A STUDY OF EXCLUSIVE CENTRAL HADRON PRODUCTION
AT THE ISR AS A SEARCH FOR GLUONIUM STATES

The Axial Field Spectrometer Collaboration

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ABSTRACT

We present first results from a study of the exclusive reaction $pp \rightarrow p\pi^+\pi^-p$ at $\sqrt{s} = 63$ GeV with π^+ and π^- produced in the central region. This reaction has been suggested as a method of searching for gluonium states. The $\pi^+\pi^-$ mass distribution shows rapid order of magnitude decreases in cross-section at both 1000 MeV/c² and 1500 MeV/c². Further structure is observed above 2000 MeV/c².

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I. INTRODUCTION

We present high statistics data with good mass resolution on the exclusive reaction $pp \rightarrow p \pi^+ \pi^- p$ at the highest ISR energy, $\sqrt{s} = 63$ GeV. These are the first results from a general study of the properties of the mesonic system, M , produced centrally via the exclusive reaction $pp \rightarrow pMp$. The two final state protons have almost the full c.m. momentum of the incident protons, with $0.015 < |t| < 0.045$ (GeV/c)², $x_F \geq 0.95$, $\bar{x}_F = 0.99$ and $|y_p| \sim 4.2$, and are well isolated in rapidity from the central region, where $|y_\pi| \leq 1$. The state M must have $Q=B=S=0$. In the framework of Regge theory such events are produced by double pomeron exchange (DPE) [1] and the quantum numbers of M are further constrained to be $I=0$, $G=+1$, $C=+1$, and one expects $J^P = 0^+, 2^+, 4^+$ etc. Such a highly constrained system is of great interest for meson spectroscopy, especially in view of the importance of establishing the existence (or non-existence) of gluonium states (glueballs) [2] and the interpretation of the pomeron in QCD as multiple gluon exchange [3]. The possible value of this reaction in gluonium searches was first pointed out by Robson [4].

Earlier experiments at lower c.m. energies [5] did not isolate the DPE process ; for example the presence of a clear ρ^0 signal in the $\pi^+ \pi^-$ channel (forbidden for DPE) demonstrated a strong contamination from non-pomeron exchange. However at the highest ISR energies experiments [6] have obtained a signal with all the expected characteristics of DPE, but they were hitherto limited in both statistics and mass resolution. A signal was observed at $M_{\pi\pi}$ around 1300 MeV/c², attributed to the $f(1270)$, but no other significant structures were seen.

II. APPARATUS

The Axial Field Spectrometer (AFS) [7] is used for measuring the central hadrons. Charged particles are measured with up to 42 space-points per track in the cylindrical central drift chamber over $40^\circ < \theta < 140^\circ$ and $\sim 85\%$ of the azimuth ϕ , giving $dp/p \sim 2.5\%$ p (GeV/c). dE/dx measurements from the chamber are used for identification of particles as π , K or $p/\bar{p}$ in the low momentum region.

The trajectories of the forward protons are measured by small drift chamber telescopes installed ~ 9 m from the intersection region above (UP) and below (DOWN) each downstream beampipe, as shown in Fig. 1. The drift chambers, described in [8], each have four horizontal sense wires. The vertical drift distance is measured with a precision of $\sigma \sim 120 \mu\text{m}$ per wire, and the wires are equipped with charge division readout to give the horizontal position to $\sigma \sim 1.2$ mm. A final state proton passes through the ISR vacuum for ~ 8 m before emerging through a thin (0.2 mm stainless steel) window in a transition from a circular to an elliptical beampipe. Multiple scattering and magnetic deflections can be neglected, and we measure dy/dz and dx/dz with $\sigma \sim 10^{-4}$ and 3×10^{-4} respectively. Each forward chamber covers $3 \leq \theta \leq 8$ mrad over $\sim 45^\circ$ of azimuth ϕ .

Two ~ 30 mm x 30 mm scintillation counters at the front and back of each telescope provide a trigger for the reaction. Most of the solid angle not covered by the central detector or the forward drift chamber is covered by 100 scintillation counters. The OR of these counters is used as a veto in the trigger logic. The trigger required an AND of the following conditions :

- (i) a coincidence between the two scintillators in both forward 'UP' arms or both forward 'DOWN' arms (thus ensuring no background from elastic scattering);
- (ii) at least 2 elements of a 44-scintillator central cylindrical 'barrel' hodoscope to have hits;
- (iii) no detected charged particles in the angular regions covered by the veto counters.

III. DATA TAKING AND RECONSTRUCTION

We present results coming from the analysis of $\sim 930,000$ triggered events at $\sqrt{s} = 63$ GeV, which represent $\sim 40\%$ of our current data sample. The central tracks were reconstructed using the standard AFS pattern-recognition and track-fitting programs. Events were required to have two and only two well measured central tracks of opposite charge, with $dp/p < 0.1$, fitting to a common vertex within the interaction diamond.

Tracks were identified using the truncated mean of the dE/dx measurements after correcting for an observed run-to-run variation resulting from small fluctuations in the drift chamber gain. All central tracks were assigned to one of five identification classes: unambiguous π , K or $p/\bar{p}$, π/K ambiguous or $\pi/K/p$ ambiguous. A track (assumed to be a proton) was then required in each of the two forward drift chamber telescopes and its direction cosines found; for dy/dz only the information from the telescope itself was used, while for dx/dz the central vertex position was included in the fit. We then calculated the momenta of the forward protons, assuming an exclusive 4-prong event and using the constraints of energy and longitudinal momentum component, p_z . For this calculation the incident momenta were corrected for momentum compaction (i.e. the correlation between momentum and position within the beam) from the vertex position. The distribution of Σp_y , the vertical momentum component, of the four final state particles is centred at zero with $\sigma = 35$ MeV/c and a cut was applied at ± 60 MeV/c. Finally, we calculated the difference between the horizontal momentum component, Σp_x , of the initial and final states, which is sharply peaked, and applied a cut at ± 150 MeV/c. We estimate that the final exclusive sample, consisting of ~ 34000 events, contains $< 5\%$ residual background (either non-exclusive events or events where one of the four tracks was badly measured).

As the events are exclusive it is sufficient to identify one of the two central hadrons unambiguously and to require that the other be consistent with having the same identity. In fact only 0.3% of the events in this final sample have inconsistent identification (eg K with π , or K/π with p etc). Only ~ 300 events are classified as K^+K^- , requiring at least one K to be uniquely identified, and 19 as $p\bar{p}$. The vast majority of the events (98.9%) are either uniquely identified as, or consistent with being, $\pi^+\pi^-$ and we take them as such. It is to be noted that the K/π ratio in this sample is much less than that in typical hadronic collisions at this energy and a study of the K^+K^- events thus requires our full experimental statistics.

IV. THE $\pi^+\pi^-$ MASS SPECTRUM

Fig. 2a shows the effective mass distribution of the $\pi^+\pi^-$ events in 25 MeV/c² bins. The distribution rises rapidly from threshold, peaks at ~ 450 MeV/c² and then falls as $1/M^2$ until 950 MeV/c², with no clear enhancement at the ρ^0 mass. Absence of the ρ^0 signal is evidence that background from reggeon exchange is small. The distribution drops very rapidly between 950 MeV/c² and 1050 MeV/c², and then shows a broad enhancement centred at 1300 MeV/c². This higher mass region is better shown with the expanded vertical scale in Fig. 2b. One sees again a relatively rapid drop between 1400 and 1600 MeV/c² followed by a rather flat continuum. However the extension of the mass scale in Fig. 2c shows (now in 50 MeV/c² bins) that this continuum decreases again over a relatively narrow mass interval from 2300-2500 MeV/c². Near 3000 MeV/c² there are few events, and none above 3500 MeV/c².

The data of Figs. 2(a-c) are not corrected for acceptance as a function of mass. A straightforward Monte Carlo has been used to simulate the DPE process, generating t_1, t_2 of the final protons exponentially as $\exp(-\alpha|t|)$ and the rapidity of the central system uniformly within the range -1 to +1. The results are insensitive to the value of exponential slope parameter; $\alpha = 6.5$ (GeV/c)² has been used. To simulate an s-wave decay of the central system the $\pi^+\pi^-$ were produced isotropically in their overall rest frame. Simple geometrical cuts were imposed on the tracks. The resulting acceptance versus mass is shown in Fig. 2d. It clearly cannot give rise to the observed structures. We have carefully investigated whether the existence of definite momentum ranges for the identification of different particles can give rise to such effects, and conclude that they cannot. Above the K^+K^- threshold, in the region 1100-1400 MeV/c², the ratio $K^+K^-/\pi^+\pi^-$ is only $(8.5 \pm 1.5)\%$. The mass resolution is calculated to be $\sigma_M \sim 15$ MeV/c² at 1000 MeV/c² rising to $\sigma_M \sim 27$ MeV/c² at 2200 MeV/c². We estimate a possible systematic error on the mass scale of 20 MeV/c² at 1000 MeV/c² and 30 MeV/c² at 1500 MeV/c².

The complete mass distribution, corrected for s-wave acceptance, is shown in Fig. 3, using a logarithmic scale in order to present the full mass range together.

We have also collected a triggered sample of 38000 events at $\sqrt{s} = 45$ GeV, and analysed them in precisely the same way. The fixed angular coverage of the forward telescopes transforms the $|t|$ range at 45 GeV to $0.008 < |t| < 0.023$ (GeV/c)². The $\pi^+\pi^-$ mass spectrum at $\sqrt{s} = 45$ GeV (not shown) is very similar to that at $\sqrt{s} = 63$ GeV, and the same structures are observed up to masses ~ 1800 MeV/c². The limited statistics at $\sqrt{s} = 45$ GeV do not allow the comparison to be extended to higher masses.

V. ANGULAR DISTRIBUTIONS

In order to investigate further the nature of the $\pi^+\pi^-$ structures, we have examined the normalized moments of the angular distributions. For the purpose, we choose a coordinate system with the z-axis along the t-channel axis, $\vec{p}_1 - \vec{p}_3$ or $\vec{p}_2 - \vec{p}_4$, in the $\pi^+\pi^-$ rest frame and the y-axis perpendicular to the production plane in the pp c.m. system. In this coordinate frame, the normalized moments are defined by [9]:

$$\langle D_{MO}^L \rangle = H(LM) = \frac{1}{N} \sum_{i=1}^N D_{MO}^L(\theta_i, \phi_i, 0)$$

where

$$D_{MO}^{L*}(\theta, \phi, 0) = \sqrt{\frac{4\pi}{2L+1}} Y_M^L(\theta, \phi)$$

The angles (θ, ϕ) describe the π^+ direction in the $\pi^+\pi^-$ rest frame and N is the number of events in a given mass bin.

We find that the moments $H(11)$, $H(20)$, $H(22)$, $H(31)$ and $H(40)$ show definite non-zero structures as a function of the mass, while all other moments up to $L = M = 4$ exhibit no significant features and are consistent with zero throughout the mass region. The moments shown in Fig. 4 are uncorrected for acceptance and the curves give the Monte Carlo predictions, assuming s-wave decay of the di-pion system. The magnitudes of the $H(20)$, $H(22)$ and $H(40)$ moments are clearly largely accounted for by the Monte Carlo calculation, and we conclude that it is the s-wave that dominates the $\pi\pi$ system below 1100 MeV/c², as expected.

However, the structure around $750 \text{ MeV}/c^2$ in $H(11)$, also seen in $H(31)$, is not caused by acceptance effects. Although a ρ^0 signal is not visible in the $\pi^+\pi^-$ mass spectrum, our data must nevertheless contain a small amount of ρ^0 , producing interference effects between the s- and p-waves. The presence of the ρ^0 in our data indicates a small but significant contribution from a process other than double pomeron exchange. Between the ρ^0 mass and $1100 \text{ MeV}/c^2$ we do not find any significant structure in the moments beyond that accounted for by the finite acceptance. In particular it seems clear that the sharp drop at $1 \text{ GeV}/c^2$ seen in the mass spectrum is confined to that of the s-wave, indicating clearly the influence of the $S^*(980)$.

There is an indication that some d-wave may be present in the data, in the $1200\text{-}1400 \text{ MeV}/c^2$ region, possibly due in part to the $f(1270)$. However, this region may also contain the s-wave $\epsilon(1300)$.

VI. DISCUSSION

Our data demonstrate very clearly the process of exclusive central $\pi^+\pi^-$ production, with little contribution from non-pomeron exchange, in contrast to experiments at lower energies. We obtain directly from the experiment a predominantly s-wave $\pi^+\pi^-$ spectrum, which contains much structure.

In the low mass region, according to Pumplin and Henyey [1], the pomeron-pomeron interaction is mediated by one-pion exchange with a strong final-state interaction giving rise to the observed s-wave behaviour. On the other hand, from duality, one may also conclude that the same sub-process is mediated via s-channel resonances. The broad peak in the region around $500 \text{ MeV}/c^2$ may then be a manifestation of the strong s-wave $\pi\pi$ attraction previously referred to as the σ or $\epsilon(600)$. To the extent that the $S^*(980)$ is seen clearly in the DPE process, which has zero quark content in the initial state, the $S^*(980)$ may well harbour a large admixture of a $J^{PC} = 0^{++}$ glueball. This has been suggested by several authors [4,10] and Novikov et al [11] (and others) conclude that there must be very strong mixing between $0^+ q\bar{q}$ and gg states.

Between 1000 and 1600 MeV/c² structures are observed in the $\pi^+\pi^-$ spectrum and the $\langle D_{00}^2 \rangle$ and $\langle D_{00}^4 \rangle$ moments are suggestive of some d-wave contribution near 1300 MeV/c². These effects are consistent with the presence of f(1270), which could be responsible for the peak in the mass plot, although the $0^+ \epsilon(1300)$ is another known resonance in this region. The f is a further state for which $q\bar{q}$ and gg mixing has previously been suggested [12]. The region is followed by a sharp drop in di-pion production near 1500 MeV/c²; a striking feature for which we have no explanation.

The existence of the rather flat plateau in the $\pi^+\pi^-$ mass spectrum from 1600-2300 MeV/c², followed by a relatively rapid decrease (see Fig.2c), is an observation that we cannot readily interpret in terms of known states. More statistics may shed light on the dynamical origin of this region of the mass spectrum, and our data in other channels eg $\pi\pi\pi\pi$, $KK\pi\pi$ may provide clues. A possible hypothesis is that a heavy state eg $\epsilon(2300)$, $I_J^{GPC} = 0^+_{4^{++}}$, plays a similar role to that of the $S^*(980)$ in causing a rapid drop in the cross section. Clearly the 3 GeV/c² region, where the cc threshold occurs, would also be of great interest to study with higher statistics.

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REFERENCES

- [1] R. Schankar, Nucl. Phys. B63 (1974) 168
D.M. Chew and G.F. Chew, Phys. Lett. 53B (1974) 191
D.M. Chew, Phys. Lett. 65B (1976) 367
J. Pumplin and F.S. Henyey, Nucl. Phys. B117 (1976) 377
B.R. Desai, B.C. Chen and M. Jacob, Nucl. Phys. B142 (1978) 258
- [2] See. e.g.
H. Fritzsch and M. Gell Mann, Proc. XVI Int. Conf. on HEP, Chicago (1972) p. 135
H. Fritzsch and P. Minkowski, Nuovo Cimento 30A (1975) 393
R.L. Jaffe, K. Johnson, Phys. Lett. 60B (1976) 201
C.E. Carlson, J.J. Coyne, P.M. Fishbane, F. Gross and S. Meshkov, Phys. Lett. 99B (1981) 353
J.F. Donoghue, K. Johnson and B.A. Li, Phys. Lett. 99B (1981) 416
H.J. Lipkin, Phys. Lett. 106B (1981) 114
I. Cohen, N. Isgur and H.J. Lipkin, Phys. Lett. 48 (1982) 1074
- [3] F.E. Low, Phys. Rev. D12 (1975) 163
S. Nussinov, Phys. Rev. Lett. 34 (1975) 1286
S. Nussinov, Phys. Rev. D14 (1976) 246
A. Donnachie and P.V. Landshoff, Phys. Lett. 123B (1983) 345
A. Donnachie and P.V. Landshoff, Cambridge DAMTP Preprint 82/33 (1983)
- [4] D. Robson, Nucl. Phys. B130. (1977) 328
- [5] M. Derrick et al., Phys. Rev. D9 (1974) 1215
J.C.M. Armitage et al., Phys. Lett. 82B (1975) 149
M. Della Negra et al., Phys. Lett. 65B (1976) 394
V. Blobel et al., Nucl. Phys. B69 (1974) 237
D. Denegri et al., Nucl. Phys. B98 (1975) 189
- [6] L. Baksay et al., Phys. Lett. 61B (1976) 89
H. de Kerret et al., Phys. Lett. 68B (1977) 385
D. Drijard et al., Nucl. Phys. B143 (1978) 61
R. Waldi, K.R. Schubert and K. Winter, Heidelberg Preprint IHEP-HD/83-2, submitted to Z. Phys.
- [7] H. Gordon et al., Nucl. Instrum. Methods 196 (1982) 303
O. Botner et al., Nucl. Instrum. Methods 196 (1982) 315
- [8] M.G. Albrow et al., Rutherford Preprint RL-83-014, to be published in Nucl. Instrum. Methods
- [9] S.U. Chung, CERN Yellow Report 71-8
- [10] Y.M. Cho, J.L. Cortes and X.Y. Pham, PAR-LPTHE 81-08 (1981)
Y.M. Cho and W. Weinzierl, PAR-LPTHE 81-10 (1981)
E. Etkins et al., Phys. Rev. D25 (1982) 2446
S. Minami, Osaka City Univ. preprint OCV-103 (1983)
- [11] V.A. Novikov, M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B191 (1981) 301
- [12] J. Rosner, Phys. Rev. D24 (1981) 1347
N.A. Törnqvist, Helsinki, preprint HU-TFT 83-23 (1983)

FIGURE CAPTIONS

- Fig. 1 Schematic side view of the apparatus. Only the right-hand forward detectors are shown ; the apparatus is left-right symmetric.
- Fig. 2 (a) Mass spectrum, not corrected for acceptance, of the central $\pi^+\pi^-$ events in 25 MeV/c² bins;
 (b) Shows the region 1000-2300 MeV/c² with an expanded vertical scale;
 (c) Shows the region 1500-3500 MeV/c² in 50 MeV/c² bins.
 (d) The relative acceptance (arbitrary scale with maximum value unity) as a function of $M(\pi^+\pi^-)$ calculated from Monte Carlo events generated within a DPE model with s-wave decay of the di-pion system.
- Fig. 3 Mass spectrum of the central $\pi^+\pi^-$ events with a logarithmic ordinate, corrected for s-wave acceptance.
- Fig. 4 The normalized moments a) $\langle \text{Re } D_{10}^1 \rangle$, b) $\langle D_{00}^4 \rangle$, c) $\langle D_{00}^2 \rangle$, d) $\langle \text{Re } D_{20}^2 \rangle$ versus mass of the $\pi^+\pi^-$ system. The solid curves are Monte Carlo results for the effective moments produced by the acceptance of the apparatus for s-wave decay of the $\pi^+\pi^-$ system.

Fig. 1

Fig. 2

Fig. 3

Fig. 4