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THE RATIO OF CHARGED-TO-TOTAL ENERGY IN HIGH-ENERGY PROTON-PROTON INTERACTIONS

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The ratio of charged-to-total energy in multiparticle hadronic systems produced in pp interactions has been measured. The analysis has been performed using our technique of subtracting the "leading" baryon effects. The results are compared with e^+e^- annihilation data.

Long ago the "energy crisis" [1] was reported in the multiparticle hadronic systems produced in low-energy e^+e^- annihilation [2]. This crisis was due to the fact that, on the average, the total energy associated with the charged particles $\langle E_{\text{charged}} \rangle$ was measured to be $\approx 50\%$ of the total energy:

$$\alpha_{e^+e^-} = [\langle E_{\text{charged}} \rangle / \langle E_{\text{total}} \rangle]_{e^+e^-} = 50\%, \quad (1)$$

the quantity E_{total} being known from the energy of the colliding beams. Interest in the energy crisis was obviously based on the suspicion that some new channel could contribute to the "missing" charged component of the total energy available for particle production in e^+e^- annihilation. Even more puzzling was the hypothesis that some neutral energy could have been carried away by neutrinos.

The crucial point however was, and still is, that the value of the ratio $\alpha_{e^+e^-}$ characterizes the multiparticle hadronic systems produced in e^+e^- annihilation. It is therefore of great interest to measure the value of the analogous quantity,

$$\alpha_{\text{pp}} = [\langle E_{\text{charged}} \rangle / \langle E_{\text{total}} \rangle]_{\text{pp}}, \quad (2)$$

for multiparticle systems produced in hadronic inter-

actions. No such measurements have ever been attempted in hadronic physics, mainly because the effects of the "leading" hadrons had never been correctly taken into account.

We report here the measurement of α_{pp} performed in pp interactions once the leading proton effects have been removed. In this case the denominator of eq. (2), the total energy available for particle production, is in fact:

$$\begin{aligned} \langle E_{\text{total}} \rangle &= m_{12} \\ &= [(E_{\text{had}_1} + E_{\text{had}_2})^2 - (\mathbf{p}_{\text{had}_1} + \mathbf{p}_{\text{had}_2})^2]^{1/2}, \end{aligned} \quad (3)$$

where $E_{\text{had}_{1,2}}$ and $\mathbf{p}_{\text{had}_{1,2}}$ are the energy and momentum associated with the hadronic system produced by the incident protons 1 and 2, respectively. As we already pointed out elsewhere [3,4], E_{had} is simply obtained as the energy difference between the incident proton and the outgoing leading proton:

$$E_{\text{had}} = E_{\text{inc}} - E_{\text{leading}}.$$

The measurement of this quantity would otherwise need a calorimetric device with all its complications and limitations.

Analogously, p_{had} is given by

$$p_{\text{had}} = p_{\text{inc}} - p_{\text{leading}}$$

The indexes 1 and 2 for m_{12} in eq. (3) refer to the two hemispheres of the event. The quantity m_{12} is then the invariant mass of the pp final state where the two leading protons have been subtracted.

The data presented in this paper have been collected at the CERN Intersecting Storage Rings (ISR) with the Split-Field Magnet (SFM) facility [5], a set-up which consists mainly of a powerful system of multi-wire proportional chambers (MWPCs) in a large-volume magnetic field.

The results have been obtained in pp interactions at $\sqrt{s} = 62$ GeV by analysing a sample of about 7000 "minimum bias" events, where at least one leading proton was selected with $0.44 < x_F < 0.84$ ($x_F = 2p_L/\sqrt{s}$, where p_L is the longitudinal momentum of the fastest positively charged particle in each hemisphere). Out of this sample, about 250 events contained two leading protons in the above x_F interval. All charged particles were required to originate from the reconstructed event vertex and to have $\Delta p/p < 30\%$, the average $\Delta p/p$ over all tracks being $\approx 7\%$. The vertex was required, in turn, to lie in the beam-crossing fiducial volume. For the leading proton, the condition on the momentum uncertainty was $\Delta p/p < 6\%$, the average value being $\Delta p/p \approx 4\%$. The visible charged energy had, on the average, an error of $\Delta E/E \approx 5\%$. Corrections for track losses caused by reconstruction in efficiency have been calculated and tested for the various topologies via Monte Carlo simulation.

The visible charged energy was first determined from the momentum measurements, assuming all particles to be π 's. Using the latest results of charged particle ratios ($\approx 85\% \pi^\pm$, $\approx 10\% K^\pm$ and $\approx 5\% p^\pm$) measured at the ISR [6], the value of α_{pp} increases by $\approx 3\% \pm 1$. There is also a correction due to K_S^0 decays producing $\approx 3\%$ of the total charged multiplicity, as derived from a Monte Carlo simulation, which compensates the above increase.

In fig. 1, the value of $\alpha_{\text{pp}} = \langle E_{\text{charged}} \rangle / \langle m_{12} \rangle$ is given for different m_{12} bands, covering the energy range from 10 to 34 GeV (this corresponds to the selected x_F range of our experiment). Such a fraction, α_{pp} , is constant versus m_{12} , with an average value

⁺¹ Using the recent results on particle ratios measured at PETRA [7], the increase of α_{pp} would be $\approx 4\%$.

$$\bar{\alpha}_{\text{pp}} = 0.57 \pm 0.07 \quad (4)$$

Notice that the errors appearing in fig. 1 are partly due to systematic effects, the statistical errors being $\approx 5\%$ only.

In order to take advantage of the higher statistics sample of one-proton events, we can use the standard technique, already described in previous publications [3,4]. In this case, only the hemisphere with the leading proton is analysed. The denominator of eq. (2) becomes E_{had} . The study of $\alpha_{\text{pp}} = \langle E_{\text{charged}} \rangle / \langle E_{\text{had}} \rangle$ follows the same chain of analysis as the two-proton case.

Fig. 2 shows the detailed values of α_{pp} in the different E_{had} bands. Notice that E_{had} is multiplied by 2, since $2E_{\text{had}}$ allows a straightforward comparison with the previously used total energy of m_{12} . Here the statistical errors are $\approx 1.5\%$ only. The average value of α_{pp} , over the total range of E_{had} , is

$$\bar{\alpha}_{\text{pp}} = 0.57 \pm 0.04 \quad (5)$$

This value is in remarkable coincidence with that measured in terms of m_{12} [formula (4)].

It has been checked, by means of a Monte Carlo simulation program, that our set-up would measure $\bar{\alpha}_{\text{pp}} = 2/3$, both in the two-proton and in the one-proton case, if pp interactions were to produce only ($\pi^+ \pi^- \pi^0$).

From the comparison of fig. 1 and fig. 2, we observe that the two different ways of evaluating the total energy available for particle production in the whole pp event, m_{12} , and in half of the event, $2E_{\text{had}}$, respectively, provide identical results in terms of $\bar{\alpha}_{\text{pp}}$. Moreover, from the measured value of $\bar{\alpha}_{\text{pp}}$ it is possible to derive the "missing" neutral energy α_{pp}^0 associated

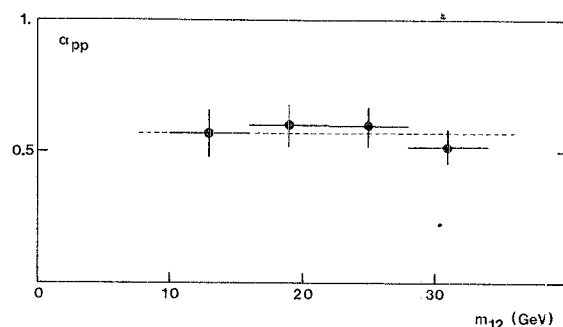


Fig. 1. The ratio of charged-to-total energy α_{pp} as a function of m_{12} in two-proton events. The dotted line shows the mean value $\bar{\alpha}_{\text{pp}}$.

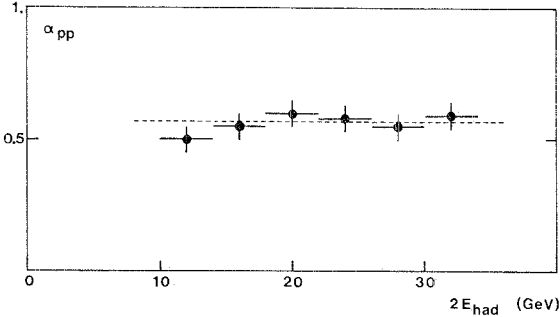


Fig. 2. The ratio of charged-to-total energy α_{pp} as a function of $2E_{\text{had}}$ in one-proton events. The dotted line shows the mean value $\bar{\alpha}_{pp}$.

with particles other than [π^0 , K^0 , \bar{K}^0 , n and \bar{n}]. This cannot exceed the fraction (see appendix)

$$\alpha_{pp}^0 = 0.10 \pm 0.10. \quad (6)$$

From the known η production in other kinematic regions [8], its contribution to α_{pp}^0 is estimated to be about 50% of the value quoted above [formula (6)].

We therefore conclude that, within the 10% level of uncertainty in α_{pp}^0 [formula (6)], there is no sign of an energy crisis in multiparticle systems produced in high-energy low- p_T pp interactions.

Finally, in fig. 3 our results are plotted, together with the e^+e^- data obtained so far, from the lowest [2] to the highest [9] energies. This shows that the multiparticle hadronic systems produced in high-energy low- p_T pp interactions, once the leading baryon effects are subtracted, have the same ratio of charged-to-total energy as do multiparticle hadronic systems produced in e^+e^- annihilations.

Appendix. The quantity α_{pp}^0 is the ratio of the neutral energy – not associated with π^0 , K^0 , \bar{K}^0 , n and \bar{n} – over the total energy:

$$\alpha_{pp}^0 = \frac{E^0}{E_{\text{total}}} = \frac{E_{\text{total}} - E_{\pi\text{KN}}}{E_{\text{total}}} = 1 - \frac{E_{\pi\text{KN}}}{E_{\text{total}}}.$$

Definitions:

$$E_{\text{total}} = (E_{\pi} + E_K + E_N) + E^0,$$

$$E_{\pi} = E_{\pi}^{\pm} + E_{\pi}^0, \quad E_{\pi}^{\pm} = E_{\pi^+} + E_{\pi^-}, \quad E_{\pi}^0 = E_{\pi^0},$$

$$E_K = E_K^{\pm} + E_K^0, \quad E_K^{\pm} = E_{K^+} + E_{K^-}, \quad E_K^0 = E_{K_L^0} + E_{K_S^0},$$

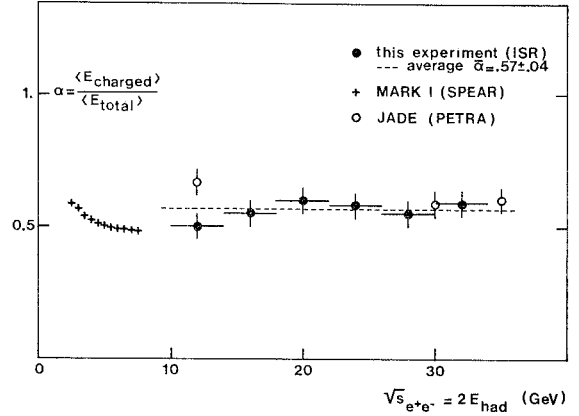


Fig. 3. Our results compared with e^+e^- data.

$$E_N = E_p^{\pm} + E_n^0, \quad E_p^{\pm} = E_p + E_{\bar{p}}, \quad E_n^0 = E_{\bar{n}}^0 = E_n + E_{\bar{n}}.$$

$$E_{\pi\text{KN}}^{\pm} = E_{\pi}^{\pm} + E_K^{\pm} + E_p^{\pm}, \quad E_{\pi\text{KN}}^0 = E_{\pi\text{KN}}^{\pm} + E_{\pi\text{KN}}^0,$$

$$E_{\pi\text{KN}}^0 = E_{\pi}^0 + E_K^0 + E_n^0.$$

$$\langle n_{\pi}^{\pm} \rangle = \text{average multiplicity of charged pions,}$$

$$\langle n_{\pi}^0 \rangle = \text{average multiplicity of neutral pions,}$$

$$\langle n_K^{\pm} \rangle = \text{average multiplicity of charged kaons,}$$

$$\langle n_K^0 \rangle = \text{average multiplicity of neutral kaons plus antikaons,}$$

$$\langle n_p^{\pm} \rangle = \text{average multiplicity of protons plus anti-protons,}$$

$$\langle n_n^0 \rangle = \text{average multiplicity of neutron plus anti-neutrons.}$$

$$\langle n_{\pi}^{\pm} \rangle + \langle n_K^{\pm} \rangle + \langle n_p^{\pm} \rangle = \langle n_{\pi\text{KN}}^{\pm} \rangle$$

$$\langle k_{\pi}^0 \rangle + \langle n_K^0 \rangle + \langle n_n^0 \rangle = \langle n_{\pi\text{KN}}^0 \rangle.$$

Measured quantities:

$$\langle n_{\pi}^{\pm} \rangle = 2 \langle n_{\pi}^0 \rangle, \quad (A1)$$

$$\langle n_K^{\pm} \rangle = \langle n_K^0 \rangle, \quad (A2)$$

$$\langle n_p^{\pm} \rangle = \langle n_n^0 \rangle, \quad (A3)$$

$$\langle n_{\pi^{\pm}} \rangle / \langle n_{\pi^{\pm}Kp} \rangle = 0.85 \pm 0.09, \quad (\text{A4})$$

$$\bar{\alpha}_{pp} = E_{\pi^{\pm}Kp}^{\pm} / E_{\text{total}} = 0.57 \pm 0.04. \quad (\text{A5})$$

The data (A1) to (A4) are from ref. [6].

Extrapolations. The validity of the above multiplicity relations (A1)–(A4) is assumed to hold for the corresponding energy relations:

$$E_{\pi^{\pm}} = 2E_{\pi}^0, \quad E_{K^{\pm}} = E_{K}^0, \quad E_{p^{\pm}} = E_{n}^0,$$

$$E_{\pi^{\pm}} / E_{\pi^{\pm}Kp}^{\pm} = 0.85 \pm 0.09. \quad (\text{A6})$$

Results. From the above definitions, extrapolations, and measurements, we get:

$$\alpha_{pp}^0 = 1 - \frac{E_{\pi KN}}{E_{\text{total}}} = 1 - \frac{3/2(E_{\pi^{\pm}}/E_{\pi^{\pm}Kp}^{\pm}) + 2(1 - E_{\pi^{\pm}}/E_{\pi^{\pm}Kp}^{\pm})}{E_{\text{total}}/E_{\pi^{\pm}Kp}^{\pm}} \\ = 0.10 \pm 0.10.$$

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