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The Leading Effect Explains the Forward-Backward Multiplicity Correlations in Hadronic Interactions.

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PACS. 13.90. – Other topics in specific reactions and phenomenology of elementary particles.

Summary. – The multiplicity correlations between forward and backward hemispheres observed since a long time in (pp) interactions at the CERN Intersecting Storage Rings (ISR), are shown to be due to the leading effect. These multiplicity correlations are reproduced following our method of classifying each (pp) interaction in terms of the effective hadronic energy available. It is this energy, and not the long-range correlation, which produces low or high multiplicities in both hemispheres of a (pp) collision. The ($\log s$)-dependence of the correlation strength follows from the energy dependence of the multiplicity. The ($\log s$)-dependence is shown to follow our prediction from FNAL and SPS, to ISR, and up to Collider energies.

A well-established effect (1) among the global properties of the multihadronic systems produced in (pp) interactions at the CERN Intersecting Storage Rings (ISR) is the forward-backward multiplicity correlation (2).

The interpretation of this effect has been in terms of a long-range correlation. In fact, one hemisphere cannot know what happens in the opposite hemisphere, unless a long-range correlation is present in the (pp) interaction. A recent attempt to explain such long-range correlations was made in terms of the production of two or more particle chains, where each single chain is not correlated (3).

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This effect and its energy dependence have been remeasured by our group at the ISR using the Split-Field Magnet (SFM) facility [4], at three energies $(\sqrt{s})_{pp} = (62, 44, 30)$ GeV for the (pp) case and at one energy $(\sqrt{s})_{p\bar{p}} = 53$ GeV for the ($p\bar{p}$) case. The results are shown in fig. 1*a*), *b*), *c*), and fig. 2. For this study we have used « minimum bias » events [5].

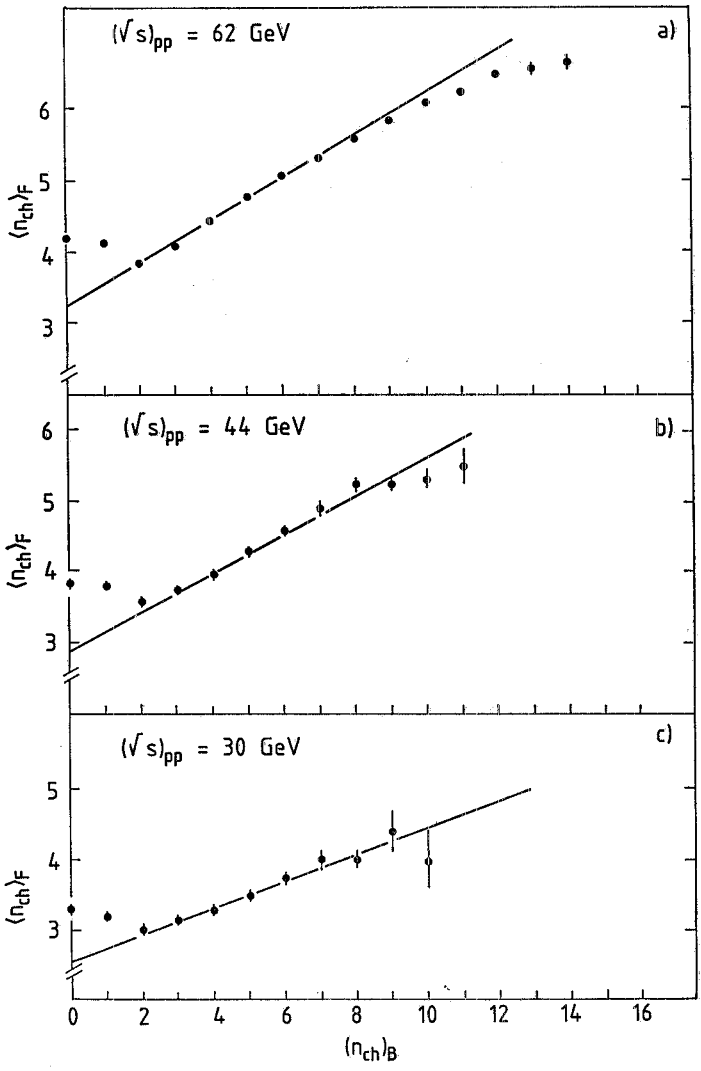

Fig. 1. – The average charged-particle multiplicity in the forward hemisphere: $\langle n_{ch}\rangle_F$ measured for fixed charged-particle multiplicities in the backward hemisphere: $(n_{ch})_B$, in (pp) interactions. *a*): $(\sqrt{s})_{pp} = 62$ GeV, *b*): $(\sqrt{s})_{pp} = 44$ GeV, *c*): $(\sqrt{s})_{pp} = 30$ GeV.

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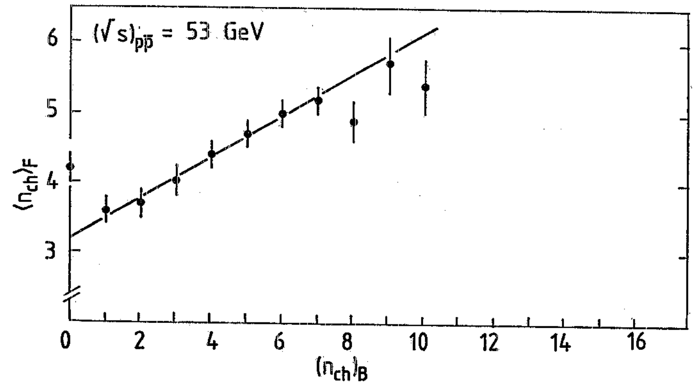

Fig. 2. – The average charged-particle multiplicity in the forward hemisphere: $\langle n_{ch}\rangle_F$ measured for fixed charged-particle multiplicities in the backward hemisphere: $(n_{ch})_B$, in $(p\bar{p})$ interactions at $(\sqrt{s})_{p\bar{p}} = 53$ GeV.

In fig. 1*a*), the abscissa shows the value of the charged multiplicity n_{ch} observed in one hemisphere, called the « backward » hemisphere:

$$(n_{ch})_B .$$

In the ordinate is reported the average value of n_{ch} observed in the opposite hemisphere, defined as the « forward » hemisphere:

$$\langle n_{ch}\rangle_F .$$

The data reproduce the well-known effect, *i.e.* a linear increase of $\langle n_{ch}\rangle_F$, with increasing $(n_{ch})_B$.

Figures 1*b*) and *c*) show the data obtained at $(\sqrt{s})_{pp} = 44$ GeV and 30 GeV, respectively.

In fig. 2 the results for $(p\bar{p})$ interactions at $(\sqrt{s})_{p\bar{p}} = 53$ GeV are presented.

Deviations from linearity, observed for $(n_{ch})_B < 2$, are due to the request for at least two charged tracks in the event. The forward-backward acceptance symmetry of the Split-Field Magnet (SFM) detector allows us to use the observed multiplicity; acceptance effects could give only a scale factor, not a slope variation.

In all figures, the full line represents the best fit to the data. This makes it possible to determine the basic quantity in all these studies, *i.e.* the so-called « strength » of the correlation function. This is given by the slopes in each set of data.

Another well-known property [1,2] of this « strength » is its energy dependence. This goes like $\log s$.

As mentioned above, the correlation between the two opposite hemispheres in a (pp) collision and its energy dependence is suggestive of a long-range effect in (pp) interactions. The same is true for $(p\bar{p})$.

Our data agree with previous experiments. However, the main point of this paper is not to report on a confirmation of a well-known effect, but to suggest for this effect an interpretation different from the generally accepted explanation in terms of the « long-range correlations » in multihadronic interactions.

We have good reasons to believe that the origin of the forward-backward multiplicity correlation, its « strength », and its energy dependence, can be understood in a very simple way, in terms of the « leading » effect (fig. 3).

In fact in a (pp) interaction, at fixed nominal energy, for example $(\sqrt{s})_{pp} = 62$ GeV, the effective energy available for particle production is not the nominal value. The multihadronic systems produced in (pp) interactions, at $(\sqrt{s})_{pp} = 62$ GeV, can be brought into excellent agreement with (e^+e^-) if the correct variables are used (5-23). A basic quantity is the effective energy available for particle production (10). This is denoted by

$$\sqrt{(q_{tot}^{had})^2} = \sqrt{(q_1^{inc} + q_2^{inc} - q_1^{leading} - q_2^{leading})^2},$$

where $q_{1,2}^{inc}$ are the four-vectors of the incident protons, and $q_{1,2}^{leading}$ the four-vectors of the leading protons. Thus $(\sqrt{s})_{pp} = 62$ GeV is a source of a large spectrum of $\sqrt{(q_{tot}^{had})^2}$ which ranges from a few GeV up to the maximum allowed.

Each value of $\sqrt{(q_{tot}^{had})^2}$ produces the number of charged particles expected from the well-known law reported in fig. 4. Notice in this figure that the ordinate is the total average charged-particle multiplicity, $\langle n_{ch}\rangle$; the abscissa is $(\sqrt{s})_{e^+e^-}$ for (e^+e^-) data (24,25) and $\sqrt{(q_{tot}^{had})^2}$ for (pp) data (19).

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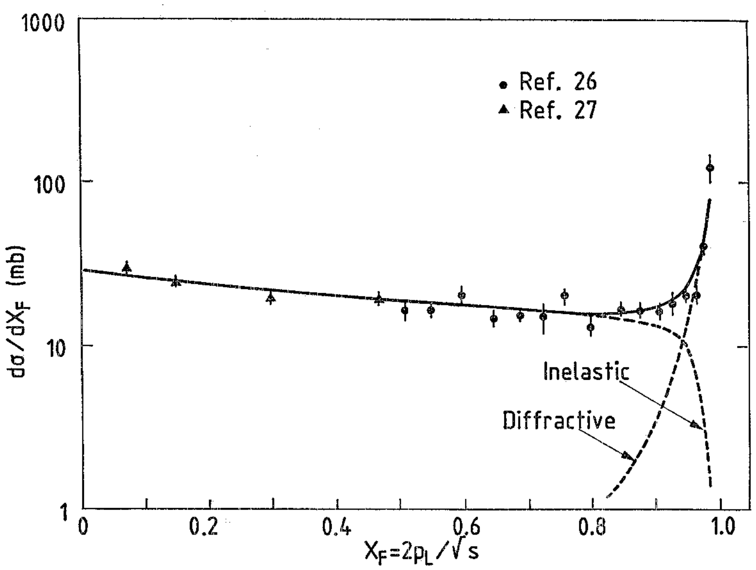

Fig. 3. – Inclusive differential cross-section $d\sigma/dx_F$ as a function of x_F $(x_F = 2p_L/\sqrt{s})$ measured [26,27] in the reaction $pp \rightarrow p + x$.

We have shown [13] that equal values of $(\sqrt{s})_{e^+e^-}$ and of $\sqrt{(q_{tot}^{had})^2}$ produce the same $\langle n_{ch}\rangle$. This is in fact one of the remarkable analogies between (e^+e^-) and (pp) interactions. The crucial point is to emphasize that, whilst in (e^+e^-) annihilation $(\sqrt{s})_{e^+e^-}$ does correspond to the effective energy available for the production of the multihadronic final states, in a (pp) interaction the correct quantity which corresponds to $(\sqrt{s})_{e^+e^-}$ is not the nominal $(\sqrt{s})_{pp}$, but the quantity $\sqrt{(q_{tot}^{had})^2}$ already mentioned.

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To select in one hemisphere a value of (n_{ch}), is a way to pick up a value of $\sqrt{(q_{tot}^{had})^2}$. For example, large values of (n_{ch}) correspond, on the average, to large values of $\sqrt{(q_{tot}^{had})^2}$; whilst small values of (n_{ch}) correspond to low values of $\sqrt{(q_{tot}^{had})^2}$.

The correlation between $\langle n_{ch}\rangle_F$ and $(n_{ch})_B$ is therefore due to the fact that different values of $\sqrt{(q_{tot}^{had})^2}$ are selected via the choice of a given value for $(n_{ch})_B$.

The proof that the correlation between $\langle n_{ch}\rangle_F$ and $(n_{ch})_B$ is due to $\sqrt{(q_{tot}^{had})^2}$ is given by the results of a detailed Monte Carlo program, constructed with two inputs of basic data.

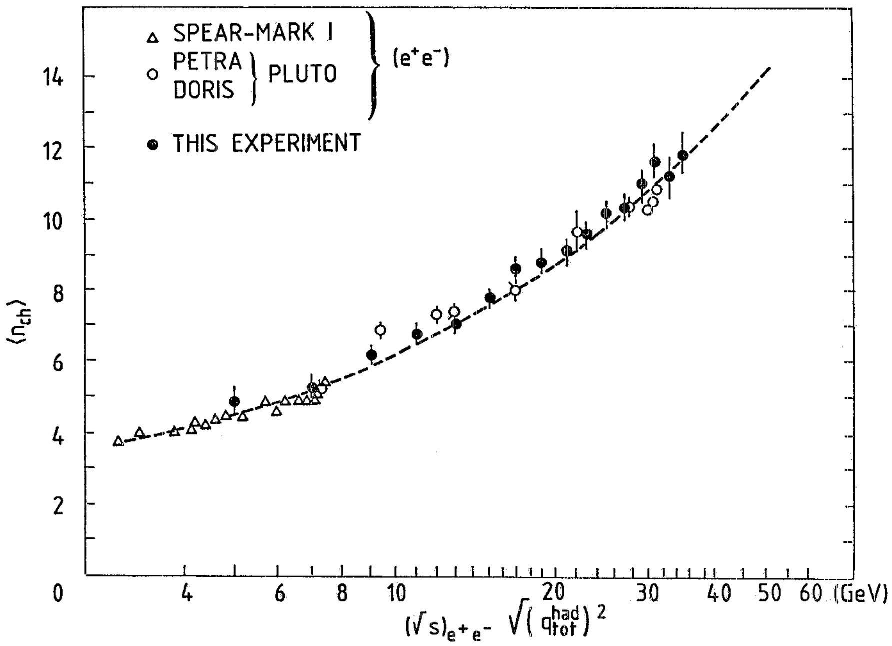

Fig. 4. – Average charged-particle multiplicity $\langle n_{ch}\rangle$ as a function of $\sqrt{(q_{tot}^{had})^2}$ in (pp) interactions [19], compared with average charged particle multiplicity as a function of $(\sqrt{s})_{e^+e^-}$ in (e^+e^-) annihilation [24,25]. The dashed line is a best fit to our data [13].

These data are shown in fig. 3 and 4. The data [26,27] of fig. 3, *i.e.* the inclusive x_F distribution for inelastic events, are the starting point for the Monte Carlo calculations. The diffractive peak is not of interest for the present analysis, its importance being strongly reduced by multiplicity selections.

Each (pp) interaction is producing two leading uncorrelated protons, according to the x_F distribution of fig. 3. Once the two leading protons are extracted, the quantity

$$\sqrt{(q_{tot}^{had})^2}$$

is calculated for that event. The use of fig. 4 allows us (the association of) $\sqrt{(q_{tot}^{had})^2}$ with $\langle n_{ch}\rangle$.

This is done using the best fit [13] whose analytic form [28-30] is

$$\langle n_{ch}\rangle = a + b\exp\left[c\sqrt{\ln\left(\frac{(q_{tot}^{had})^2}{\Lambda^2}\right)}\right],$$

with $\Lambda = 0.5$ GeV and $a = 2.47$, $b = 0.03$, $c = 1.97$.
To each hemisphere of that event an average multiplicity equal to $\frac{1}{2}\langle n_{ch}\rangle$ is attributed. This value is allowed to fluctuate independently, in each of the two hemispheres, according to a Poisson distribution. This procedure is followed throughout 10^5 Monte Carlo events.

Thus the Monte Carlo results produced at a given nominal value of the total energy in the (pp) c.m., $(\sqrt{s})_{pp}$, are analysed in terms of $\langle n_{ch}\rangle_F$ *vs.* $(n_{ch})_B$. A wide range of $(\sqrt{s})_{pp}$ has been used for the Monte Carlo study.

The « strength » of the correlation function is calculated by our Monte Carlo at different values of $(\sqrt{s})_{pp}$ in order to cover the wide range where the experimental results have been obtained [2,31,32]. This allows us to check if our Monte Carlo calculation predicts the correct log s dependence of the « strength » of the correlation function. The results are shown in fig. 5.

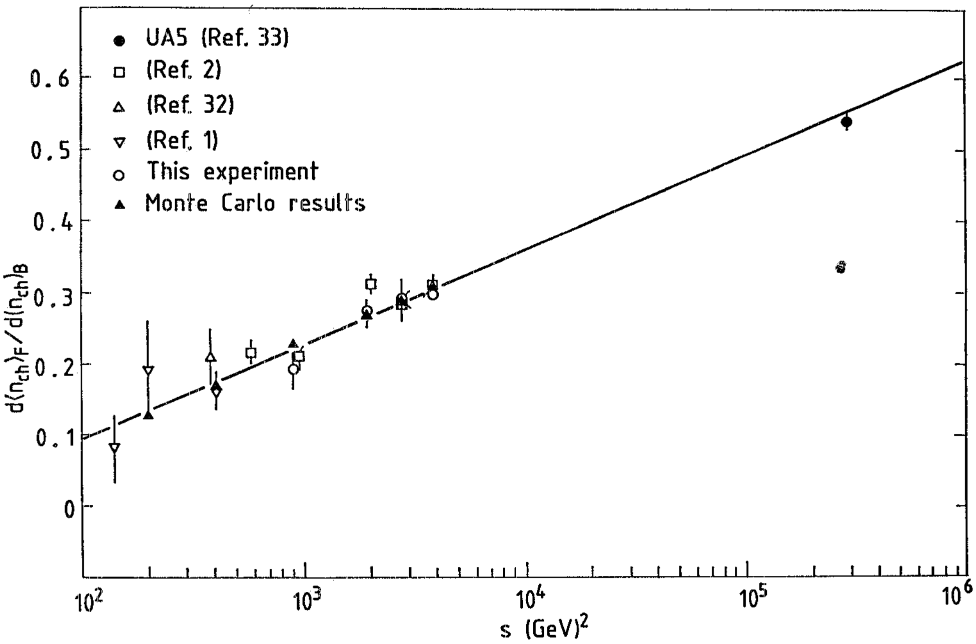

Fig. 5. – Comparison of our prediction with the « correlation-strength » $b = \mathrm{d}\langle n_{ch}\rangle_F/\mathrm{d}(n_{ch})_B$ measured, in (pp) and ($p\bar{p}$) interactions as a function of s. The full line is the best fit of our Monte Carlo results.

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The agreement between Monte Carlo predictions and experimental data is very good, up to the highest ISR energies.

If at the CERN ($p\bar{p}$) Collider the two basic functions:

i) the inclusive x_F distribution for the « leading » proton (antiproton),

ii) the average charged-particle multiplicity $\langle n_{ch}\rangle$ as a function of $\sqrt{(q_{tot}^{had})^2}$,

had been measured, we would have been able to predict the « strength » of the multiplicity correlation expected at 540 GeV.

It is nevertheless remarkable that the « strength » of the multiplicity correlation, measured [33] at 540 GeV, lies on the extrapolation of our Monte Carlo results.

This suggests that, even at Collider energies, what we have done at the ISR energies will hold true.

Conclusion. The multiplicity correlation between two opposite hemispheres in hadronic interactions, and its energy dependence, are explained as a direct consequence of the « leading » effect.

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