CORRELATIONS BETWEEN MISSING MASS AND MULTIPLICITY IN PROTON-PROTON COLLISIONS

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We show how correlations between missing mass and multiplicity in high energy reactions are easily explained by fire-ball production, and try in a simple manner to illustrate the properties of the fire-balls.

1. *Introduction*

There is today overwhelming evidence [1–7] that particle production at high energy is dominated by the production of clusters or fire-balls which subsequently decay into stable particles.

Analyses of secondaries produced with relatively small longitudinal momentum show that the centrally produced clusters are predominantly neutral with a mean charged multiplicity [2, 3, 5] of 2–2.5 and that the properties of the clusters are rather independent of the incoming energy of the particles.

In this article we will present a very simple (and hopefully pedagogical) exclusive model for particle production in terms of cluster formation, and show how easily this explains the correlations between a leading proton and the multiplicity distribution associated with the corresponding missing mass.

A possible interpretation of these correlations is in terms of pomeron exchange [9], or more generally in terms of a recursive hypothesis [10] for many particle production. We want to illustrate how they can also be explained in a cluster formation model, and to test how important the details of the cluster properties are for the multiplicity distribution as a function of the energy loss of the incoming protons during the reaction.

We shall study proton-proton reactions between 100 and 300 GeV/c laboratory momentum and the plan of the paper is as follows:

We first make a definite exclusive model where the fire-balls have the same properties (mass and decay distribution) as proton-antiproton annihilating at rest. It will then be

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shown (and this was not completely evident to us) that these clusters have a too big mean multiplicity of the decay products. We then show that a fire-ball with a decay distribution similar to proton annihilation but with the mean number of charged decay products 2.3 instead of 3.05 works very well.

2. *Protonium as a fire-ball*

It would be very nice to be able to connect very high energy phenomena with experimentally observed low energy phenomena.

Which are then the low energy reactions that could give us a hint of what a fire-ball looks like? If fire-balls are manifestations of hadronic vacuum fluctuations brought on the mass shell under the influence of the incoming colliding particles, then we would like to associate fire-balls with hadronic clusters having the quantum numbers of vacuum.

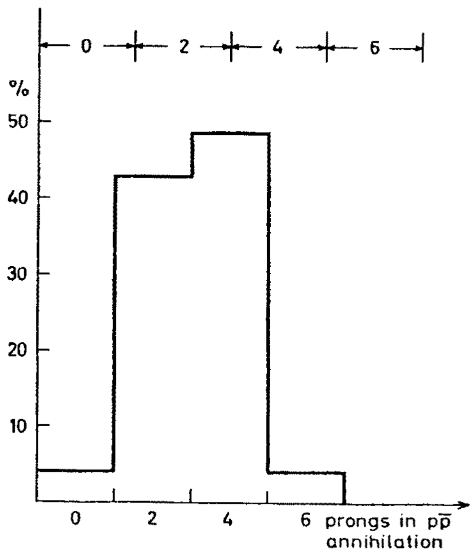

Fig. 1. Prong distribution in proton-antiproton annihilation at rest. (The area under each bin on the upper abscissa defines the fire-ball used in Section 3)

Another question is the mass or the mass distribution of the fire-balls. The first estimate of the mean fire-ball mass comes from Hasegawa [1] who finds a mass around 2 GeV, later estimates seem to be somewhat lower. This points to the protonium annihilation as a possible candidate for a fire-ball. Although the parity of the ground-state is negative and the isospin is a mixture of isospin 0 and 1 with both values of the G parity, it is a well explored system, and it might still have many of the characteristics of the fire-balls that are produced at high energy.

The same could be said about electron-positron annihilation into hadrons in flight, but experimental data are here still few.

We shall now explore some consequences that would follow from the assumption that a fire-ball has the same properties as protonium. The prong distribution of the fire-ball is therefore in our model taken as input and we shall use a zero-width approximation for the mass-distribution of the fire-ball. Fig. 1 shows the percentage of protonium [8] decays into 0, 2, 4 and 6 charged particles. (The upper abscissa shows the binning we will use later on to simulate the decay of a fire-ball with lower mean multiplicity.) The decay products are mostly pions and it is evident that we do not get any antiprotons produced, unless we go away from the zero (mass) width approximation of the fire-ball by including also some proton-antiproton reaction in flight.

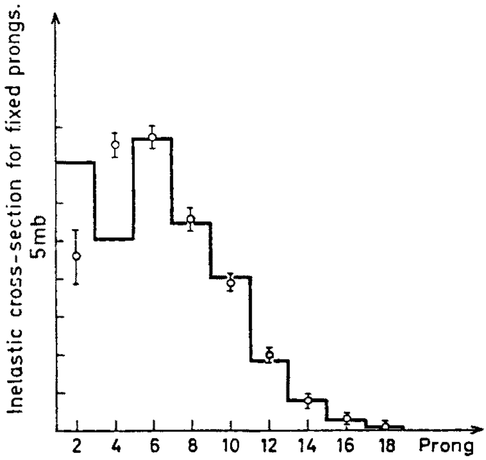

Fig. 2. Fitted total prong distributions with protonium-like fire-balls for proton-proton reactions [11] at 100 GeV/c

Having decided what we will call a fire-ball we have from the observed prong distribution in a given reaction a rather unique manner of decomposing the cross-section into what fractions come from zero, one, two, three or more fire-ball production. An ambiguity lies in the treatment of diffraction which we will characterize as zero fire-ball production.

In the experiments we shall study, p–p collisions from 100 to 300 GeV/c laboratory momentum [9, 11–13], most of the diffractive component contributes to two and four prong events [13]. We shall in the following keep outside the kinematical region where the missing mass relative to the observed proton is smaller than 4 GeV. We now fix the amount of production of different numbers of fire-balls by fitting the observed total prong distribution from six prong cross-sections and upwards, and check a posteriori if the amount of diffraction is approximately correct.

As an example we take the 100 GeV results [11]. On Fig. 2 we see the observed 2–18 prong cross-sections together with a theoretical curve obtained by assuming 20.7% zero-cluster, 33.3% one cluster, 32.3% two-cluster, 12.0% three-cluster, and 1.7% four-cluster formation.

The theoretical curve has been obtained by fitting the cross-section from 6 prongs upwards, assuming that each fire-ball has the same prong distribution as a proton-antiproton annihilation at rest, and for convenience that all diffraction leads to two prong events. The total diffractive contribution is therefore correctly around 20% of the inelastic cross-section, and we see that the excess of two prong events we have coming from diffraction fills up the missing part of the four prong cross-section, if we use the information that diffraction also leads to 4 prong events.

As we have now fixed the relative amount of production of different fire-ball numbers, we shall show how very naive dynamical assumptions lead to qualitatively correct (and in the next section also quantitatively correct) prong distributions as functions of missing mass (or Feynman x), and at the same time lead to a reasonable proton spectrum in our energy range. We assume an almost pure cylindrical phase space distribution with trans-

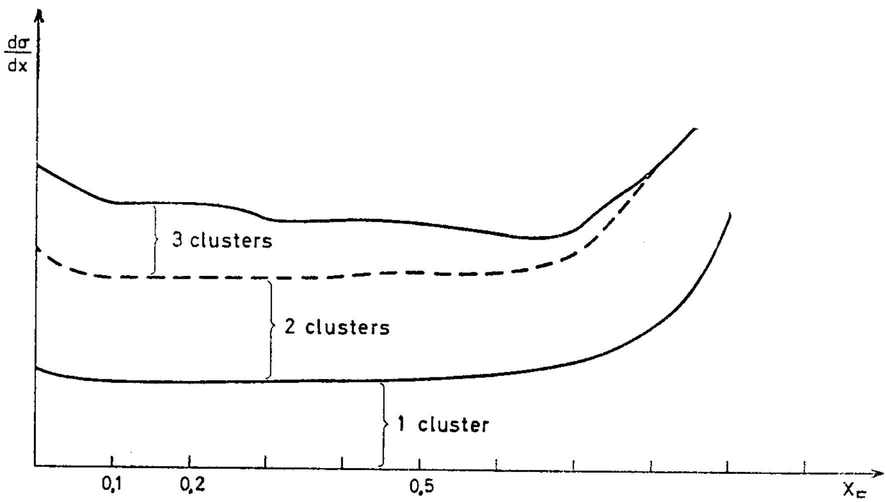

Fig. 3. The proton inclusive spectrum at 100 GeV/c decomposed into parts belonging to one, two, and three fire-ball production

verse momentum limited by exp $(-4\sum p_T^2)$, the sum running over all produced fire-balls and the two nucleons. We impose only the conditions that the two nucleons come out in the forward an backward hemisphere (defined with respect to the incoming beam direction in the center of mass system), respectively, and that the observed proton recoils against a missing mass greater than 4 GeV. The last restriction is made in accordance with our intention to stay out of the diffractive region where our model is meaningless.

There is now no free parameter left and we have an exclusive model for p–p reactions in a certain energy range which in principle could be used to calculate anything as long as we keep out of the kinematical region, where the energy going into particle production is very small.

The simplest thing we can do is to compute the multiplicity distribution when one proton is observed with a definite x, where x is the Feynman ratio of the proton CM longitudinal momentum to the incoming CM momentum or the corresponding missing mass. This we do with the numerical integration program FOWL.

It is clear that energy momentum conservation leads to a proton spectrum over x that is more and more compressed towards smaller x values, as the number of produced fire-balls increases. As the integrated cross-sections are fixed by the total amount of production of 1, 2, 3 ... fire-balls, the relative importance of one fire-ball production will decrease with decreasing x (or increasing missing mass).

Fig. 3 shows the proton spectrum (integrated over transverse momentum) and its decomposition into different number of fire-balls as a function of x at 100 GeV/c. The

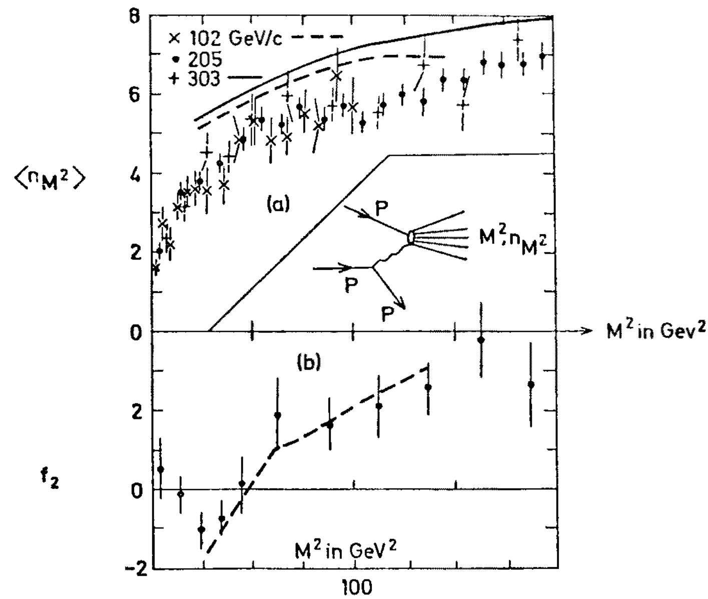

Fig. 4. Mean multiplicity and f_2 as a function of missing mass squared in our protonium fire-ball model. Data from Ref. [9]

curves are smooth interpolations through the FOWL generated spectrum to neutralize statistical fluctuations.

It is obvious that if we let the energy increase up to ISR energies we would get a too low mean energy for the outgoing protons. The reason why the approximate phase space dynamics works in our energy range is that we have a production of few fire-balls.

From Fig. 3 we then know when the proton is emerging with a definite longitudinal momentum or associated missing mass, how large is the probability that the proton is emerging from a reaction producing a definite number of fire-balls. As an example, defining $s' = M^2$, where M is the missing mass associated with the outgoing proton we find from the figure that with $s' = 42\,(\text{GeV})^2$ there is 50.5% one fire-ball production and 49.5% two fire-ball production, whereas at $s' = 102\,(\text{GeV})^2$ we have 35.2% one, 43.2% two, 19.4% three and 2.2% four fire-ball production.

The corresponding mean number $\langle n \rangle$ and $f_2 \equiv \langle n(n-1)\rangle - \langle n \rangle^2$ for charged particles produced as a function of missing mass is shown in Fig. 4.

Qualitatively the figures are correct but $\langle n \rangle$ is definitely too high. This shows that we have assumed a too high mean multiplicity for each fire-ball in our dynamical model.

This result is in complete agreement with other recent estimates of the mean [2, 3, 5, 7] multiplicity for each fire-ball.

3. A more realistic fire-ball model

It is clear from the preceding results that we would come quite close to the experimental results if we had a lower mean multiplicity for each fire-ball. We therefore take a basis in our original protonium fire-ball, but rebin its prong distribution as illustrated by the upper abscissa in Fig. 1. The resulting fire-ball has a distribution with 15% zero prong, 57% two, 27% four and 1% six prongs in its decay. The mean number of charged decay particles is therefore 2.3.

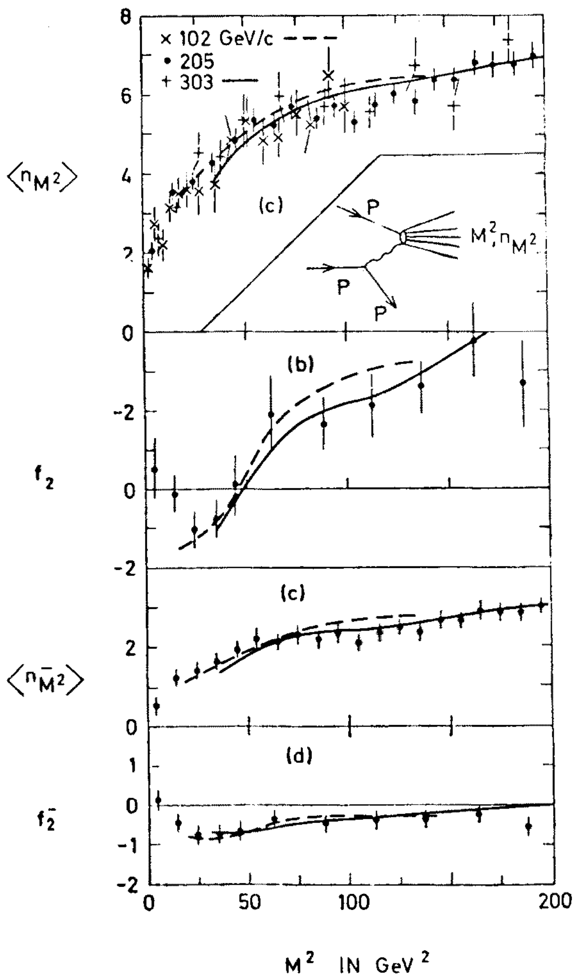

Fig. 5. The same as Fig. 4 but with a fire-ball as described in Section 3

TABLE I

Relative distribution of prongs (percentage) as function of missing mass squared in (GeV)^2

(Missing mass)^2	36–48	72–84	108–120	156–168	228–240 (GeV)^2
2 prongs	9.26	6.38	5.49	4.72	4.0
4 prongs	38.82	27.93	24.62	21.26	18.0
6 prongs	33.15	29.13	27.65	24.78	21.33
8 prongs	14.63	20.18	21.19	20.82	19.65
10 prongs	3.90	11.03	12.92	14.70	16.22
12 prongs	0.25	4.12	5.73	8.17	10.92
14 prongs	—	1.07	1.90	3.72	6.06
16 prongs	—	0.2	0.45	1.37	2.68
18 prongs	—	—	0.08	0.41	0.91
20 prongs	—	—	—	0.1	0.22
22 prongs	—	—	—	—	0.04

With this input we repeat the calculations described in the preceding section obtaining the results of Fig. 5.

The agreement with published quantities is so good that we feel encouraged to predict the full distribution for a range of missing masses. This is shown in Table I.

4. Conclusions

We have made an attempt to use low energy information from annihilation processes to illustrate some high energy phenomena. By the choice of our fire-balls we are ensured strong positive short range correlations in rapidity between pions of opposite charge and somewhat weaker correlations between equally charged particles. Our attempt to use protonium as representing the fire-balls produced at high energy was not a quantitative success but the phenomenological protonium, as the system used in Section 3, might have many desired properties. Unhappily, at the moment this is not an experimentally produced system and cannot be reached by nucleon-antinucleon as its mean mass which we guess to be around 1450 MeV (assuming the ratio of the fire-ball and protonium masses being the same as the ratio of their mean multiplicity) would be below the proton-antiproton threshold. We do not know to what extent the fire-ball used in Section 3 resembles the $e^+e^- \to$ hadrons system at around 1.5 GeV.

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