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QUARK MODEL AND CONSERVED CURRENTS IN VECTOR MESON Δ PRODUCTION*

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ABSTRACT

The quark model applied to reactions like $\pi^+ p \to \rho^0 \Delta^{++}$ requires certain decay moments for ρ and Δ to vanish (so-called class A predictions). These predictions are found in good agreement with the data at 7 GeV/c. If one assumes in addition that ρ and Δ couple to a conserved current as proposed by Cho and Sakurai, one gets further relations between the production amplitudes leading to additional constraints for the moments. These replace the usual so-called class B or C quark model predictions. They are also found to be in good agreement with experiment. With the assumption of class A type coupling the S wave background under the ρ or the K^* in $K^+ p \to K^{*0} \Delta^{++}$ can be determined. The S-wave cross sections are in good agreement with recent $\pi\pi$ and πK phase shift analyses. The more restrictive assumption of conserved current allows the determination of the phase between natural and unnatural exchange for ρ-production. This phase is found to be incompatible with the phase derived from Regge signature factors for π and A_2 exchange.

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I. QUARK MODEL PREDICTIONS AND CONSERVED CURRENT

In any analysis of only the cross section and moments from a reaction like

$$\pi^+ p \to \underset{\to \pi^+ \pi^-}{\rho^0} \; \underset{\to \pi^+ p}{\Delta^{++}} \tag{1}$$

one is faced with the difficulty that 20 measurable double decay moments are not sufficient to determine the 12 complex amplitudes. Therefore additional assumptions have to be made. To discuss these we write the helicity amplitudes $H_{r_p r_\Delta, r}$ for reaction (1) (r_p, r_Δ and r denote the helicities of p, Δ and ρ) in the form

$$H_{r_p r_\Delta, r} = \sum_{\ell=1,2} \langle \tfrac{1}{2}\, r_p \ell m \,|\, \tfrac{3}{2}\, r_\Delta \rangle \sqrt{\frac{2\ell+1}{4}}\, (T_{mr}\, \delta_{\ell,1} + U_{mr}\, \delta_{\ell,2}). \tag{2}$$

The least restrictive assumption consists in neglecting the double flip amplitudes $m = \pm 2$ at the baryon vertex

$$U_{\pm 2\, r} = 0 \,. \tag{3}$$

In principle this already allows one to perform an amplitude analysis, however the statistics of available data demand a more restricted set of amplitudes. In the additive quark model [1] ℓ has the meaning of the total spin of the H interacting quark pair. Since this spin cannot exceed 1, the seven $\ell = 2$ amplitudes have to vanish (usually called class A predictions [1]):

$$U_{mr} = 0 \tag{Q}$$

(Q) is not confined to the quark model [2]. Any theory of basically vector type interaction will have this property, for example the ρ-exchange model of ref. [3]. To get further restrictions we follow an idea of Cho and Sakurai [4]. Suppose one has a simple reaction $\pi p \to \rho p$ with scalar ρ and π. The helicity amplitudes T_r can be written as

$$T_r = \epsilon_\mu(r)\, j^\mu. \tag{3}$$

In their formulation of vector dominance they require the current j^μ to be conserved. This means:

$$j^\mu = p^\mu A_1 + p'^\mu A_2 \tag{4a}$$

and

$$k_\mu j^\mu = 0 \tag{4b}$$

(4b) must hold as an identity as the invariant mass squared $k^2 = m_\rho^2$ of the vector meson varies (p and p' denote the momenta of the incoming particle π and p). For the s-channel helicity (SCH) amplitudes, (4) leads to the relation (in the limit of large total energy $\sqrt{s}$ and fixed momentum transfer t):

$$T_0 = \sqrt{\frac{k^2}{-2t}}\; T_1 \tag{5}$$

(5) means helicity conservation in a frame where one chooses the vector

$$\vec{C} = \vec{p} + \frac{t-m_\pi^2}{s}\,\vec{p}' \tag{6}$$

in the rest frame of the ρ as z-axis. The coefficient in front of T on the r.h.s. of (5) is essentially the angle χ between $\vec{C}$ and the s-channel helicity direction $\vec{p}'$:

$$\mathrm{tg}\chi = 2\sqrt{\frac{-t}{k^2}}\,. \tag{7}$$

As pointed out in ref. [4] evaluation of (4b) as an identity in k^2 depends on the choice (4a) of invariant amplitudes for j^μ. The choice adopted in ref. [4] reflects the empirical rule that vector dominance should be formulated in terms of the SCH-amplitudes. The idea of ref. [4] originally developed for the reaction $\pi N \to \rho N$ can be generalized [5] to our case of production of a vector meson and a spin 1 "meson" as it occurs in (2). In this letter we state merely the results of the calculation and refer for details to ref. [5]. One finds that the condition analogous to (4) requires two relations of the type (5) for both the meson and the baryon side (again in the SCH system):

$$T_{01} = \sqrt{2}\, tg\chi \;\; T_{00} \tag{CC.1}$$

$$T_{10} = \sqrt{2}\, tg\chi' \;\; T_{00} \tag{CC.2}$$

$tg\,\chi$ is given by (7) and χ' is the analogous angle between the SCH direction for the Δ and the vector

$$\vec{C}' = \vec{p}' + \frac{t - m_p^2}{s}\,\vec{p} \tag{8}$$

in the Δ rest frame. Assumption (Q) reduces the 12 independent amplitudes to 5, imposing in addition our current conservation leads to three independent amplitudes. It is interesting to compare our conditions (CC) with the so-called quark model Class (B) or (C) predictions [1]: Class (B) says that the quark-quark interaction is independent of whether the quark is contained in a ρ or Δ. Therefore T should be a symmetric matrix:

$$T_{rm} = T_{mr}. \tag{9}$$

Due to the different masses of ρ and Δ prediction (9) is frame dependent. If (CC) are true, (9) cannot hold in the SCH system. However, it turns out, that crossing the relation (9) into the t-channel helicity system (TCHS) together with the empirical values of $T_{1\pm1}$ makes (9) hold numerically in a very good approximation in the TCHS. Class (C) requires helicity conservation in some frame [6]. (CC) state this only for the T_{0m} or T_{m0} amplitudes choosing the $\vec{C}$ or $\vec{C}'$ vector as axis for ρ or Δ. They are much weaker than Class (C) since no assumption about $T_{1\pm1}$ is involved. It is well known that Class (C) predictions are violated experimentally [7]. We close this section with a discussion of earlier proposals to perform a vector meson Δ analysis. The "dipole" model of ref.[8] is essentially the quark model (Q). An additional factorization assumption has been made to derive the quark model Class (B) prediction in the TCH system. Irving [9] imposes (Q) except that he keeps U_{01} which is required by some absorption models. Both methods have been

compared with $\rho\Delta$ data [7,9] at 3.9 GeV/c. The analysis of ref. [9] suffers from the improper treatment of the S-wave background under the ρ. The idea of a conserved current coupling for mesons [10] has been applied to the data [11]. However, this assumes factorization of the meson and baryon part. The finite cross section found at t = 0 for the natural exchange at t = 0 rules out any factorizable model (see next section).

II. COMPARISON WITH THE DATA

In this letter we want to present only the most sensitive tests of our assumption (CC) and (Q) and refer for a detailed analysis to ref. [5]. Experimentally there are two possible kinds of tests. The first requires the vanishing of certain linear combinations of moments. The second requires equality of phases and involves non-linear relation between moments. For example out of the eleven constraints in reaction (1) assuming (Q), six turn out to be linear. Usually these are called Class A predictions. Present statistics are too poor for a meaningful test of the non-linear ones. The linear constraints resulting from (Q) can be understood as follows: Assuming no S-wave background under the Δ, the following moment of the Δ decay distribution projects on natural exchange:

$$\mathcal{Y}_+(\Omega_\Delta) = \frac{1}{\sqrt{4\pi}} - \sqrt{5}\ Y_0^2(\Omega_\Delta) - \sqrt{30}\ \mathrm{Re}\ Y_2^2(\Omega_\Delta)\ . \tag{10}$$

The z axis can be chosen anywhere in the plane. For convenience we use the SCH direction throughout in this paper. Parity conservation implies only natural exchange contribution to (10) from the ρ. Choosing for the ρ-decay moments the normal to the production plane as z-axis only M = 0 moments can contribute to

$$\langle \mathcal{Y}_+ {}^{L}_{M} \rangle_N = \langle \mathcal{Y}_+(\Omega_\Delta) \cdot \mathrm{Re}\ Y_M^L(\Omega_N) \rangle\ . \tag{11}$$

The vanishing of the M = 1,2 moments $\langle \mathcal{Y}^{2}_{+m} \rangle_N$ leads to two constraints. A third follows that $\langle \mathcal{Y}^{2}_{+0} \rangle_N$ is proportional to $\langle \mathcal{Y}^{0}_{+0} \rangle_N$ ($\pi\pi$ S-wave cannot be produced by natural exchange)

$$\langle \mathcal{Y}^{2}_{+0} \rangle_N = \sqrt{\frac{4}{5}} \langle \mathcal{Y}^{0}_{+0} \rangle_N \qquad (12)$$

$$\langle \mathcal{Y}^{2}_{+M} \rangle_N = 0 \qquad M = 1,2 \ .$$

The other three Class A predictions can hold only in the case of vanishing S-wave under the ρ which is experimentally not the case. The experimental moments for (12) are shown in fig. 1a for the reaction $\pi^+ p \to \pi^+ \bar{\pi} \Delta^{++}$ at 7 GeV/c [12] as function of $\sqrt{-t}$. The prediction of (Q) are in excellent agreement with the data. This consists in a very sensitive test, since natural exchange contributes only 5% of the cross section at small t. Any $\ell = 2$ coupling in the dominant unnatural exchange would show up by large $M \neq 0$ moments in (12).

To test the more restrictive prediction of (CC) we project out the SCH m = 0 component at the Δ vertex by the moment

$$\mathcal{Y}_0(\Omega_\Delta) = \frac{1}{\sqrt{4\pi}} + 2\sqrt{5} \ Y^2_0(\Omega_\Delta) \ . \qquad (13)$$

Assumption (CC.1) relates the r = 0,1 amplitudes T_{0r} by a rotation around χ in the plane to a helicity conserving amplitude. Taking $\vec{C}$ as z-axis for the meson state in the moment

$$\langle \mathcal{Y}_0{}^{L}_{M} \rangle_C = \langle \mathcal{Y}_0(\Omega_\Delta) \cdot \ \mathrm{Re}\, Y^L_M(\Omega_C) \rangle \qquad (14)$$

we predict helicity conservation

$$\langle \mathcal{Y}_0{}^{2}_{M} \rangle_C = 0 \qquad M = 1,2$$

$$\langle \mathcal{Y}_0{}^{2}_{0} \rangle_C = \sqrt{\frac{4}{5}} \ \langle \mathcal{Y}_0{}^{0}_{0} \rangle_C \qquad (15)$$

From fig. 1b we see that (15) is again nicely satisfied experimentally. That means, that ρ couples to a conserved current as it does in the reaction

$$\pi^- p \to \rho^0 n . \tag{16}$$

Comparing $\langle \mathcal{Y}^2_{+0} \rangle_N$ and $\langle \mathcal{Y}^2_{00} \rangle_C$ one sees that at small t unnatural exchange (π) dominates, whereas at large t natural exchange gives the dominant contribution to the cross section. This same feature has also been seen in the reaction (16).

Due to the S-wave background under the ρ relation (CC.2) does not allow such a simple test.

III. APPLICATIONS

Assumptions (Q) or (CC) are useful to extract the amplitudes for Δ reactions. As examples we discuss:

(i) A derivation of S-wave cross section under the ρ assuming (Q)

(ii) Determination of the relative phase between the π exchange dominated amplitude T_{00} and the natural exchange amplitude $T_{++} = \frac{1}{2}(T_{11} + T_{1-1})$ assuming (CC).

With assumption (Q) the moments (14) cannot get any natural exchange contribution. In this case the S-wave cross section can be calculated from the ρ-decay moments alone. Therefore the following double moments project on the S-wave

$$\langle \mathcal{Y}_{0S} \rangle = \left\langle \mathcal{Y}_0(\Omega_\Delta) \left(\frac{1}{\sqrt{4\pi}} - \sqrt{\frac{5}{4}}\, Y^2_0(\Omega) - \sqrt{\frac{15}{2}}\, \mathrm{Re}\, Y^2_2(\Omega) \right) \right\rangle . \tag{17}$$

As z axis for ρ we can choose any axis in the plane. Multiplying (17) by the number of events one gets the S-wave cross section which is displayed for reaction (1) at 7 GeV/c [12] in fig. 2 as function of the $\pi\pi$ mass integrated over $|t| \leq 0.4\ \mathrm{GeV}^2$. Absence of any ρ signal provides again a sensitive test of assumption (Q). No narrow ϵ-resonance is seen. Near 1 GeV the cross

sections drops to zero giving direct experimental support for the $K\overline{K}$ cusp effect found in recent $\pi\pi$ analyses [12-14]. Assuming dominance of π-exchange we can convert these $\pi\pi$ amplitudes into S-wave cross section for reaction (1) to which we compare our S-wave cross section. The curve represents the energy dependent analysis of ref. [13]. The solution of ref. [12] and the (preferred) solution 1 of ref. [14] give very similar results. Above 1 GeV t_{min} effects cause the deviation between data and the curve which is based on the assumption $t_{min} = 0$. The dashed line represents solution 2 of ref. [14]. Our S-wave cross section clearly rules this out. The authors of ref. [14] already found this solution imcompatible with $\pi^0\pi^0$ mass spectrum from $\pi^- p \to \pi^0\pi^0 n$.

The same analysis can be performed for the reaction

$$K^+ p \to K^+ \pi^- \Delta^{++}. \tag{18}$$

The test of (Q) and (CC) for K^* using the data at 12 GeV/c from ref.[15] gives inside bigger errors the same results as displayed in fig. 1 for reaction (1). Figure 3 shows the $K\pi$ S-wave cross section from these data compared with the phase shift analysis of ref. [15]. The satisfactory agreement supports both the validity of our model and the analysis of ref. [15]. Due to the higher energy we encounter no difficulties with t_{min} effects.

In principle (Q) is sufficient for doing an amplitude analysis and therefore determining all relative phases. However, this requires highly non-linear expressions in the momenta. If one adds the stronger assumption (CC) the phase ϕ between the π-exchange amplitude T_{00} in the SCH system and the natural exchange amplitude T_{++} is a simple expression in terms of SCH moments:

$$\cos\phi = 4\sqrt{5}\,\langle \mathrm{Im}\, Y_1^2(\Omega_\Delta) \cdot \mathrm{Im}\, Y_1^2(\Omega)\rangle \cdot \left[-\langle \mathcal{Y}_+(\Omega_\Delta)\, \mathcal{Y}_2(\Omega)\rangle \cdot \langle \mathcal{Y}_0(\Omega_\Delta)\, \mathcal{Y}_2(\Omega)\rangle\right]^{-\frac{1}{2}} \tag{19}$$

where the SCH moments $\mathcal{Y}_{0,+}(\Omega_\Delta)$ are given by (11) and (13), and

$$\mathcal{Y}_2(\Omega) = Y_0^2(\Omega) + \sqrt{\frac{2}{3}}\,\mathrm{Re}\, Y_2^2(\Omega) \,. \tag{20}$$

Figure 4 shows the experimental results for ϕ from the 7 GeV/c data of ref. [12] as function of $\sqrt{-t}$ in the ρ-region. If T_{00} and T_{++} are dominated by a Regge π and A_2 exchange a constant $\phi = 45°$ would be expected. From fig. 4 we conclude that at least one of the amplitudes does not have the simple Regge signature factor (presumably T_{00}). The data are compatible with $\phi = \frac{\pi}{2}(\alpha_{A_2}(t)-1)$ indicating a Regge A_2 interfering with an elementary π exchange. However, due to absorptive corrections -- if they are present -- almost any phase can be expected. Therefore such a conclusion should be taken with caution.

IV. SUMMARY

The Class (A) predictions of the quark model have been found in very good agreement with the data on the reaction $\pi^+ p \to \rho^0 \Delta^{++}$. The assumption, that ρ couples to a conserved current à la Cho-Sakurai, replaces the usual Class (B) and (C) relation in the quark model. The prediction of this assumption has been found in excellent agreement with the same data. It has been demonstrated in two examples, that these assumptions consist in a very useful tool for analyzing Δ reactions.

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FIGURE CAPTIONS

Fig. 1(a). Double $\rho\Delta$ moments $\langle \mathcal{Y}_{+\,0}^{\;2}\rangle_N(\phi)$, $\langle \mathcal{Y}_{+\,2}^{\;2}\rangle_N(\phi)$, $\langle \mathcal{Y}_{+\,1}^{\;2}\rangle_N(\phi)$ and $\sqrt{\frac{5}{4}}\langle \mathcal{Y}_{+0}^{\;0}\rangle_N(\phi)$ for the reaction $\pi^+ p \to \rho\Delta^{++}$ at 7 GeV/c [12] as function of $\sqrt{-t}$. Quantization axis for the ρ is the normal to the decay plane. At the Δ vertex natural exchange has been projected out. The quark model predicts $\langle \mathcal{Y}_{+\,M}^{\;2}\rangle_N = 0$ for $M = 1,2$ and $\langle \mathcal{Y}_{+\,0}^{\;2}\rangle_N = \sqrt{\frac{5}{4}}\,\langle \mathcal{Y}_{+\,0}^{\;0}\rangle_N$.

(b). The double $\rho\Delta$ moments $\langle \mathcal{Y}_{0\,0}^{\;2}\rangle_C(\phi)$, $\langle \mathcal{Y}_{0\,2}^{\;2}\rangle_C(\phi)$, $\langle \mathcal{Y}_{0\,1}^{\;2}\rangle_C(\phi)$ and $\sqrt{\frac{5}{4}}\langle \mathcal{Y}_{0\,0}^{\;0}\rangle_C(\phi)$ for the same data as fig. 1(a) at function of $\sqrt{-t}$. The ρ quantization axis is the conserved current direction described in the text. S-channel helicity no flip at the Δ vertex is projected out. If couples to a conserved current, the $M = 1,2$ moments vanish and $\langle \mathcal{Y}_{0\,0}^{\;2}\rangle_C = \sqrt{\frac{5}{4}}\,\langle \mathcal{Y}_{0\,0}^{\;0}\rangle_C$.

Fig. 2. $\pi\pi$ S-wave cross section as function of the $\pi\pi$ mass integrated over $|t| \leq 0.4\ \mathrm{GeV}^2$ (same data as for fig. 1). The solid curve gives the prediction of K-matrix fit of the analysis of Ochs [13]. The dashed curve represents solution 2 of Estabrooks et al. [14].

Fig. 3. $K\pi$ S-wave cross section from $K^+p \to K^+\pi^-\Delta^{++}$ at 12 GeV/c [15] as function of the $K\pi$ mass for $|t| \leq 0.4$. The curve represents the effective range S-wave solution of ref. [15].

Fig. 4. Cosine of the phase between natural (T_{++}) and unnatural (T_{00}) exchange amplitude for $\pi^+p \to \rho\Delta^{++}$ at 7 GeV/c [12]. Regge signature factors for both π and A_2 exchange predict a constant. The line represents ϕ as suggested by a Regge A_2 and an elementary π exchange.

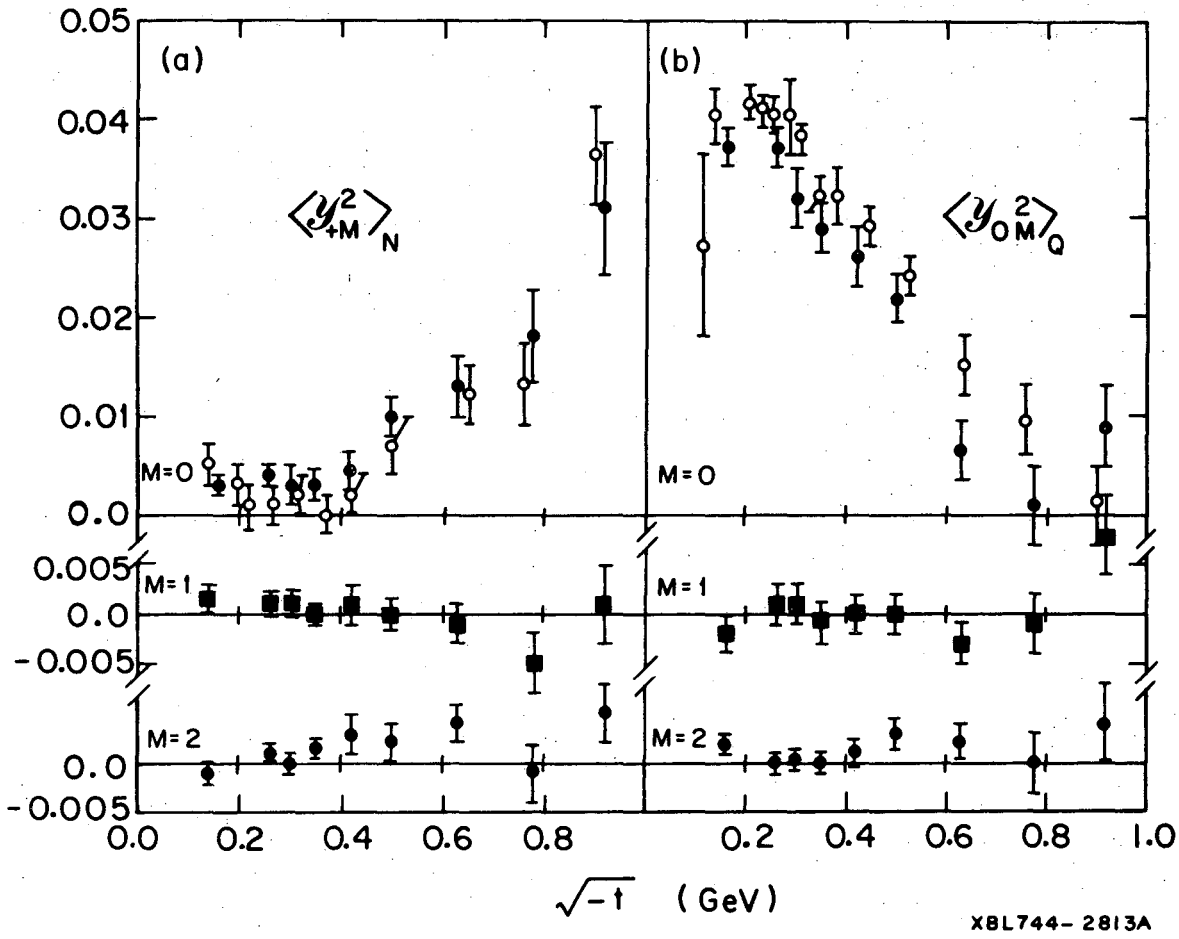
(a)
(b)
$\langle y^2_{+M} \rangle_N$
$\langle y^2_{0M} \rangle_Q$
M=0
M=1
M=2
0.05
0.04
0.03
0.02
0.01
0.0
0.005
-0.005
0.2
0.4
0.6
0.8
1.0
$\sqrt{-t}$ (GeV)
XBL744-2813A

Fig. 1.

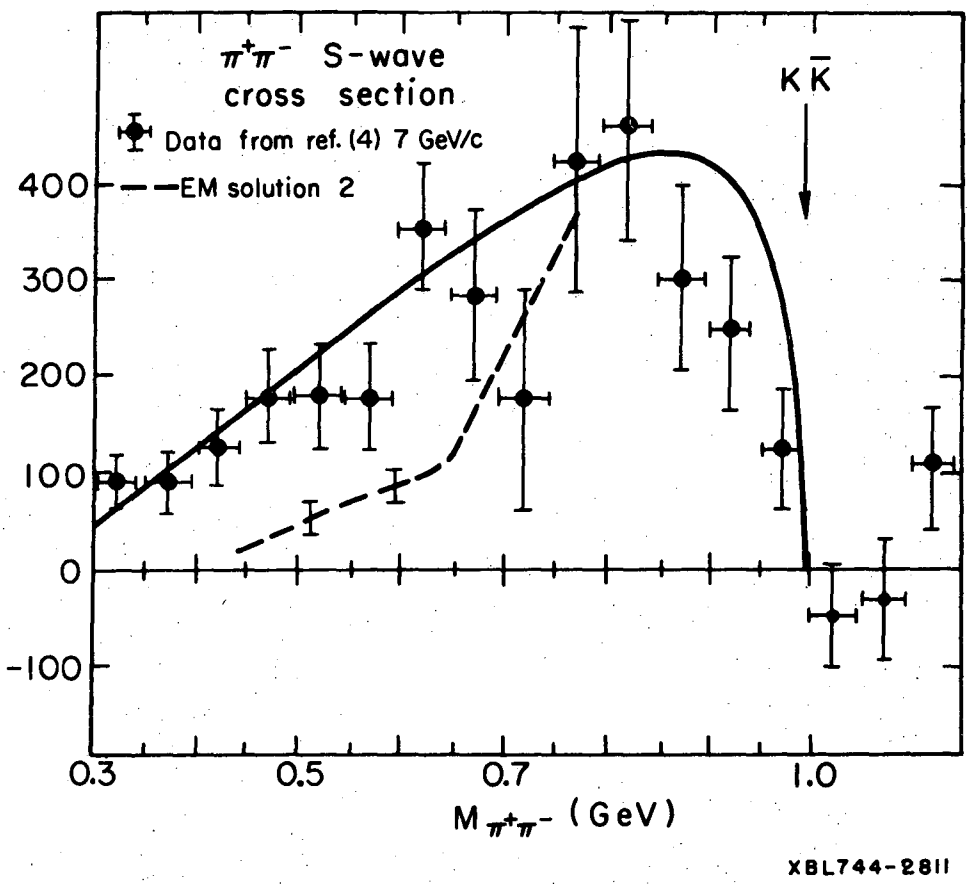
$\pi^+\pi^-$ S-wave
cross section
Data from ref. (4) 7 GeV/c
EM solution 2
$K\bar{K}$
400
300
200
100
0
-100
0.3
0.5
0.7
1.0
$M_{\pi^+\pi^-}$ (GeV)
XBL744-2811

Fig. 2.

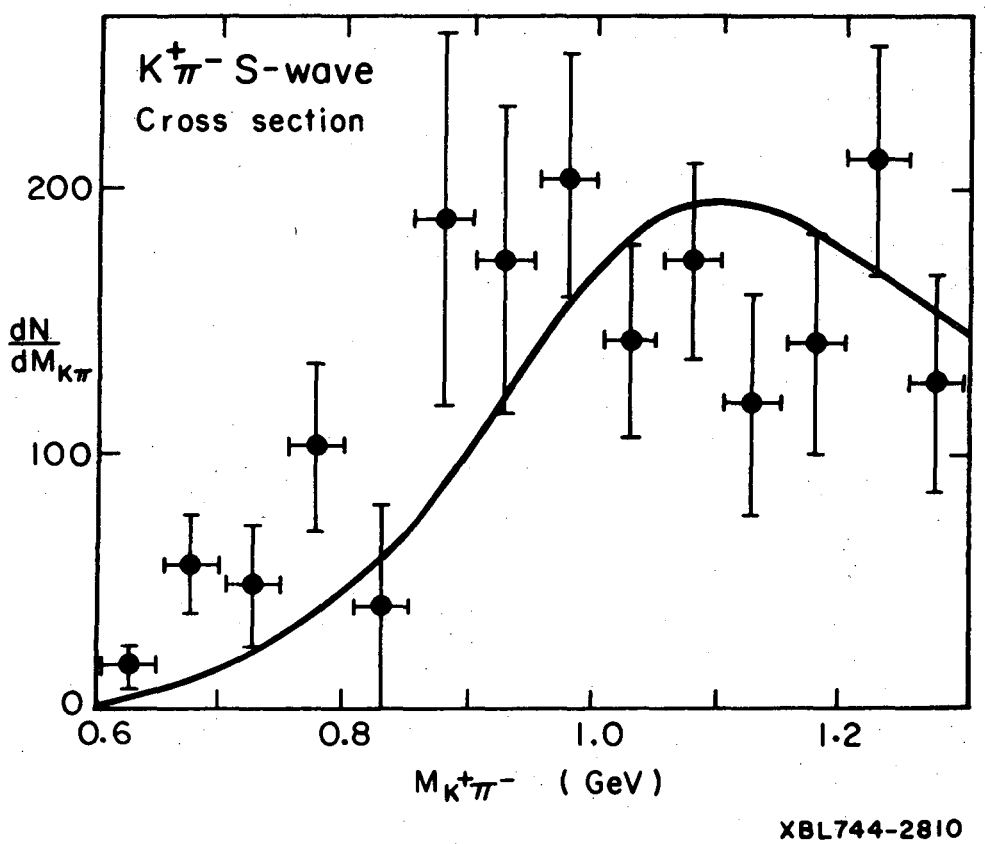
K+π− S-wave
Cross section
200
100
0
dN/dMKπ
0.6
0.8
1.0
1.2
MK+π− (GeV)
XBL744-2810

Fig. 3.

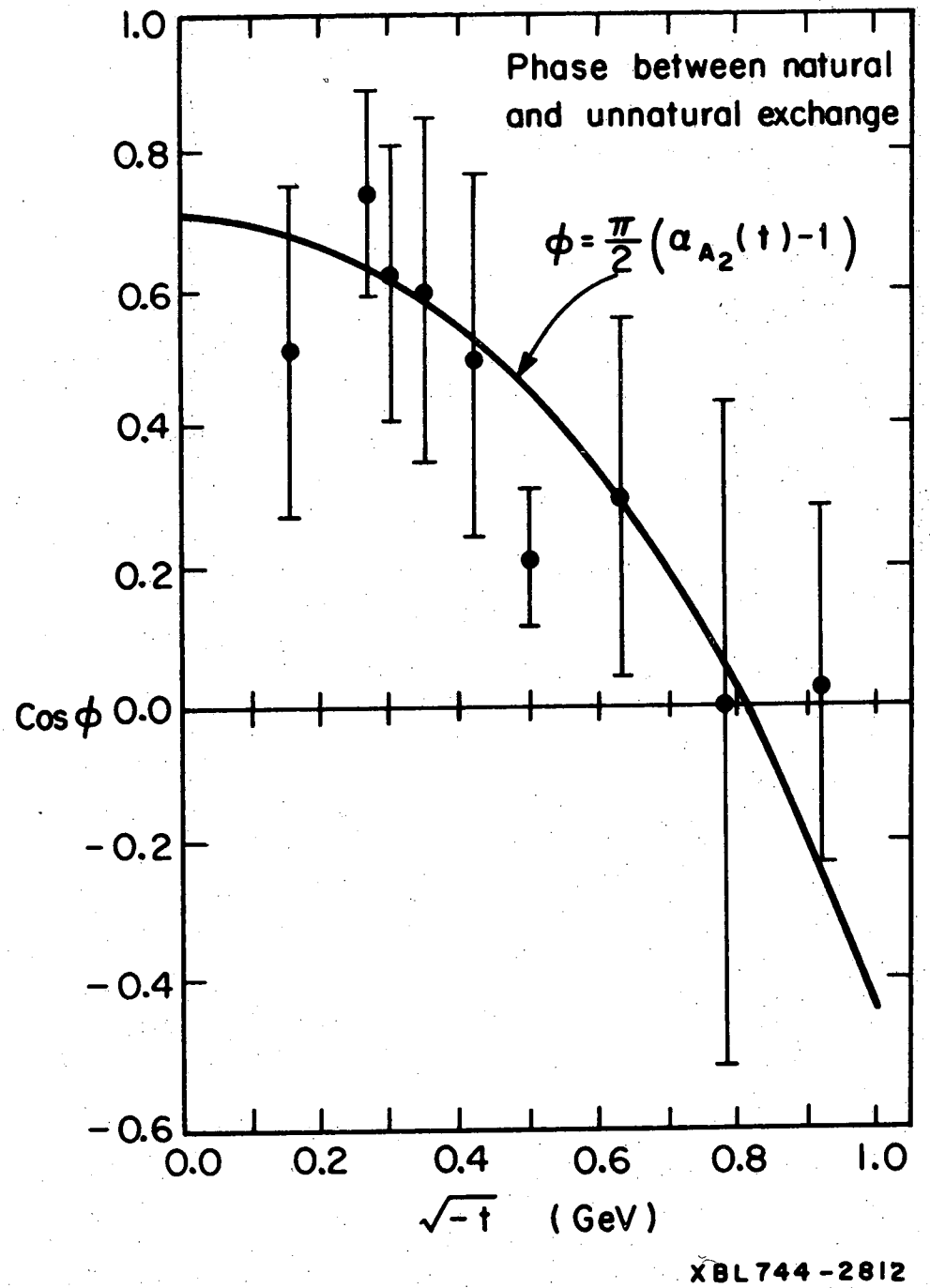
Phase between natural
and unnatural exchange
$\phi = \frac{\pi}{2}(\alpha_{A_2}(t)-1)$
1.0
0.8
0.6
0.4
0.2
Cos ϕ 0.0
-0.2
-0.4
-0.6
0.0
0.2
0.4
0.6
0.8
1.0
$\sqrt{-t}$ (GeV)
XBL744-2812

Fig. 4.

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