SEARCH FOR POMERON-POMERON-2π EVENTS IN 205 GeV/c π^-p INTERACTIONS*

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ABSTRACT

Pomeron-Pomeron-2π vertices have been sought in the reaction $\pi^-p \to \pi^-\pi^+\pi^-p$ at 205 GeV/c. From a sample of 186 of these events, about 2/3 have been extracted for which the rapidity ordering of the four outgoing particles makes them candidates for the double-Pomeron exchange process (i.e., the fastest and the slowest particle are respectively a π^- and a proton). A separation from single-Pomeron processes has been attempted with the help of a rapidity triangle plot. The number of possible double-Pomeron-type events has also been estimated from a Regge-propagator fit to the nonhomogeneous distribution of the events within this triangle. The number of such events obtained by either method gives a cross-section upper limit of 65 μb for double-Pomeron exchange, consistent with the predictions of a pion-pole dominance model.

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We report an investigation of the possibility that the Pomeron link may be repetitive; i.e., that two Pomerons may occur simultaneously in the exchange mechanism for collisions at sufficiently high energy.[1] (The shorthand notation DPE -- for "Double-Pomeron Exchange" -- will be used to refer to this process.) This study is based on 186 events kinematically fitted to the reaction

$$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$$

at 205 GeV/c, observed in the NAL 30-inch bubble chamber. Reference 2 gives details of the experiment, including the criteria for the selection of these events.

A reaction of such low multiplicity at this high energy is expected theoretically[3] to be dominated by (at least a single) Pomeron exchange, because at least one of the rapidity gaps between produced particles must be large. That is to say, the total rapidity interval of about 7 units for the present experiment must be spanned by only three gaps, and any gap $\gtrsim 2.0$ is usually expected to be Pomeron-dominated.[4] One expects to find that wherever a large gap appears, it will separate two particle clusters that can be interpreted as produced by diffractive dissociation, each cluster carrying the same quantum numbers as one of the incident particles, as shown in Figs. 1a and 1b. There may, however, be some events in which two large gaps appear, both gaps separating particle clusters that satisfy the quantum-number requirements of diffractive dissociation, as in Fig. 1c. The question to be investigated is whether the number and distribution of such events supports the important theoretical idea that these two large gaps are simultaneously mediated by Pomeron exchange in the same sense that Pomerons have been verified to control single large gaps. Previous attempts[5] to detect double-Pomeron processes were made at such a low energy (25 GeV/c maximum) that it was impossible for two sufficiently large gaps to appear.

This study deals primarily with a straightforward but novel representation of our data based on the rapidity variable. In addition, the data are compared to some theoretical predictions using the pion-pole dominance hypothesis.

I. SEARCH FOR DPE USING RAPIDITY VARIABLES

Figure 2a-d shows the distribution of the rapidity variable* in the center of mass for the proton, π^+, slow π^- and fast π^-, respectively. One observes that (1) all protons have negative c.m. rapidity (average value ≈ -3.0), (2) the fast π^- always has positive and large c.m. rapidity (average value $\approx +3.6$), and (3) the π^+ and the slow π^- have similar c.m. rapidity distributions with two distinct peaks. These single-variable distributions taken alone do not yield direct information as to which events should be classified as DPE. We shall find it necessary to study a distribution in two variables.

A. Description of the Triangle Plots

If the four outgoing particles are designated A, B, C, D according to increasing order of their respective rapidities, R_A, R_B, R_C and R_D, the three gaps between adjacent particles are defined as $R_{AB} = R_B - R_A$, $R_{BC} = R_C - R_B$, and $R_{CD} = R_D - R_C$. Plotting R_{AB} versus R_{CD} (Fig. 3a), one observes two clusters of events: (a) Events with $R_{AB} \geq 2$ and $R_{CD} \leq 2$. For all of these events, it may be verified that particle A is the proton. Consequently, they may be identified as corresponding to Fig. 1a; i.e., pion dissociation. (b) Events with $R_{AB} \leq 2$ and $R_{CD} \geq 2$. Here it turns out that particle D is always a π^-, and so we are dealing with proton dissociation (Fig. 1b). Between these two clusters are scattered a few events, for all of which particle A is a proton and particle D a π^-. These events are tentatively associated with Fig. 1c.

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*Defined as usual by $\frac{1}{2}\log[(E+p_{\parallel})/(E-p_{\parallel})]$ for a particle whose energy and longitudinal momentum are E and $p_{\parallel}$ respectively.

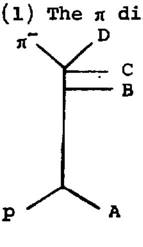
The striking diagonal boundary of the populated region in Fig. 3a is easy to understand since at very high energy, with small transverse momenta, the total rapidity interval spanned by all outgoing particles must become roughly equal to that spanned by the two incoming particles.[6] The distribution of the total rapidity interval $R_{AD} = R_D - R_A$ (Fig. 4) is peaked at 6.75 (to be compared to the incident pion laboratory rapidity of 7.9) with a full width of about one. The dispersion is small enough that it becomes a good approximation to consider $R_{AD} = R_{AB} + R_{BC} + R_{CD}$ as a constant. In other words, only two of the three gaps are independent. The diagonal boundary in Fig. 3a represents the constraint $R_{AB} + R_{CD} \leq R_{AD} \approx 6.75$.

To take advantage of the reduction of the analysis to two dimensions, we renormalize the rapidity gaps for each event by a factor (close to one) that makes R_{AD} exactly equal to 6.75. When the events of Fig. 3a are shifted (slightly) according to this rule, they fall within a common triangle (Fig. 3b). R_{BC} is now proportional to the perpendicular distance from a point to the third (diagonal) side of the triangle.

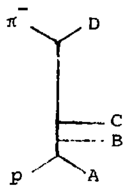
The analysis may be symmetrized by constructing an equilateral triangle, each of whose sides has length $2R_{AD}/\sqrt{3} \approx 8.0$, such that the perpendicular distances to each side are the three rapidity gaps. Figure 5 shows such a plot for the events under consideration. Each event is represented by one point (or a plus, or a solid circle; these symbols will be defined below) and the corresponding altitudes to the three sides are R_{AB}, R_{BC} and R_{CD}.

B. Qualitative Features Deducible from the Triangle Plots

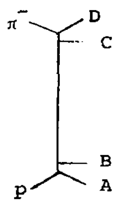
(1) The π diffraction dissociation events are such that R_{AB} is large while R_{BC} and R_{CD} are relatively small. These events occur in the densely populated upper left-hand corner of Fig. 3a-b and in the lower right-hand corner of Fig. 5.



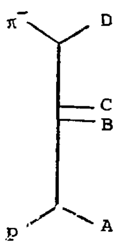
(2) The proton diffraction dissociation events are such that R_{AB} and R_{BC} are small relative to R_{CD}. These events populate the right-hand corner of Fig. 3a-b and the lower left-hand corner of Fig. 5.



(3) Quasi-two-body events (such as $\rho\Delta$) should be found in an area where both R_{AB} and R_{CD} are small compared to R_{BC} and thus should populate the lower left-hand corner of Fig. 3a-b and the upper corner of Fig. 5. These regions, in fact, are observed to be empty except for one event close to the boundary of the proton-diffractive region. This suppression of odd G-parity exchange supports the assumption of Pomeron dominance across large rapidity gaps.



(4) There remains a region which we define by R_{AB} and R_{CD} both > 2.0 and which includes 13 events.* The events of this region are expected to be largely understood through an exchange of a Pomeron (P) across each of the large gaps R_{AB} and R_{CD}. These events, if they could really be confirmed as double-Pomeron exchange, would constitute the first experimental evidence for this theoretically important mechanism.[7]



We now proceed to discuss the possibility that these events result from the two-Pomeron exchange process, at the same time comparing our results to some theoretical predictions.

An experimental fact which supports the choice of the 2-unit rapidity interval to define this last region lies in the fact that the events with an ordering of the particles A, B, C, D inappropriate to P-P (i.e., a double-

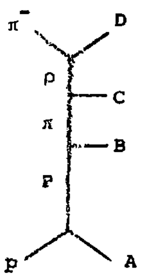
*Or 12 events if one considers the "non-normalized" triangle (Fig. 3a). The smallness of the difference supports the use of the normalized plots (Figs. 3b and 5).

Pomeron event requires particle A to be a proton and particle D to be a π^-) all lie outside the region defined by a 2-unit criterion, as can be observed from the points indicated by a "plus" on Fig. 5.

A different way to isolate the P-P mechanism depends on a simple theoretical model to describe the three classes of those events which are candidates for such a mechanism (and which naturally must exhibit as a first condition the "right-ordering" defined above).

C. Data Analysis Using a Multi-Regge Model

A fit to the non-uniformly populated triangle (Figs. 3b and 5) has been performed on the basis of the following model: for π dissociation, the events are described by the exchange of a Pomeron (gap AB), a π (BC) and a ρ (CD),



and are represented by a corresponding simple multi-Regge propagator of the form[8]

$$e^{2(\alpha_P-1)R_{AB}}\; e^{2(\alpha_\pi-1)R_{BC}}\; e^{R_{BC}}\; e^{2(\alpha_\rho-1)R_{CD}} \qquad (1)$$

where the kinematic factor $e^{R_{BC}}$ is included to approximate the phase-space constraint on the π exchange.* With $\alpha_P = 1$, $\alpha_\pi = 0$, $\alpha_\rho = 0.5$,** the expression is proportional to $e^{-R_{BC}}\, e^{-R_{CD}}$. Using the relation $R_{AB} + R_{BC} + R_{CD} = R_{AD}$ = constant, the density of the π diffractive dissociation events can then be fitted by an expression

$$Ae^{aR_{AB}} \quad . \qquad (2)$$

The model can be made more flexible if the coefficient a of R_{AB} in the exponent is left a free parameter; if the above assumptions are correct, we expect $a \approx 1$.

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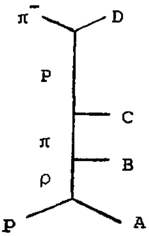
* Because of the very small pion mass, the t dependence of the π-link is roughly $\propto dt/t^2$ which integrates to $[|t|_{min}]^{-1} \propto e^{R_{BC}}$. The kinematic lower limit on $|t|$ is less important for non-pion links.

**We assume that the average of each of the three t values is close to zero, an assumption supported by the results of our fit.

Similar reasoning applied to the proton dissociation events, where the exchanged trajectories are similar but in opposite order, gives the product:



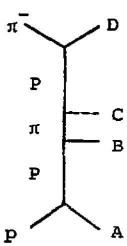
$$e^{2(\alpha_\rho-1)R_{AB}}\, e^{2(\alpha_\pi-1)R_{BC}}\, e^{R_{BC}}\, e^{2(\alpha_P-1)R_{CD}} \cong e^{-R_{AB}}\, e^{-R_{BC}}, \quad (3)$$

which reduces to

$$Be^{bR_{CD}} \quad (4)$$

with $b \approx 1.0$.

Regarding the two Pomeron exchange events, their dependence on the rapidity intervals is:



$$e^{2(\alpha_P-1)R_{AB}}\, e^{2(\alpha_\pi-1)R_{BC}}\, e^{R_{BC}}\, e^{2(\alpha_P-1)R_{CD}} \quad (5)$$

so that the density of these events can be described by an expression proportional to $e^{-R_{BC}}$, or,

$$Ce^{c(R_{AB}+R_{CD})} \quad (6)$$

with $c \approx 1.0$.

Qualitatively speaking, our experimental distribution agrees rather well with the prediction, as Expressions (2) and (4) will populate the regions of maximum values for R_{AB} and R_{CD} respectively, while Expression (6) will populate the region of small R_{BC}. Note that the latter is only a function of the distance from the diagonal of Fig. 3b (or from the lower boundary of the triangle of Fig. 5). Demonstration of the existence of a flat plateau in the central region along the lower boundary of Fig. 5 would, in the absence of any alternative interpretation, support the double-Pomeron hypothesis. For the present, our limited statistics only allow us to ask whether a fit to the distribution which includes this last term (6) is an improvement over a fit which only takes into account terms (2) and (4), representing the π and proton dissociations.

This question is investigated with fits[9] Nos. 1 and 3 of Table I; the only difference between them is the introduction of term (6), all slopes of the exponents being taken equal to 1.0. The improvement of fit No. 3 corresponds to about one standard deviation. Its results are compatible with an interpretation of (16±14) DPE events inside the whole triangle plot. These facts give a second indication, although not compelling from a statistical point of view, that the so-called DPE events may not be merely the tails of the distribution fitted with Expressions (2) and (4). If the coefficients a, b, c in the exponent are left free, one finds similar results, as shown by comparison of fits Nos. 2 and 4.*

Because the DPE contribution given by Expression (6) extends into the singly diffractive corners of the triangle plot, the 16 events determined by this last criterion do not correspond individually with the 13 events determined by the earlier strict rapidity cut.** Nevertheless the number of DPE events estimated via the two criteria agree well.

We have thus estimated the total number of events produced by the DPE mechanism using two independent criteria. Under the empirical assumption that these events are exactly the population of the inner triangle of Figs. 3b and 5 (defined by the rapidity cuts R_{AB} and R_{CD} both greater than 2.0), we find 13 events from which we calculate with 90% confidence an upper limit of 65 μb for the DPE cross section in the reaction $\pi^- p \to \pi^- \pi^+ \pi^- p$ at 205 GeV/c. Under

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* The values of these coefficients when determined by a best fit turn out close to the theoretically expected values of 1.0. This tends to support the validity of our simple model.

**Of the 16 events determined as DPE from the fit, 11 should lie inside the single-diffraction corners, while the tails of the first two terms of the fit should give a population of about 10 events inside the central region.

a multi-Regge model assumption in which the DPE events populate by contrast the entire phase-space with density described by Expression (6), we have obtained a comparable number of events.

II. STUDY OF DPE USING TWO-PARTICLE SUBENERGIES

Using the pion-pole dominance (πPD) hypothesis, Shankar[10] gives estimates of the double-Pomeron cross section. For this model, DPE is defined in terms of minimum subenergies of pairs of particles A, B, C and D, rather than minimum rapidity gaps. Our data have been analyzed to determine how many of the events could be called DPE according to this definition.

A. The πPD Hypothesis

Let us first review briefly the πPD hypothesis. In this model, the Pomeron is defined quite generally as the mechanism controlling elastic amplitudes at high energies; that is, after the elastic and total cross sections have become approximately flat.* Consequently for any pair of interacting particles a and b, a minimum squared energy S^*_{ab} can be chosen beyond which the elastic amplitude is assumed to be Pomeron dominated. For the "right-ordered events" defined above let us designate the four momenta P_i as follows:

$$p(P_a) + \pi^-(P_b) \rightarrow p(P_A) + \pi^{\mp}(P_B) + \pi^{\pm}(P_C) + \pi^-(P_D)$$

where the rapidities are such that $R_A < R_B < R_C < R_D$. As illustrated in Fig. 6, the production amplitude factorizes at the pion pole, $(t = (P_A + P_B - P_a)^2 = \mu^2)$:

$$M \xrightarrow[t\rightarrow\mu^2]{} \frac{A^{e\ell}_{\pi^- p}(v_L) \cdot A^{e\ell}_{\pi^+\pi^-}(v_R)}{t - \mu^2} . \qquad (7)$$

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*In fact, one may start by defining the Pomeron as the mechanism controlling all diffraction amplitudes at high energies. In the present case, only the subset of elastic amplitudes is relevant.

In Eq. (7), $A^{el}_{\pi^- p}(V_L)$ is the $\pi^- p$ elastic amplitude as a function of the independent variables V_L (i.e., P_A, P_B and P_a) at the left blob in Fig. 6. A similar definition holds for $A^{el}_{\pi^+\pi^-}(V_R)$ at the right blob.

It is clear from the definition of the Pomeron in this model that if the subenergies $S_{AB} = (P_A + P_B)^2$ and $S_{CD} = (P_C + P_D)^2$ exceed the minimum squared energies S^*_{AB} and S^*_{CD}, beyond which the elastic amplitude for the reactions $(AB \to AB)$ and $(CD \to CD)$ respectively are Pomeron dominated, the Pomeron occurs in both blobs and the event is then DPE. This is however strictly true only at $t = \mu^2$ where M factorizes. The πPD hypothesis is that in the physical region $(t < 0)$ the factored form of Eq. (7) still holds, provided t-dependent form factors are incorporated. Shankar has evaluated the DPE cross section[10] using this πPD model and making the following supplementary assumptions: (1) a simple form factor $f(t) = 1$ for $|t| < T$ and $f(t) = 0$ for $|t| > T$ was employed, with $T = 0.25\ \text{GeV}^2$ (Ref. 11). (2) The squared energies above which the (πp) and the $(\pi\pi)$ elastic cross sections are Pomeron dominated were respectively $S^*_{p\pi} = 4\ \text{GeV}^2$ and $S^*_{\pi^+\pi^-} = 2\ \text{GeV}^2$.† (3) The average value of the (πp) and $(\pi\pi)$ elastic cross sections in the region between the Pomeron thresholds and the kinematically allowed maxima were taken to be 5 mb and 3 mb respectively. The resulting total DPE cross section was calculated to be 33 μb.

B. Comparison with Experiment

According to this model, the events depicted in Fig. 6 may be classified as DPE if subenergies S_{AB} and S_{CD} are greater than S^*_{AB} and S^*_{CD} respectively.‡

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†Because of the absence of resonances in the $(\pi^-\pi^-)$ channel, there is no natural choice for $S^*_{\pi^-\pi^-}$. Shankar has proposed using the minimum rapidity interval of 2 units.

‡Except in the case where C and D are both π^- (see previous footnote).

In addition, it has been required that $S_{AC} > S^*_{AC}$ and $S_{BD} > S^*_{BD}$. These latter conditions will automatically be satisfied if the first two conditions on S_{AB} and S_{CD} are satisfied, because at very high energies longitudinal momenta are much larger than transverse momenta. In the present experiment this added condition turns out to eliminate only one event.

When the events were analyzed in terms of these criteria the following results were obtained:

(i) 8 events satisfied the subenergy criteria.

(ii) All of these (indicated by solid circles on Fig. 5) satisfied the rapidity gap requirements (defined as R_{AB} and R_{CD} both greater than 2.0); i.e., the 8 events that satisfied the subenergy condition form a subset of the 13 events selected on the basis of rapidity intervals. The 2-unit rapidity gap requirement thus constitutes a roughly equivalent condition.

(iii) On the basis of the model, the 5 events (13 minus 8) that met with the rapidity but not the subenergy requirements were rejected, since in these cases either A and B or C and D are in a resonance mass region. Consider for example one such event shown in Fig. 7. Since $t = 0.02\ \text{GeV}^2$, the pole approximation Eq. (7) for the amplitude is very reliable, and thus the event of Fig. 7 may be associated with the mechanism of Eq. (7). At the right blob we have a π^+ almost on-shell, colliding with the incident π^-, the two-pion mass being 0.77 GeV. Since it lies in the region of the ρ meson the right blob is not necessarily Pomeron dominated even though $\Delta y > 2.0$. The other four events were rejected from similar considerations. But as shown in Fig. 5, slightly more restrictive rapidity cuts would make the number of events so selected compatible with the number selected with the above mass cuts. The 8 selected events which satisfy Shankar's criteria correspond to a cross section of 30±10 μb, consistent with the above πPD model prediction.

In conclusion, we have shown three different ways to isolate DPE events if the energy is sufficiently high (and if the statistics are sufficient!).

The first method is based on a triangle plot in rapidity. It should be emphasized that as the energy increases, the triangle is expected to expand in such a way that the population distribution in the π-diffraction and the proton-diffraction corners will remain the same, while the central part will expand linearly with the log of the energy. A population component in the expanding central region which is independent of energy ultimately would constitute a decisive demonstration of the recurrence of the Pomeron.

A method based on a multi-Regge propagator fit also gives the proportion of events which could be classified as DPE. Though these events cannot be compared individually with the events selected above, their number is in close agreement.

At the same time, working with the presently available energy and limited statistics, another selection based on πPD analysis has given results qualitatively compatible with the triangle analysis, also being consistent in magnitude with theoretical expectations. The events selected with these πPD model criteria constitute a subsample of the events selected from the triangle plot. The same order of magnitude for the upper limit of the double-Pomeron cross section is therefore given by all three methods.

Although such limited statistics (roughly 10 events) cannot compel a unique theoretical interpretation, we have shown that a double-Pomeron interpretation is consistent with the data from several different points of view.

We are very grateful to G. F. Chew for having suggested this study and for his constant attention to this work, and to R. Shankar for his interpretation of our data and for helpful discussions.

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4. The reason for choosing two rapidity units is that because of the spacing ($\Delta\alpha \approx 1/2$ unit) between the Pomeron and the next trajectory the Pomeron should dominate over a Regge trajectory (such as ρ) by a factor of e in amplitude when the rapidity interval is 2.0. See for instance, W. Frazer, D. R. Snider and Chung I. Tan, UCSD preprint 10P10-127 (1973).

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9. We used the program OPTIME of P. E. Eberhard and W. O. Koellner, Computer Physics Communication 3, 296 (1972).

10. R. Shankar, LBL-2068, to be published in Nuclear Physics B.

11. This value of 0.25 GeV^2 for T used in the theoretical estimate is subject to uncertainties since there exists, to date, no unambiguous off-shell

continuation of the pion exchange amplitude. One may however be reasonably sure that the value of T will not be less than 0.125 GeV^2--which in turn implies that the theoretical estimate is not likely to fall below half the quoted value of 33 μb (R. Shankar, private communication and Ref. 10).

Table I. Results of fit to triangle plot distribution (119 events with "right ordering").[a]

$$Y = Ae^{aR_{AB}} + Be^{bR_{CD}} + Ce^{c(R_{AB}+R_{CD})}$$

No. fit	Free parameters	a	b	c	No. events π diff.	No. events p diff.	No. events P-P-2π	ln (ℒ)
1	A,B (a=b=1.0)	1.0	1.0	-	83.4±9.3	35.6±6.3	-	155.84
2	A,B,a,b	0.86±0.09	1.175±0.23	-	86.7	32.3	-	156.61
3	A,B,C (a=b=c=1.0)	1.0	1.0	1.0	74.6±12.0	28.2±9.0	16.0±14.0	156.54
4	A,B,C,a,b,c	0.906±0.244	1.31±0.45	1.03±1.0	76.4	24.5	17.5	157.43

[a]These events are such that the slowest and the fastest particle of the reaction are respectively the proton and a π^-.

FIGURE CAPTIONS

Fig. 1. The combinations of final particles along a rapidity axis: (a) and (b) correspond to diffractive dissocation: one large rapidity gap separates the two clusters. (c) Corresponds to the events that are expected to be dominated by DPE.

Fig. 2. Center-of-mass rapidity of the outgoing particles of the reaction $\pi^- p \to p\pi^+\pi^-\pi^-$ for the proton (a), π^+ (b), slow π^- (c), fast π^- (d).

Fig. 3. (a) R_{AB} versus R_{CD}. (b) R_{AB} versus R_{CD} normalized. (See text for definition of these variables.)

Fig. 4. Longitudinal rapidity interval between fastest and slowest outgoing particles, R_{AD}. (See text for definition of this variable.)

Fig. 5. Equilateral triangle built so that the altitudes from each point to the three sides represent respectively R_{AB}, R_{BC}, and R_{CD}. Events with (+) have "wrong ordering"; i.e., particle $A \neq$ proton (for region where $R_{AB} <$ 2.0) or $D \neq \pi^-$ (where $R_{CD} < 2.0$). Events with small solid circle (∘) have "right ordering" ($A = p$, $D = \pi^-$). Events with large solid circle (●) satisfy πPD mass cuts (see text) as well.

Fig. 6. The amplitude at the pion pole.

Fig. 7. An event satisfying the rapidity gap condition but not the πPD mass condition: the invariant mass $M_{\pi^+\pi^-}$ of the right-hand pair of pions lies in the ρ region.

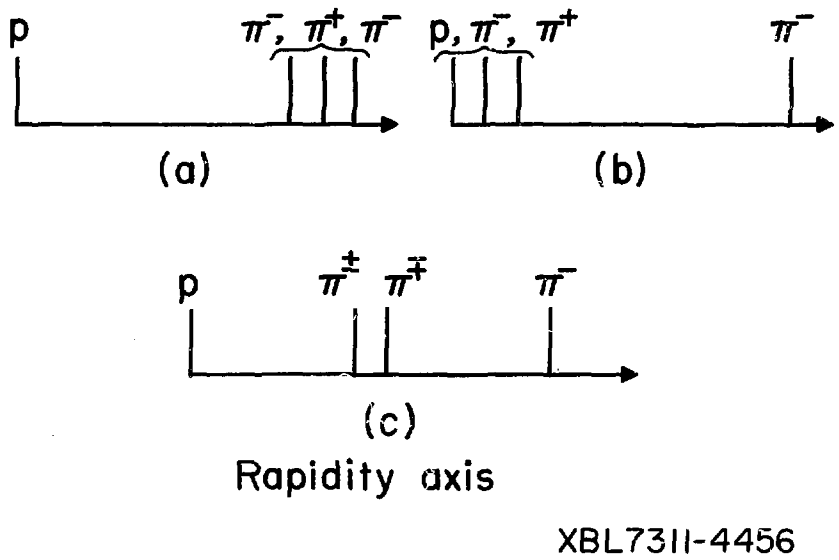

p
π^-, π^+, π^-
(a)
p, π^-, π^+
π^-
(b)
p
$\pi^\pm$
$\pi^\mp$
π^-
(c)
Rapidity axis
XBL7311-4456

Fig. 1

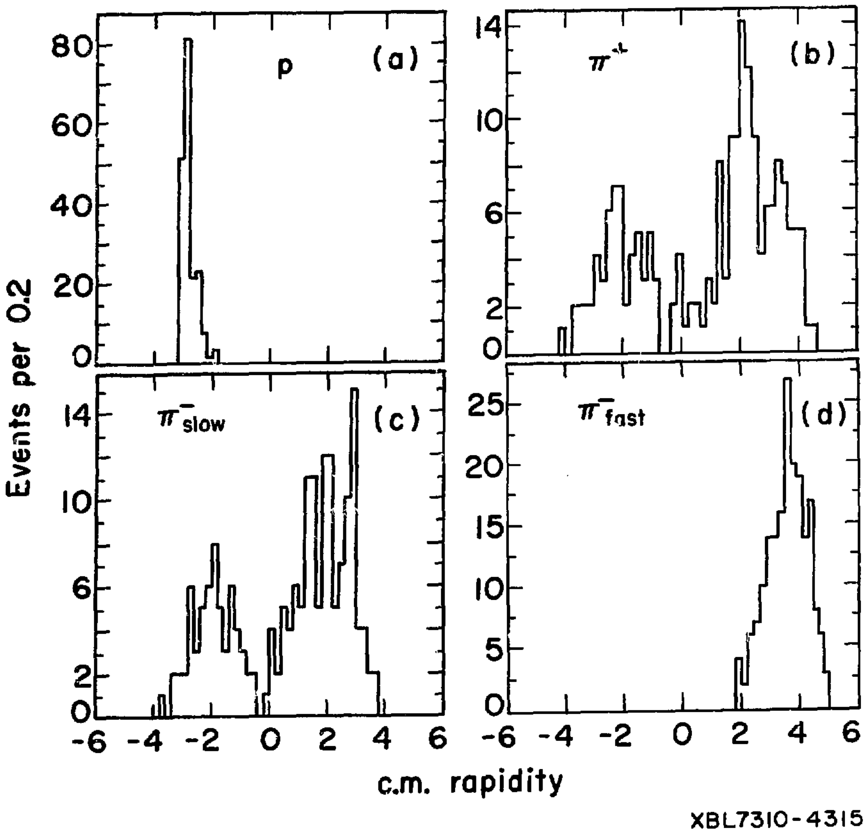

Events per 0.2
p
(a)
π^+
(b)
π^-_{slow}
(c)
π^-_{fast}
(d)
c.m. rapidity
XBL7310-4315

Fig. 2

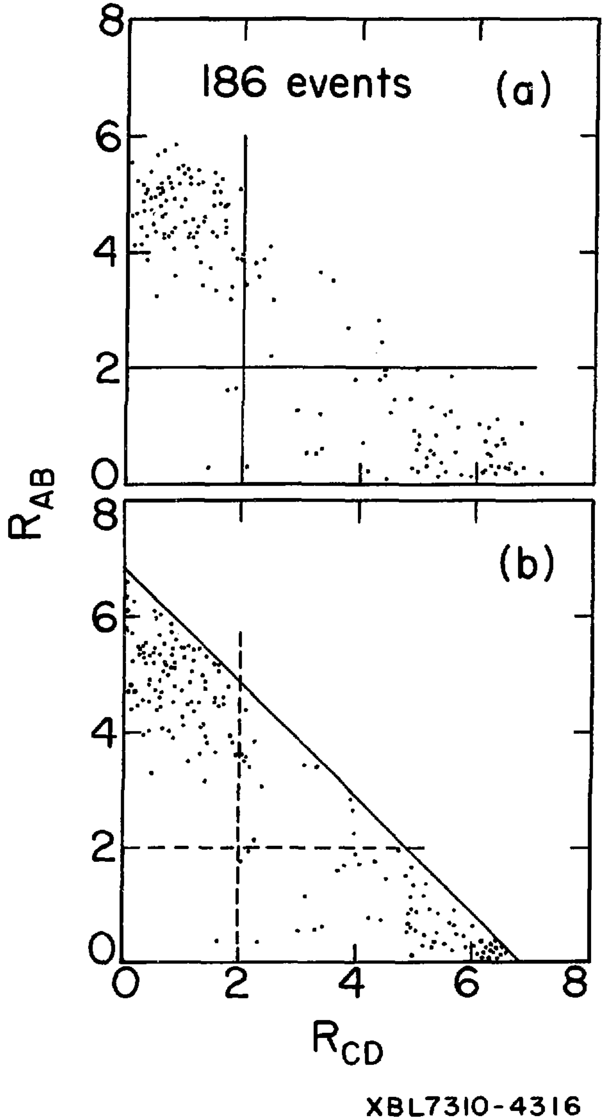


Fig. 3

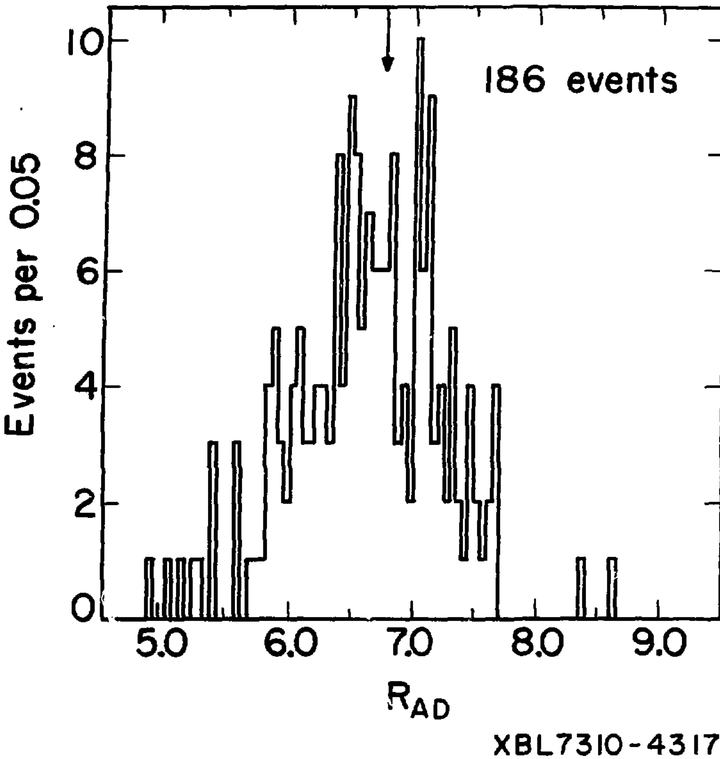
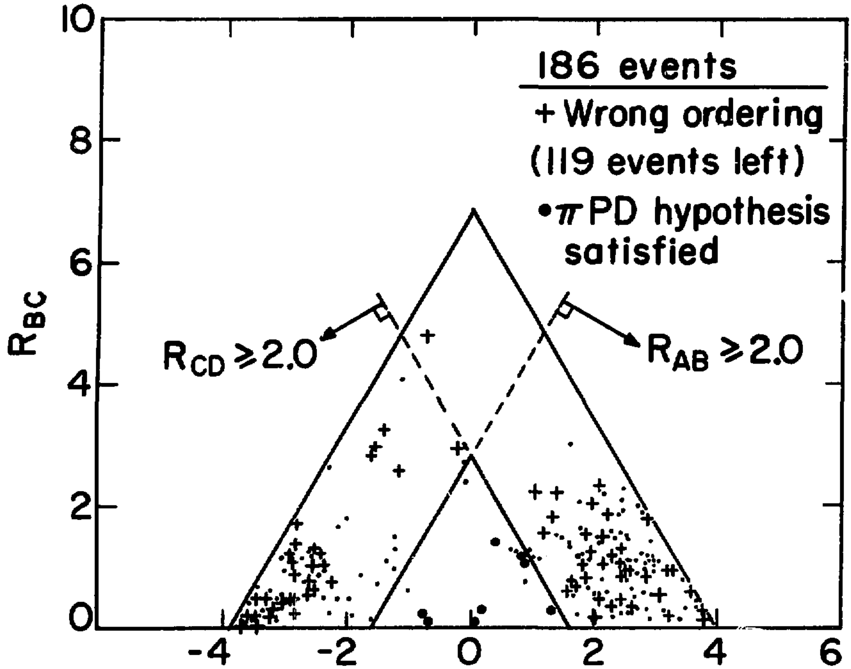

10
8
6
4
2
0
Events per 0.05
186 events
5.0
6.0
7.0
8.0
9.0
R_{AD}
XBL7310-4317

Fig. 4



XBL7310-4318

Fig. 5

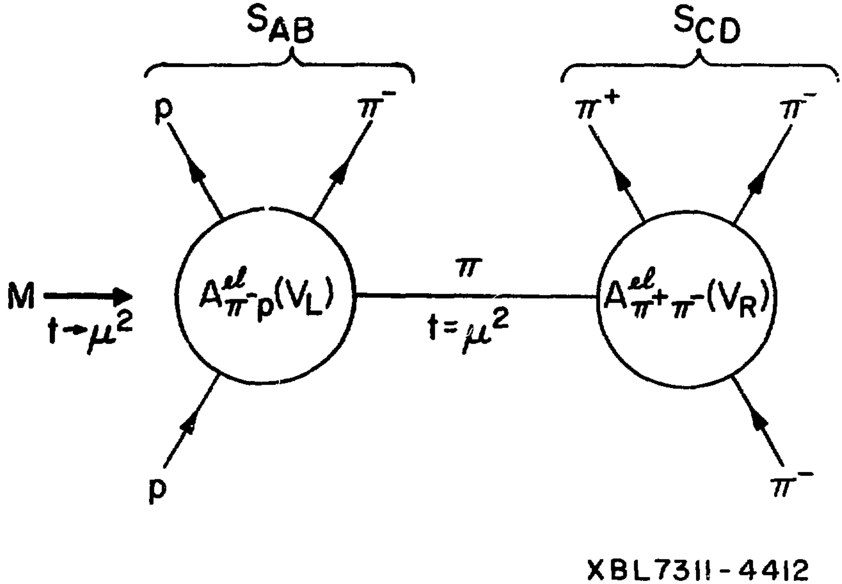
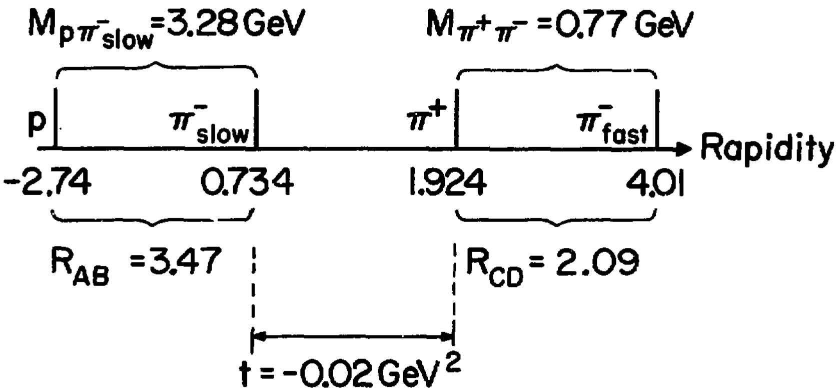

S_{AB}
S_{CD}
p
π^-
π^+
π^-
M
$t \to \mu^2$
$A^{el}_{\pi^- p}(V_L)$
π
$t = \mu^2$
$A^{el}_{\pi^+ \pi^-}(V_R)$
p
π^-
XBL7311-4412

Fig. 6



XBL7311-4411

Fig. 7