EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/79-07
1 February 1979

# A STUDY OF THE REACTION $p + p \to p + p + X$ AT ISR ENERGIES

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We have performed an experiment to investigate the reaction $p + p \to p_1 + p_2 + X$ at the CERN Intersecting Storage Rings (ISR). The dependence of the cross-section on the mass and rapidity of the system X, and on the momentum transfer squared $t_1$, $t_2$ to the outgoing protons is studied. We observe signals for the production of $\rho$, $\omega$, f, and $A_2$ mesons in the missing-mass spectra, and conclusions are made about the contribution of double-Pomeron exchange.

Geneva - 8 January 1979
(Submitted to Physics Letters)

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We have performed an experiment at the CERN ISR to study the reaction $p + p \to p_1 + p_2 + X$ with the Feynman x of each of the two outgoing protons larger than 0.8. This study has been prompted by previous experiments[1] on the reaction $p + p \to p + X$ with the x of the outgoing proton close to 1. This latter process exhibits a large peak in the inclusive cross-section for low masses of the system X. The dependence of the cross-section corresponding to this peak on the c.m. energy $\sqrt{s}$ and the momentum transfer $\sqrt{|t|}$ is characteristic of diffractive excitation. The dependence of this cross-section on the mass of X is well described in Regge theory by the exchange of a Pomeron.

In analogy with the characteristics of this process, it is of interest to examine the features of the process where two high-x protons emerge, and to observe a possible contribution to the cross-section from double Pomeron exchange. One approach is to study the features of the inclusive cross-section as a function of the missing mass M and rapidity y of system X, and as a function of the momentum transfers squared, $t_1$ and $t_2$, to the outgoing protons; M and y are approximately related to the x of protons 1 and 2 by:

$$\frac{M^2}{s} \simeq (1 - x_1)(1 - x_2) \quad ; \quad y = \frac{1}{2} \ln\left(\frac{1 - x_1}{1 - x_2}\right) .$$

Alternatively, one can search for resonances in the missing-mass spectra of final states with specified multiplicity. Only resonances with vacuum quantum numbers such as the f and f′ can be produced by the exchange of two Pomerons; the occurrence of mesons with odd C or G parity necessarily results from other exchanges.

In this letter we present data showing both the features of the inclusive cross-section and the results of a missing-mass analysis for specific exclusive channels. The data were taken at c.m. energies $\sqrt{s}$ = 23, 30, 45, 52, and 63 GeV. At the two lowest energies the mass resolution and the number of events collected were sufficient to exhibit resonances in the missing-mass spectra.

The two protons $p_1$ and $p_2$ were detected by two high-resolution ($\Delta p/p \sim 0.6\%$) single-arm spectrometers positioned at forward angles [1,2] in intersection 2 of the CERN ISR. One of the spectrometers covered the range of polar angles $10 < \theta < 30$ mrad below the downstream beam 2; the other one covered the range $30 < \theta < 50$ mrad above the downstream beam 1. The polar angles were always chosen such that elastically scattered protons were not accepted. The geometrical acceptance of the first spectrometer was $0.7 \times 10^{-4}$ sr and the geometrical acceptance of the second spectrometer was $3 \times 10^{-4}$ sr. In each spectrometer only particles with Feynman $x > 0.7$ were accepted in the trigger. In the mass range $0 < M < 3$ GeV the acceptance varied nearly linearly with mass. In addition, a hodoscope system [3] covering $\simeq 98\%$ of $4\pi$ provided a measurement of the direction vectors of the charged particles of the system X. No particle identification was required since in the momentum region of the protons detected at forward angles ($x > 0.8$) the contamination of other particles is less than 0.1% [4].

The dependence of the inclusive cross section on missing mass is indicated in figs. 1a and 1b. There the cross-section, integrated over the indicated rapidity intervals, is shown as a function of $M^2/s$ for $s = 939$ GeV$^2$, $t_1 = -0.30$ GeV$^2$, and $t_2 = -0.04$ GeV$^2$, and for $s = 2783$ GeV$^2$, $t_1 = -0.68$ GeV$^2$, and $t_2 = -0.16$ GeV$^2$, respectively. For increasing $M^2/s$, the cross-section drops and then flattens out. The dependence on rapidity is shown in figs. 1c and 1d for $0.006 < M^2/s < 0.008$ at $s = 939$ GeV$^2$ and $s = 2783$ GeV$^2$. In the region of rapidity $-0.6 < y < 0.6$ the cross-section is approximately flat and it rises as $|y|$ increases. The cross-section at positive values of y is slightly higher than at negative values as the two production angles are different. The y-dependence at other values of $M^2/s$, s, $t_1$, and $t_2$ shows similar features. Generally the data tend to scale in $M^2/s$, and this has been used to study the t-dependence over the full range of the data. In fig. 1e, the data at fixed $M^2/s$ and y are plotted against $(t_1 + t_2)$ and, despite the fact that there is only partial overlap in t between the different s-values, we observe a smooth dependence on t. Fitting to the form $\exp[B(t_1 + t_2) + C(t_1^2 + t_2^2)]$ we find $B = 6.3 \pm 0.4$ GeV$^{-2}$, $C = 0.9 \pm 0.4$ GeV$^{-4}$.

averaged over $M^2/s \leq 0.15$, $-0.6 \leq y \leq 0.6$. These values agree within errors with the slope parameters found in single diffraction data ($p + p \to p + x$) [1]. This simple dependence on $t_1 + t_2$ suggests some form of factorization.

The above features of the data can be understood in terms of the exchange of two trajectories between the leading protons and the system X. We have considered four possible exchanges: PP, RP, PR, and RR, where P = Pomeron and R = effective non-Pomeron trajectory. The data were fitted to the expression

$$\sigma_{inv} = \sum_{ij} \frac{\sigma_{ij}(M^2, t_1, t_2)}{(2\pi)^2} g_i^2(t_i) g_i^2(t_j) e^{-2y[\alpha_i(t_1) - \alpha_j(t_2)]} \left(\frac{M^2}{s}\right)^{1-\alpha_i(t_1)-\alpha_j(t_2)} ,$$

which describes the exchange of two trajectories characterized by the slopes $\alpha_i$ and $\alpha_j$. We have used the following trajectories indicated by our earlier data on single diffraction:

$$\alpha_P(t) = 1.0 + 0.1\ t\ ; \quad \alpha_R(t) = 0.45\ t\ .$$

The results of the fit are indicated in figs. 1a to 1d for s = 939 and 2783 $GeV^2$ Both the contributions of each of the four exchange terms and their sum are shown. This fit shows that the rise in the cross-section at low $M^2/s$ and the flatness of the y-distributions are not inconsistent with a PP contribution. If, however, the slope and intercept of the effective non-Pomeron trajectory are left as free parameters, no PP contribution is *required* to fit the data. The presence or absence of a PP term as deduced from the inclusive cross-sections is thus strongly tied to the choice of the non-Pomeron trajectory.

With the same apparatus we also measured single inclusive cross-sections for the reaction $p + p \to p + X$. We were thus able to determine the correlation factor R defined as:

$$R = \sigma_{tot} \frac{d^6\sigma}{dp_1^3 dp_2^3} \Big/ \left(\frac{d^3\sigma}{dp_1^3} \cdot \frac{d^3\sigma}{dp_2^3}\right) .$$

We find that in the ranges $x_1$, $x_2 > 0.8$, $|t_1 + t_2| \lesssim 1.3$ $GeV^2$, and M > 2 GeV, the factor R is constant and equal to $1.5 \pm 0.2$. A naïve double Pomeron model without absorption would predict factorization with R = 1.

Integration of the double inclusive cross-section over the range $M^2/s \leq 0.01$, $|y| \leq 0.6$ yields 200 ± 30 μb averaged over the energy range of the data.

In a search for resonance signals in the missing-mass spectra, we integrate the data over y and t. As the resolution depends strongly on both the c.m. energy and the rapidity of the system X, and has a minimum at y = 0, we limit the search for resonances to the two lowest c.m. energies and select a region in rapidity $-0.8 < y < 0.8$. For s = 550 GeV$^2$ this results in a $\sigma(M)$ of ≃ 150 MeV; and for s = 940 GeV$^2$ in a $\sigma(M)$ ≃ 200 MeV.

The missing-mass spectra within these limits of rapidity are shown in Fig. 2. We observe resonance signals at mass values of 770 ± 70 MeV and 1270 ± 70 MeV with FWHMs of around 400 MeV for both c.m. energies. Given the experimental resolution, the mass and the width of the first peak are compatible with the presence of the ρ and/or the ω resonance, while those of the second peak are compatible with the presence of the $A_2$ and/or f resonance.

Separation of the ρ/ω and f/$A_2$ signals is obtained by selecting those resonances that decay into two charged pions. The branching ratios for the ρ and f to two charged pions are 100% and 66.7%, respectively, whereas those of the ω and $A_2$ are 1.3% and 0%. With the mass of the decay particles fixed to the pion mass, a two-constraint fit has been applied to the kinematics of the process $p + p \rightarrow p + p + \pi^+ + \pi^-$. Events that do not correspond to two-body decays, but still count in the spectra with charged multiplicity 2 -- for example the $A_2$ decay into $\pi^+\pi^0\pi^-$ and no gammas converting -- will in general not satisfy the kinematics for two-body decays. Using the $\chi^2$ cuts applied in this analysis we have calculated the sensitivity of this procedure by fitting the kinematics of events with charged multiplicity 4, for which two of the four available direction cosines are selected at random. On the average, 17% of those events, depending slightly on the c.m. energy and on the mass, are accepted by the fit.

The missing-mass spectra for two-body and non-two-body decays are shown in fig. 3. The non-resonant backgrounds have been calculated from a Poisson distribution for charged and neutral pions using as input a flat non-resonant background for the missing-mass spectra with no cut on the multiplicity and an averaged charged multiplicity in agreement with that recorded by the hodoscopes; this average multiplicity is a function of the mass of system X. In fig. 3 these backgrounds are shown to describe the shapes of the high-mass end of the two-body and non-two-body decay spectra adequately.

At the $\rho/\omega$ mass, clear signals for $\rho$ and $\omega$ production are seen. At the $f/A_2$ mass, a signal for f production is only just statistically significant above the evaluated background and the residual contamination by non-two-body decays, and a strong $A_2$ peak is seen in the three-body data. Differential cross-sections for these resonances in the interval of rapidity $-0.8 < y < 0.8$ for both energies are listed in table 1. Corrections for conversion, absorption and random counts in the counter hodoscope have been applied.

Assuming the same t-dependence as was observed for the inclusive data, we obtain integrated resonance cross-sections for $|y| \leq 0.8$ in the range 10-30 μb (see table 1). Integration of the non-resonant background puts an upper limit of $20 \pm 6$ μb for $s = 550$ GeV$^2$ and $15 \pm 5$ μb for $s = 940$ GeV$^2$ on the production of double-Pomeron-generated two-body final states.

Several experiments [5-7] have previously investigated the reaction $p + p \to p + p + \pi^+ + \pi^-$ at ISR energies. The experiment of Drijard et al. [5] reports cross-sections integrated over the total mass-range of $14.4 \pm 3.1$ μb and $11.0 \pm 1.2$ μb for $s = 550$ and $940$ GeV$^2$, respectively. These authors apply different rapidity and mass cuts to their data, and application of their cuts to our total two-body sample gives an integrated cross-section of $12 \pm 2$ μb at $s = 550$ GeV$^2$. None of the above-mentioned experiments show evidence for the production of the $\rho$ or f resonances.

The energy dependence of the production cross-section of the resonances seen in the present experiment follows by comparing the data with those of Blobel et al. [8] at $s = 25$ and $49$ GeV$^2$. Integrating their data between $-0.8 < y < 0.8$ results in cross-sections of 50-100 μb for the $\rho$, $\omega$, and f (see fig. 4). (There are no data on $A_2$ in this energy range.)

In Regge theory, the energy dependence of the cross-section for a fixed interval in rapidity and at a fixed mass is given by

$$\sigma \sim s^{\alpha_i(0) + \alpha_j(0) - 2} ,$$

where $\alpha_i(0)$ and $\alpha_j(0)$ are the exchanged Regge trajectories taken at $t = 0$.

An eye-ball fit to the data gives a slope $\alpha_i(0) + \alpha_j(0) - 2 = -0.70 \pm 0.15$. Considering three types of trajectory, i.e. the Pomeron trajectory (P), the vector-meson trajectory (V), and the pseudo-scalar-meson trajectory (S) with $\alpha(0) = 1.0$, 0.5 and 0.0, respectively, we find that any of the combinations PV, VV, and PS are in reasonable agreement with the $\rho$ and $\omega$ data. As the energy dependence of f production is similar to that observed for the $\rho$ and $\omega$, we deduce that it is unlikely that the double-Pomeron exchange process dominates in its production.

In summary [9] we have presented the dependence of the inclusive cross-section for the reaction $p + p \rightarrow p + p + X$ in terms of the variables $M^2/s$, $y$, and $t_1 + t_2$. A Regge fit to this inclusive data indicates that a double-Pomeron contribution could be present, but this conclusion depends on the choice of the effective non-Pomeron trajectory. We have defined a correlation factor R relating this cross-section to that of the single inclusive reaction $p + p \rightarrow p + X$, and found that this factor is constant and equal to $1.5 \pm 0.2$ in the given kinematic region. The total cross-section for the double inclusive reaction has been found to be $200 \pm 30$ μb in the rapidity range $-0.6 \leq y \leq 0.6$ and for $M^2/s < 0.01$.

We have observed signals for $\rho$, $\omega$, f, and $A_2$ production at $s = 550$ and 940 GeV$^2$. The cross-sections in the interval of rapidity $-0.8 \leq y \leq 0.8$ are of the order of 10–30 μb. The relatively strong excitation of the three mesons with odd G or C parity as well as the observed energy dependence of the f meson indicates that the bulk of the low multiplicity final states is not produced through double-Pomeron exchange.

This experiment was supported by the Nederlandse Organisatie voor Zuiver Wetenschappelijk & Onderzoek through FOM, and by the UK Science Research Council through the Daresbury Laboratory.

We would like to pay a special tribute to our colleague and friend Peter Benz. It was with great sadness that we learned of his death on 13 July, 1977.

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**Table 1**

Cross-sections of observed resonances
in the rapidity range $-0.8 \leq y \leq 0.8$

| | s ($GeV^2$) | $t_1$ ($GeV^2$) | $t_2$ ($GeV^2$) | $\rho$ | $\omega$ | f | $A_2$ |
|---|---|---|---|---|---|---|---|
| $\frac{d^2\sigma}{dt_1 dt_2}$ ($\mu b\ GeV^{-4}$) | 550 | -0.26 | -0.06 | 71 ± 19 | 76 ± 24 | 55 ± 50 | 190 ± 56 |
| | 940 | -0.35 | -0.09 | 19 ± 6 | 19 ± 7 | 19 ± 10 | 56 ± 16 |
| $\sigma$ ($\mu b$) | 550 | | | 13 ± 4 | 14 ± 5 | 11 ± 10 | 36 ± 11 |
| | 940 | | | 8 ± 2 | 8 ± 3 | 8 ± 4 | 23 ± 7 |

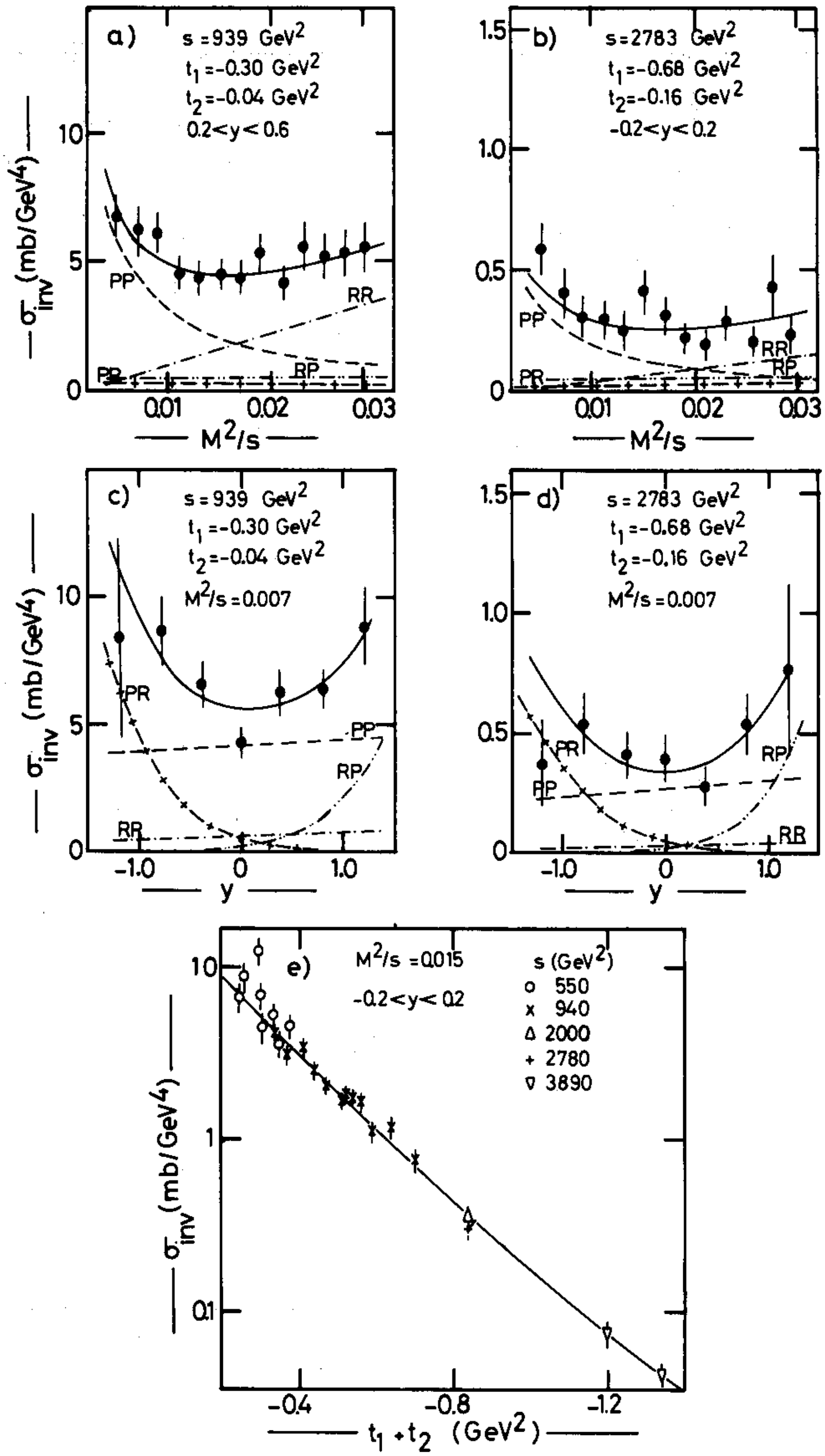
## Figure captions

Fig. 1 : The double inclusive cross-section for $p + p \to p_1 + p_2 + X$ at $s = 939$ and $2783\ GeV^2$ versus $M^2/s$ (a,b) and rapidity y (c,d). The curves show the fit with a double Regge model and its breakdown into four terms as discussed in the text; e) double inclusive cross-section versus $t_1 + t_2$. The dotted line is the fit discussed in the text.

Fig. 2 : Inclusive cross-sections versus missing mass of the reaction $p + p \to p + p + X$ at $s = 550$ and $940\ GeV^2$. The rapidity of the missing-mass system X lies in the range $-0.8 < y < 0.8$. The resolution in rapidity decreases with decreasing missing mass and is less than 0.5, a third of the range in rapidity, to the left of the broken lines.

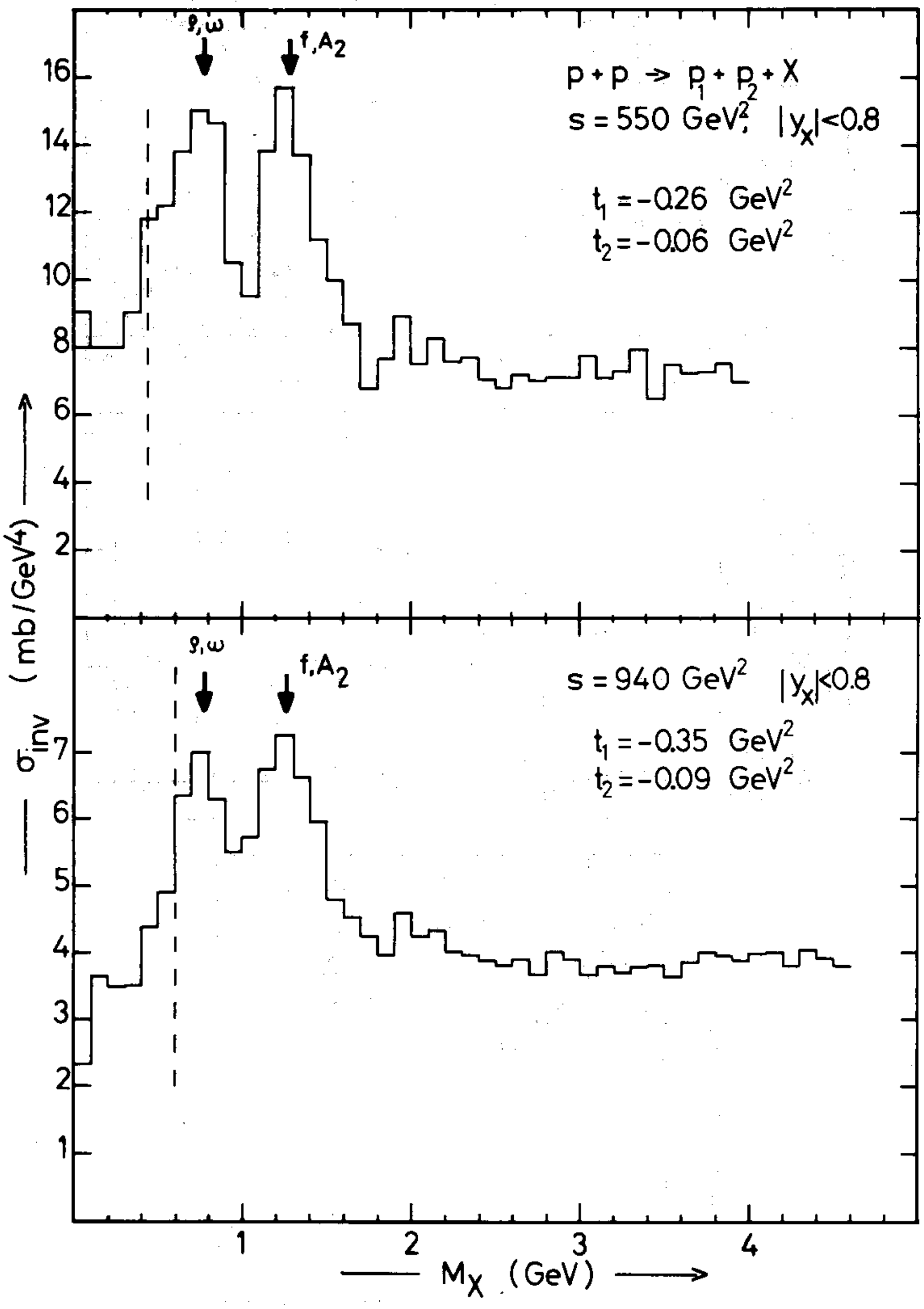
Fig. 3 : Missing-mass spectra of the reaction $p + p \to p + p + X$ with selection criteria. The non-resonant background is indicated by the dash-dot line.

Fig. 4 : Total cross-sections for resonance production in the reaction $p + p \to p + p + X$ as a function of $\sqrt{s}$.



a)
s = 939 GeV2
t1 = -0.30 GeV2
t2 = -0.04 GeV2
0.2 < y < 0.6
b)
s = 2783 GeV2
t1 = -0.68 GeV2
t2 = -0.16 GeV2
-0.2 < y < 0.2
c)
s = 939 GeV2
t1 = -0.30 GeV2
t2 = -0.04 GeV2
M2/s = 0.007
d)
s = 2783 GeV2
t1 = -0.68 GeV2
t2 = -0.16 GeV2
M2/s = 0.007
e)
M2/s = 0.015
-0.2 < y < 0.2
s (GeV2)
o 550
x 940
Δ 2000
+ 2780
∇ 3890
σinv (mb/GeV4)
M2/s
y
t1 + t2 (GeV2)
PP
RR
PR
RP


Fig. 1



ρ,ω
f,A2
p + p → p1 + p2 + X
s = 550 GeV², |yX|<0.8
t1 = -0.26 GeV²
t2 = -0.06 GeV²
s = 940 GeV² |yX|<0.8
t1 = -0.35 GeV²
t2 = -0.09 GeV²
σinv (mb/GeV⁴)
MX (GeV)


Fig. 2

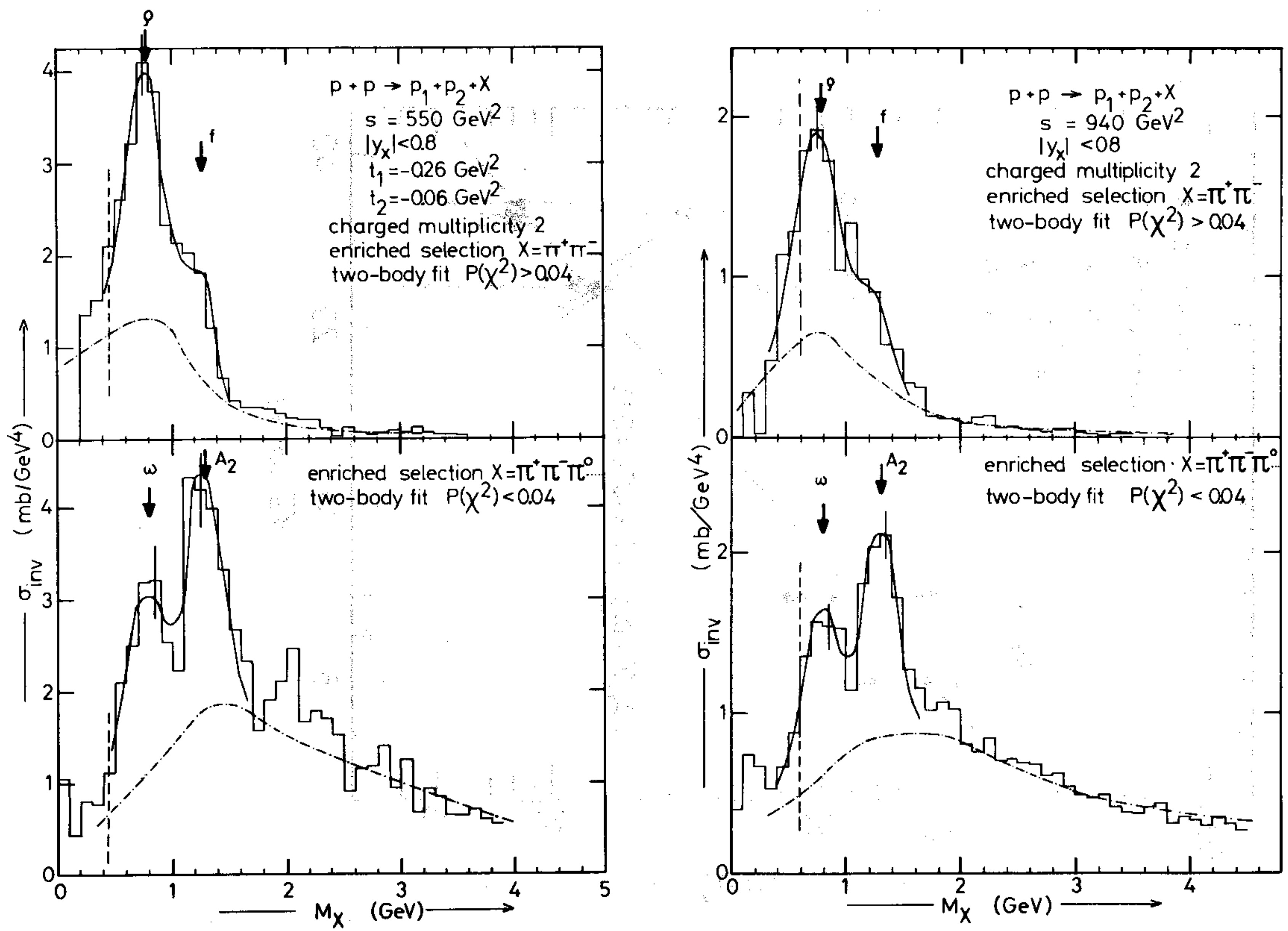
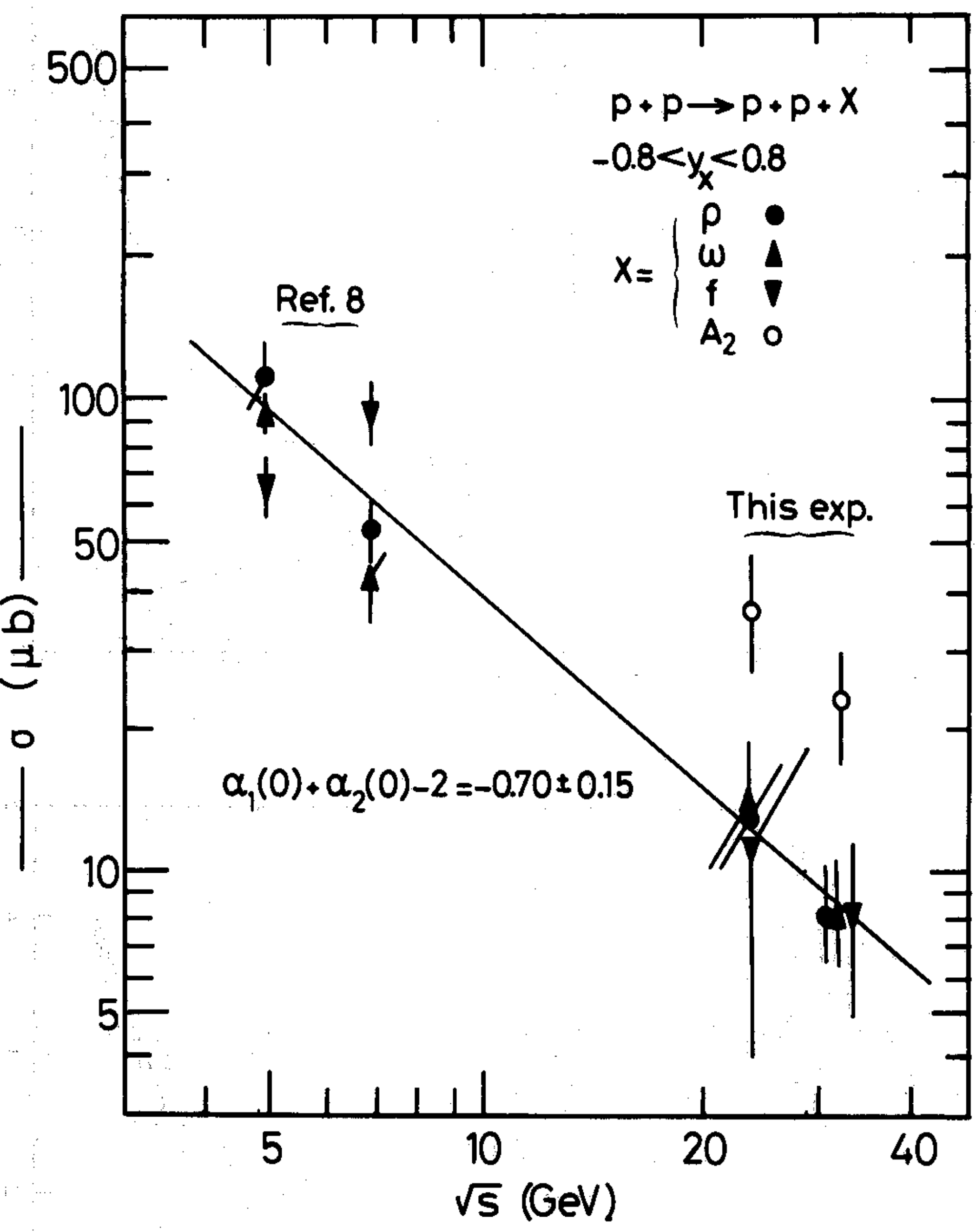

p + p → p1 + p2 + X
s = 550 GeV2
|yx|<0.8
t1 = -0.26 GeV2
t2 = -0.06 GeV2
charged multiplicity 2
enriched selection X=π+π−
two-body fit P(χ2)>0.04
enriched selection X=π+π−π0
two-body fit P(χ2)<0.04
ρ
f
ω
A2
σinv (mb/GeV4)
MX (GeV)
p + p → p1 + p2 + X
s = 940 GeV2
|yx| <0.8
charged multiplicity 2
enriched selection X=π+π−
two-body fit P(χ2) > 0.04
enriched selection X=π+π−π0
two-body fit P(χ2) < 0.04

Fig. 3



500
100
50
10
5
5
10
20
40
√s (GeV)
σ (μb)
p + p → p + p + X
-0.8<y_X<0.8
X = ρ ● ω ▲ f ▼ A2 ○
Ref. 8
This exp.
α1(0) + α2(0) - 2 = -0.70 ± 0.15


Fig. 4

13