 2$ GeV/c for T (Sec. II) and $x \leq 0.2$ for b (Sec. III). The results are shown in Figs. 5(a) and 5(b).

Consider first the behavior of T. Assuming a power law in $E_{\text{c.m.}}$ (GeV)

$$T\ (\text{MeV}) = A E_{\text{c.m.}}^{a} \tag{13}$$

we find

$$a=0.248\pm0.002, \quad A=87.5\pm0.6 \ .$$

The fit is shown by the solid line in Fig. 5(a).

It is interesting to note that a is very close to $\frac{1}{4}$ as in the case of Stefan's law. This implies that the chemical

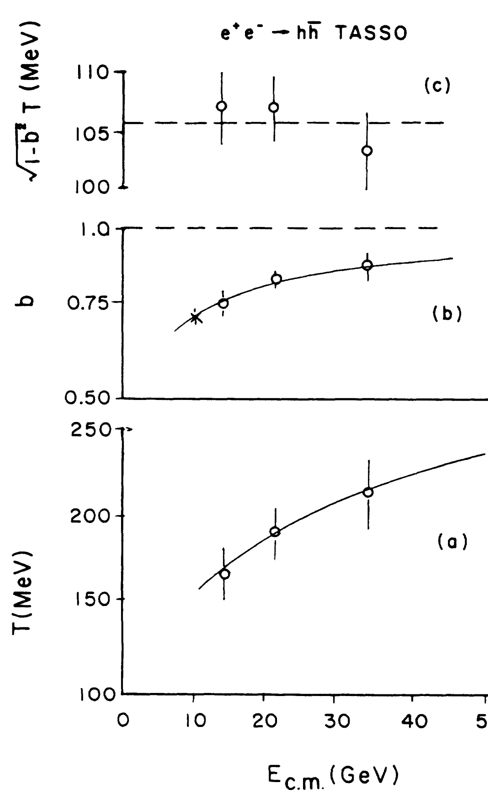

FIG. 5. Energy dependence of T and b for $e^+e^- \to h\bar{h}$ ($m_\pi = 140$ MeV) of the TASSO Collaboration, Ref. 9. (a) Plot of the fit $T \propto E_{\text{c.m.}}^{1/4}$, (b) Behavior of b according to the relationship Eq. (14) implied by *only T and only one b* for $e^+e^- \to h\bar{h}$ as shown in (c), see text.

potential μ_π of π is negligible, so that the pions actually do behave like a photon gas.[18]

As regards other hadrons, we note that if we generalize (2) to include the chemical potential μ_h, this amounts to changing the coefficient $C_2 \to C_2 e^{\mu_b/T}$. But in a previous analysis of various multiplicities of $e^+e^- \to h\bar{h}$ using (12), it has been found that the coefficient C_2 as defined in (12), is actually constant, independent of the hadron h under consideration.[5(b)] This result agrees with what has been found: $\mu_\pi \simeq \mu_K$ for π and K production by pp collision at 12 GeV/c [Ref. 11(b)]. It is therefore unnecessary to specify explicitly the chemical potential in our semiempirical formula (12), notwithstanding that $\mu^\lambda s^\mu$ actually represents the fugacity of the hadron.

Turn now to the behavior of b, Fig. 5(b). Clearly, it is different from T [Fig. 5(a)]; the curve represents Eq. (14) below, i.e., a relationship between the two parameters T and b, an important property of the Chou-Yang prediction to be discussed in the next section.

VII. RELATIONSHIP BETWEEN T AND b

We have estimated T using the $P_\perp$ distribution and studied (Sec. IV) its property in the FB system whose velocity is determined by the $P_\parallel$ distribution in the c.m.s., $\beta = b$. Now we may regard the FB as a rest frame of hadrons and transform T back to the c.m.s. In other words, let us consider the ratio T/γ of the TASSO data we have analyzed in the previous section. We find T/γ practically constant as is shown in Fig. 5(c).

Thus we are led to consider the following relationship:

$$b = [1-(T_0/T)^2]^{1/2} , \qquad (14)$$

T_0 being a constant. From the TASSO data, we get

$$T_0 = 106 \pm 2 \text{ MeV} .$$

Note that $b \to 1$ as $E_{\text{c.m.}} \to \infty$ as it should.

This relationship (14), together with Stefan's law (13), enables us to predict the behavior of the impact parameter b. The result is shown by the solid curve in Fig. 5(b). As a further check, we have used the CLEO data at 10.5 GeV for $e^+e^- \to \pi$, K, p, Λ, and Ξ (Ref. 19). As no $P_\perp$ are available, we estimate $T \simeq 150$ MeV by (13) and obtain for the average $b = 0.68 \pm 0.01$, shown by the cross in Fig. 5(b). We find all the values of b in good agreement with the prediction according to (14).

As regards the physical meaning of the constant $T_0 = 106$ MeV of the relationship between T and b, Eq. (14), we note that it sets a lower limit to the temperature T of e^+e^- annihilation. Indeed, in the case $T = T_0$, $b = 0$, the FB is at rest, i.e., the same as the c.m.s.; corresponding to an energy $E_{\text{c.m.}} = 2.14$ GeV, above the threshold of nucleon-antinucleon production: $e^+e^- \to p\bar{p}$. Furthermore, we may relate this temperature T_0 to the mass of quarks constituting the hadrons of e^+e^- annihilation. Assuming that the light quark has no intrinsic mass, we find, for its average energy according to (10),

$$E_q = 3T_0 \simeq 318 \text{ MeV} ,$$

comparable to the effective mass of quarks constituent of hadrons observed in e^+e^- annihilation.

Finally, we note that T_0 is almost half the critical temperature $T_c \simeq 200$ MeV of quark-gluon plasma.[3] It would be interesting to know if this is due to some quantum effect.

VIII. CONCLUDING REMARKS

To sum up, our analyses of hadrons of the PEP experiments[6-8] indicate that there is only one temperature T for $e^+e^- \to h\bar{h}$ as predicted by Chou and Yang.[2] We find $T \approx E_{\text{c.m.}}^{1/4}$ using the TASSO data[9] and a relationship, Eq. (14), between T and the impact parameter b, the latter determining as well the velocity of the fireball system, where equipartition of energy as well as long-range correlation among hadrons, as in the case of a mixture of perfect gasses, has taken place. It follows that the charged-particle multiplicity is Poissonian as has been observed experimentally.

The multiplicity of $\pi, K, \ldots, \Omega$ of the PEP experiments[6-8] are accounted for by a semiempirical formula, Eq. (12), based on the Boltzmann factor (2) with quark contents of the hadron. The good agreement between the computed and the experimental values, with only one temperature $T = 196$ MeV justifies our parametrization of T using (3) and a cutoff $P_\perp \le 2$ GeV/c mentioned in Sec. II. It is imperative to know if the behavior $T \approx E_{\text{c.m.}}^{1/4}$ still holds at higher energies.

The relationship Eq. (14) between T and b sets a minimum temperature equal to $T_0 = 106$ MeV, leading to a light-quark mass $m_q = 3T_0 \simeq 318$ MeV. This property is characteristic of "only one temperature" for e^+e^- annihilation. For pp interaction, e.g., we know that Stefan's law holds approximately, whereas the kinematics of the FB is such that $\gamma \simeq \sqrt{E_{\text{c.m.}}}$ [Refs. 11(c) and 11(d)] therefore the ratio T/γ is no longer constant as it is for e^+e^- annihilation.

Finally, we note that in the Mark II data of $\Xi/\bar{\Xi}$ and $\Omega/\bar{\Omega}$ [Refs. 6(a) and 6(b)] only a single hyperon has been identified.[20] The following question arises: how is the strangeness conserved in e^+e^- annihilation? Namely, when a primary antiquark $\bar{s}$ fragments, e.g., into an $\bar{\Xi}$ together with some other nonstrange hadrons, does the other primary s quark give rise to a Λ and a $\bar{K}$ rather than a Ξ? It would be interesting to investigate this point as far as particle-antiparticle conservation is concerned.

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APPENDIX

We discuss another physical meaning of the dimensionless parameter b of the Boltzmann factor (2) from the

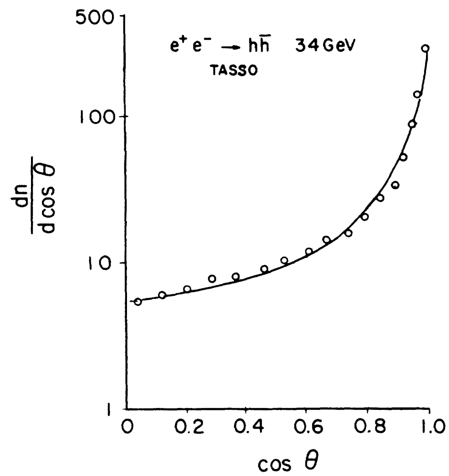

FIG. 6. Angular distribution of charged particles from e^+e^- annihilation at 34 GeV. TASSO data, Ref. 9. The curve is the fit with Eq. (A5), see the Appendix.

viewpoint of the angular distribution of hadrons in the c.m.s. of e^+e^- annihilation (1). For this purpose, we rewrite (2) in terms of another parameter λ, which has been used to describe Feynman-Yang scaling:[12] namely,

$$E - bP_{\parallel} = (P_{\perp}^2 + \lambda^2 P_{\parallel}^2 + m^2)^{1/2} \ . \tag{A1}$$

In the high-energy limit, $P_{\parallel} \approx E$, we get

$$1 - b = \lambda \ . \tag{A2}$$

Thus, instead of (2), we may use

$$f \sim \exp[-(P_{\perp}^2 + \lambda^2 P_{\parallel}^2 + m^2)^{1/2}/T] \tag{A3}$$

and obtain

$$\langle P_{\perp} \rangle / \langle P_{\parallel} \rangle = \frac{\pi}{2} \lambda \tag{A4}$$

indicating that $\lambda = 1$ corresponds to an isotropic angular distribution, whereas $\lambda < 1$ measures the anisotropy, so that $b \leq 1$ according to (A2).

If θ denotes the hadron angle in the c.m.s. with respect to the jet axis, we find, by neglecting the mass,

$$\frac{d\sigma}{d\cos\theta} \sim \frac{1}{[1-(1-\lambda^2)\cos^2\theta]^{3/2}} \tag{A5}$$

and

$$\langle |\cos\theta| \rangle = \frac{1}{1+\lambda} = \frac{1}{2-b} \ . \tag{A6}$$

The validity of this distribution (A5) has been tested using inclusive $pp \to \pi^-$ at $P_{\text{lab}} = 205$ GeV/c [Ref. 12(b)]. Note that the angular distribution (A5) depends only on b, so that we may interpret b as an impact parameter as in the Fermi model.[4]

We now apply (A5) to the angular distribution of charged particles from e^+e^- annihilation at 34 GeV of the TASSO Collaboration.[9(b)] Their data are shown in Fig. 6, together with the fit. We find $\lambda = 0.14 \pm 0.02$ leading to $b = 0.86 \pm 0.02$ in agreement with the average $b = 0.85 \pm 0.02$ in agreement for $\pi, K, p, \ldots$ estimated from the α distributions.

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[10]See, e.g., J. Synge, *Relativistic Electron Gas* (North-Holland, Amsterdam, 1957), p. 61.

[11]T. F. Hoang, (a) Z. Phys. C **18**, 19 (1983); (b) Phys. Rev. D **6**, 1328 (1971); (c) **19**, 147 (1979); (d) **24**, 1406 (1981).

[12]For a discussion on the covariance of the Boltzmann factor, and an alternative form relating the scaling property, we refer to a previous work: (a) T. F. Hoang, Phys. Rev. D **12**, 296 (1975); (b) T. F. Hoang and K. K. Phua, *ibid.* **17**, 927 (1978).

[13]T. S. Li and K. Young, Rev. Phys. D **34**, 142 (1987).

[14]See, e.g., P. Baranger *et al.*, Phys. Rev. Lett. **56**, 1346 (1986), Fig. 2. It should be noted that the TASSO data in their figure are of different energy, and therefore not to be compared with the PEP data.

[15]For a survey, see, e.g., H. Yamamoto, in *Proceedings of the 1985 International Symposium on Lepton and Photon Interactions at High Energies*, Kyoto, Japan, 1985, edited by M. Konuma and K. Takahashi (Research Institute for Fundamental Physics, Kyoto University, Kyoto, 1986), p. 50; LBL Report No. 20749 (unpublished).

[16]This factor is deduced from the decay factor $e^{-\Gamma\tau}$ by replacing the characteristic strong decay time τ by $1/T$.

[17]TASSO Collaboration, M. Althoff *et al.*, Z. Phys. C **27**, 27 (1985).

[18]L. D. Landau, Izu. Akad. Nauk. SSSR Ser. Fiz. **17**, 53 (1953).

[19]CLEO Collaboration, S. Behrends *et al.*, Phys. Rev. D **31**, 2161 (1986).

[20]S. Klein (private communication).