Observation of tensor glueball in the reactions $p\bar{p} \to \pi\pi, \eta\eta, \eta\eta'$

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Partial wave analysis of the reactions $p\bar{p} \to \pi\pi, \eta\eta, \eta\eta'$ in the region of invariant masses 1900–2400 MeV indicates to the existence of four relatively narrow tensor-isoscalar resonances $f_2(1920)$, $f_2(2020)$, $f_2(2240)$, $f_2(2300)$ and the broad state $f_2(2000)$. The determined decay couplings of the broad resonance $f_2(2000) \to \pi^0\pi^0, \eta\eta, \eta\eta'$ satisfy the relations appropriate to those of tensor glueball, while the couplings of other tensor states do not, thus verifying the glueball nature of $f_2(2000)$.

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In [1], the combined partial wave analysis was performed for the high statistics data on the reactions $p\bar{p} \to \pi^0\pi^0, \eta\eta, \eta\eta'$ taken at antiproton momenta 600, 900, 1150, 1200, 1350, 1525, 1640, 1800 and 1940 MeV/c together with data obtained for polarised target in the reaction $\bar{p}p \to \pi^+\pi^-$ [2] that resulted in the determination of a number of isoscalar resonances f_J with $J = 0, 2, 4$ (for the review see [3 – 5]). In the 02^{++}-sector, five states are required to describe the data [1, 3]:

Resonance	Mass(MeV)	Width(MeV)	
$f_2(1920)$	1920 ± 30	230 ± 40	
$f_2(2000)$	2010 ± 30	495 ± 35	
$f_2(2020)$	2020 ± 30	275 ± 35	(1)
$f_2(2240)$	2240 ± 40	245 ± 45	
$f_2(2300)$	2300 ± 35	$290 \pm 50.$	

The resonance $f_2(1920)$ was observed earlier in spectra $\omega\omega$ [6 – 8] and $\eta\eta'$ [9, 10], see also compilation [11]. For the broad tensor-isoscalar resonance in the region around 2000 MeV the recent analyses give: $M = 1980 \pm 20$ MeV, $\Gamma = 520 \pm 50$ MeV in $pp \to pp\pi\pi\pi\pi$ [12] and $M = 2050 \pm 30$ MeV, $\Gamma = 570 \pm 70$ MeV in $\pi^-p \to \phi\phi n$ [13]. Following [1, 12, 13] , we denote the broad resonance as $f_2(2000)$.

The description of data in the reactions $p\bar{p} \to \pi^0\pi^0, \eta\eta, \eta\eta'$ is illustrated by Fig.1. In Fig.2,3, one can see differential cross sections $p\bar{p} \to \pi^+\pi^-$, while Fig.4 presents the polarisation data. In Fig.5, we show cross sections for $p\bar{p} \to \pi^0\pi^0, \eta\eta, \eta\eta'$ in the ${}^3P_2\bar{p}p$ and ${}^3F_2\bar{p}p$ waves (dashed and dotted curves) and total ($J = 2$) cross section (solid curve) as well as the Argand-plots for the ${}^3P_2$ and ${}^3F_2$ wave amplitudes at invariant masses $M = 1.962$, 2.050, 2.100, 2.150, 2.200, 2.260, 2.304, 2.360, 2.410 GeV.

Partial wave analysis [1, 3] together with recent data for $\gamma\gamma \to K_SK_S$ [14] and re-analysis of $\phi\phi$-spectra [13] have clarified the situation with f_2-mesons in the mass region 1700 – 2400 MeV. Based on these data, there was performed in [15] a systematisation of the non-exotic f_2-mesons on the (n, M^2)-trajectories, where n is the radial quantum number of the $q\bar{q}$-state. The systematisation [15] shows us that the broad resonance $f_2(2000 \pm 30)$ is an extra state for the (n, M^2)-trajectories being apparently the lowest tensor glueball. However, the statement about glueball nature of $f_2(2000)$ was based on indirect arguments.

(i) The leading Pomeron trajectory $\alpha_P(M^2) = \alpha_P(0) + \alpha'_P(0)M^2$ has the following values for the intercept and slope : $\alpha(0) \simeq 1.10 - 1.30$ and $\alpha'_P(0) \simeq 0.15 - 0.25$ (see, for example, [16 – 18]). These Pomeron parameters give for the tensor glueball $M \simeq 1.7 - 2.5$ GeV.

(ii) In the lattice calculations, a close value was obtained, namely, $M \simeq 2.2 - 2.4$ GeV [19].

(iii) The large width of $f_2(2000)$ can be considered as a signature of the glueball origin of this state. Exotic state appearing in a set of $q\bar{q}$ resonances accumulates their widths, thus transforming into broad resonance [20]. The phenomenon of width accumulation has been studied in [21, 22] for scalar glueball $f_0(1200 - 1600)$, and much earlier this phenomenon was observed in nuclear physics [23 – 25].

Direct arguments for the glueball nature of $f_2(2000)$ can be provided by the relations between decay coupling constants, and for tensor glueball such relations were presented in [15]. In [1, 3], the extraction of the decay couplings $f_J \to \pi\pi, \eta\eta, \eta\eta'$ was not performed — in the present paper we fill in this gap. The $\bar{p}p \to \pi^0\pi^0, \eta\eta, \eta\eta'$ amplitudes provide us the following ratios for the f_2 resonance couplings, $g_{\pi^0\pi^0} : g_{\eta\eta} : g_{\eta\eta'}$:

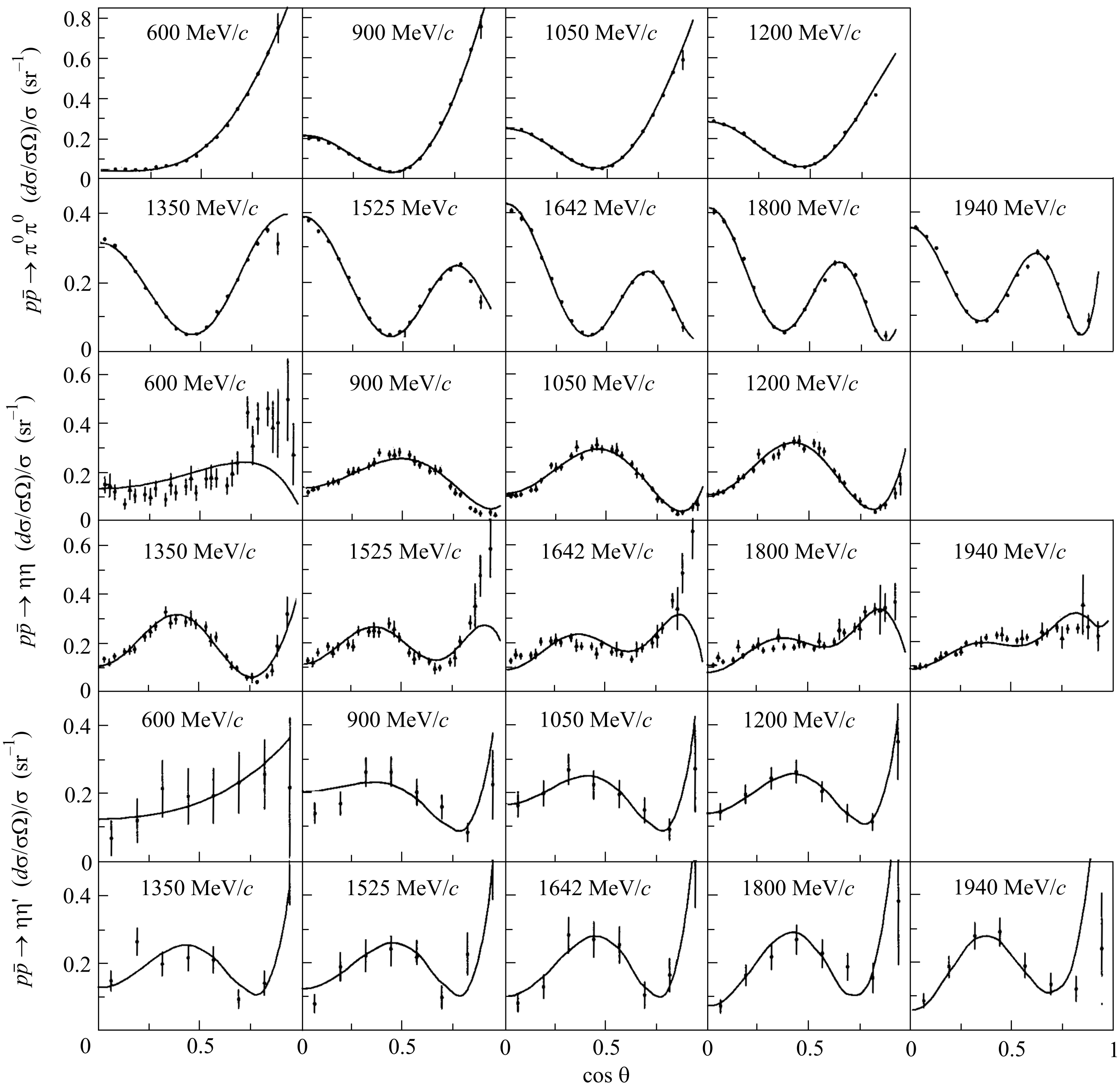

Fig.1. Angle distributions in the reactions $p\bar{p} \to \pi\pi, \eta\eta, \eta\eta'$ and their fit to resonances of eq.(1)

$$
\begin{aligned}
f_2(1920):&\quad 1 : 0.56 \pm 0.08 : 0.41 \pm 0.07,\\
f_2(2000):&\quad 1 : 0.82 \pm 0.09 : 0.37 \pm 0.22\\
f_2(2020):&\quad 1 : 0.70 \pm 0.08 : 0.54 \pm 0.18,\\
f_2(2240):&\quad 1 : 0.66 \pm 0.09 : 0.40 \pm 0.14,\\
f_2(2300):&\quad 1 : 0.59 \pm 0.09 : 0.56 \pm 0.17. \qquad (2)
\end{aligned}
$$

These ratios are to be compared with those given in [15].

In the leading terms of $1/N_c$-expansion [26], there exist definite ratios for the glueball decay couplings. The next-to-leading terms in the decay couplings give the corrections of the order of $1/N_c$ (see, for example, [4]); numerical calculations of diagrams tell us that $1/N_c$ factor leads to a smallness of the order of 1/10, and we neglect them. For the transitions tensor glueball $\to$

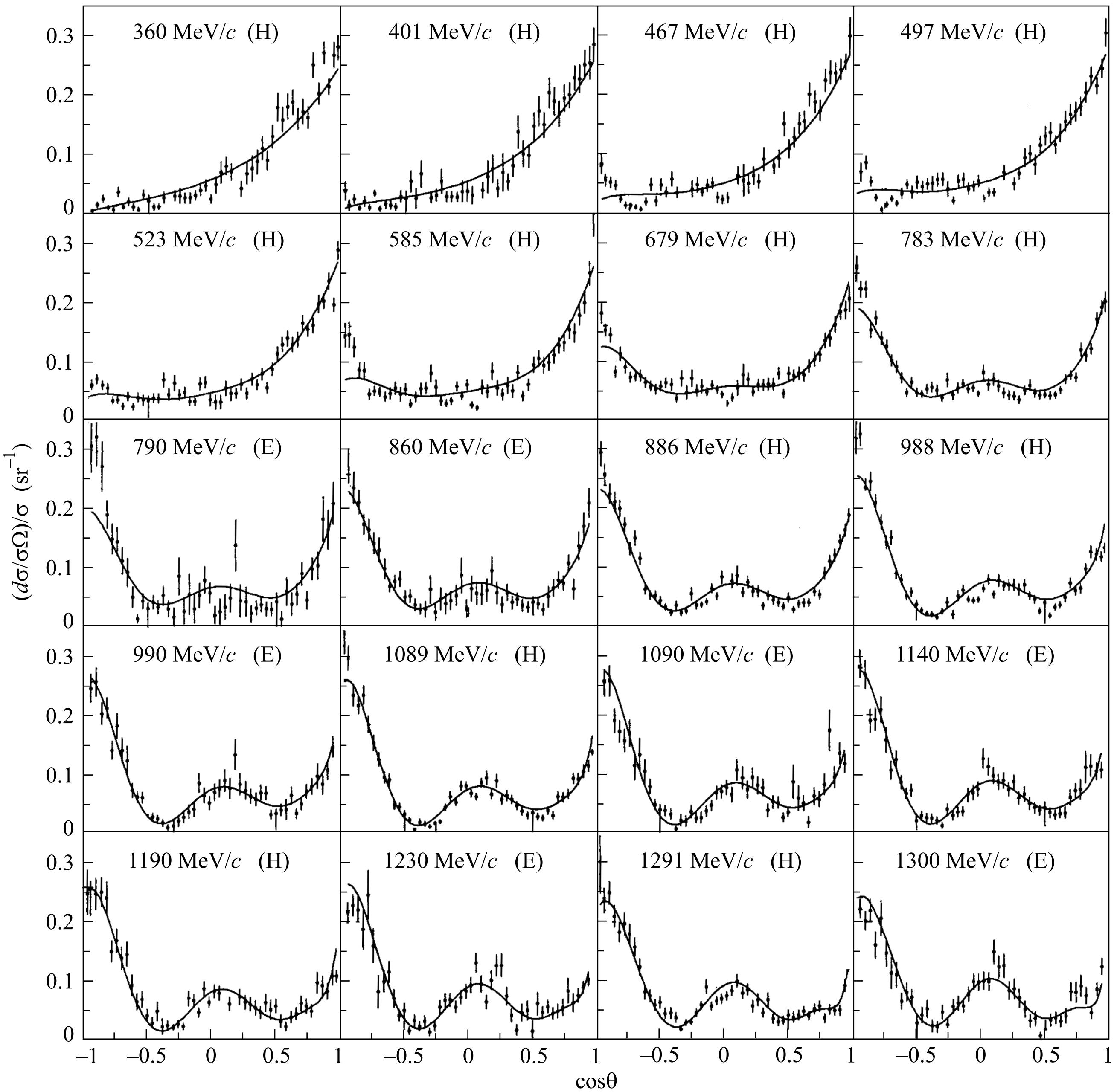

Fig.2. Differential cross sections in the reaction $p\bar{p} \to \pi^+\pi^-$ at proton momenta 360-1300 MeV and their fit to resonances of eq.(1), (E) and (H) refer to experimental data [2] of E. Eisenhandler et al. and A. Hasan et al., correspondingly

$\to \pi^0\pi^0, \eta\eta, \eta\eta'$ the relations in the leading terms of $1/N_c$-expansion read (see Table in [15]):

$$g^{(\mathrm{glueball})}_{\pi^0\pi^0} : g^{(\mathrm{glueball})}_{\eta\eta} : g^{(\mathrm{glueball})}_{\eta\eta'} =$$

$$= 1 : (\cos^2\theta + \lambda \sin^2\theta) : (1-\lambda)\sin\theta\cos\theta. \qquad (3)$$

Here θ is the mixing angle for $\eta - \eta'$ mesons: $\eta = n\bar{n}\cos\theta - s\bar{s}\sin\theta$ and $\eta' = n\bar{n}\sin\theta + s\bar{s}\cos\theta$, where $n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$. We neglect a possible admixture of the gluonium component in η and η' (according to [27], the gluonium admixture in η is less than 5%, and in η' it is less than 20%). For the mixing angle θ we use $\theta = 37°$.

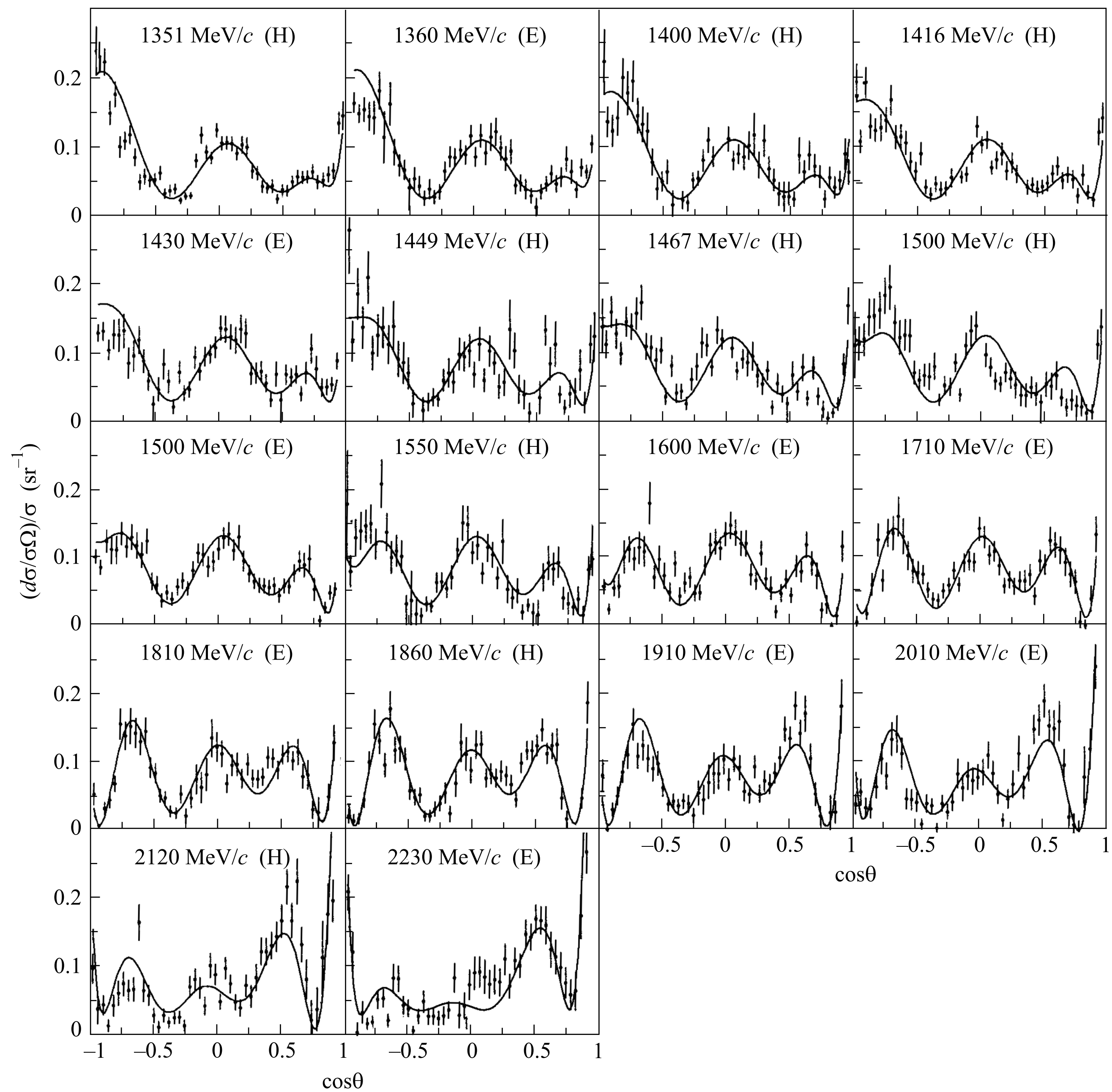

Fig.3. Differential cross sections in the reaction $p\bar{p} \to \pi^+\pi^-$ at proton momenta 1350-2230 MeV and their fit to resonances of eq.(1)

Suppression parameter λ determines relative production probability of strange quarks by gluon field $u\bar{u} : d\bar{d} : s\bar{s} = 1 : 1 : \lambda$ with $0 \le \lambda \le 1$. The data provide us with the following values of this parameter: $\lambda \simeq 0.5$ [28] for central hadron production in hadron–hadron high energy collisions, $\lambda = 0.5 - 0.8$ [29] for the decay of tensor mesons and $\lambda = 0.5 - 0.9$ [30] for the decays of 0^{++} mesons.

For ($\lambda = 0.5$, $\theta = 37°$) eq. (3) gives us $1 : 0.82 : 0.24$, and for ($\lambda = 0.85$, $\theta = 37°$), correspondingly, $1 : 0.95 :$

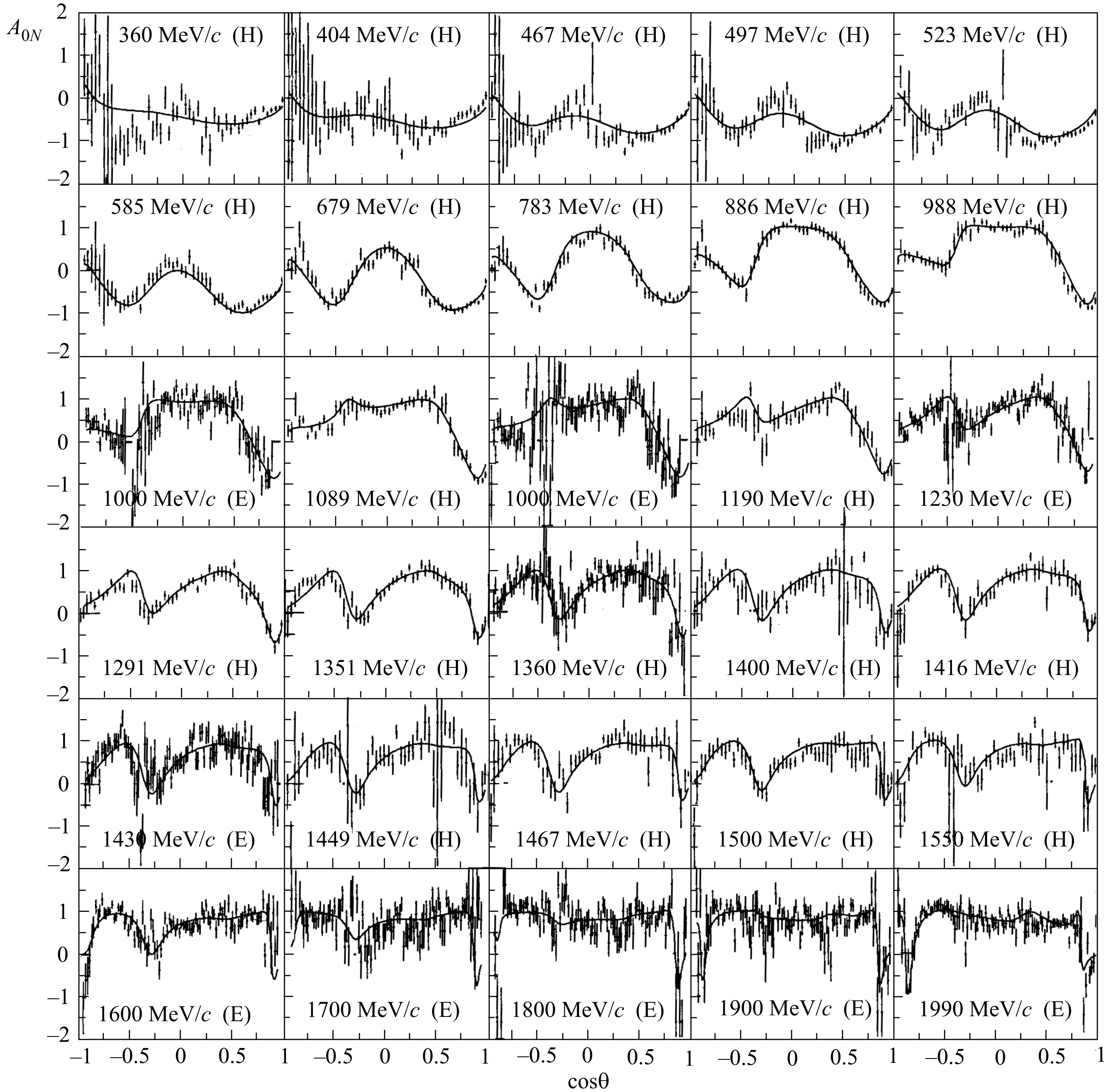

Fig.4. Polarisation in $p\bar{p} \to \pi^+\pi^-$ and its fit to resonances of eq.(1)

0.07. Consequently, the relations between the coupling constants $g_{\pi^0\pi^0} : g_{\eta\eta} : g_{\eta\eta'}$ for the glueball are to be as follows:

$$2^{++}\text{glueball} \quad g_{\pi^0\pi^0} : g_{\eta\eta} : g_{\eta\eta'} = \\ = 1 : (0.82 - 0.95) : (0.24 - 0.07). \qquad (4)$$

We see from (2) that precisely the coupling constants of the broad $f_2(2000)$ resonance are inside the intervals: $0.82 \le g_{\eta\eta}/g_{\pi^0\pi^0} \le 0.95$ and $0.24 \ge g_{\eta\eta'}/g_{\pi^0\pi^0} \ge 0.07$. Hence, it is just this resonance which can be considered as tensor glueball, with λ being fixed in the interval $0.5 \le \lambda \le 0.7$.

Taking into account that there is no room for $f_2(2000)$ on the (n, M^2)-trajectories [15], it becomes clear that this resonance is indeed the lowest tensor glueball.

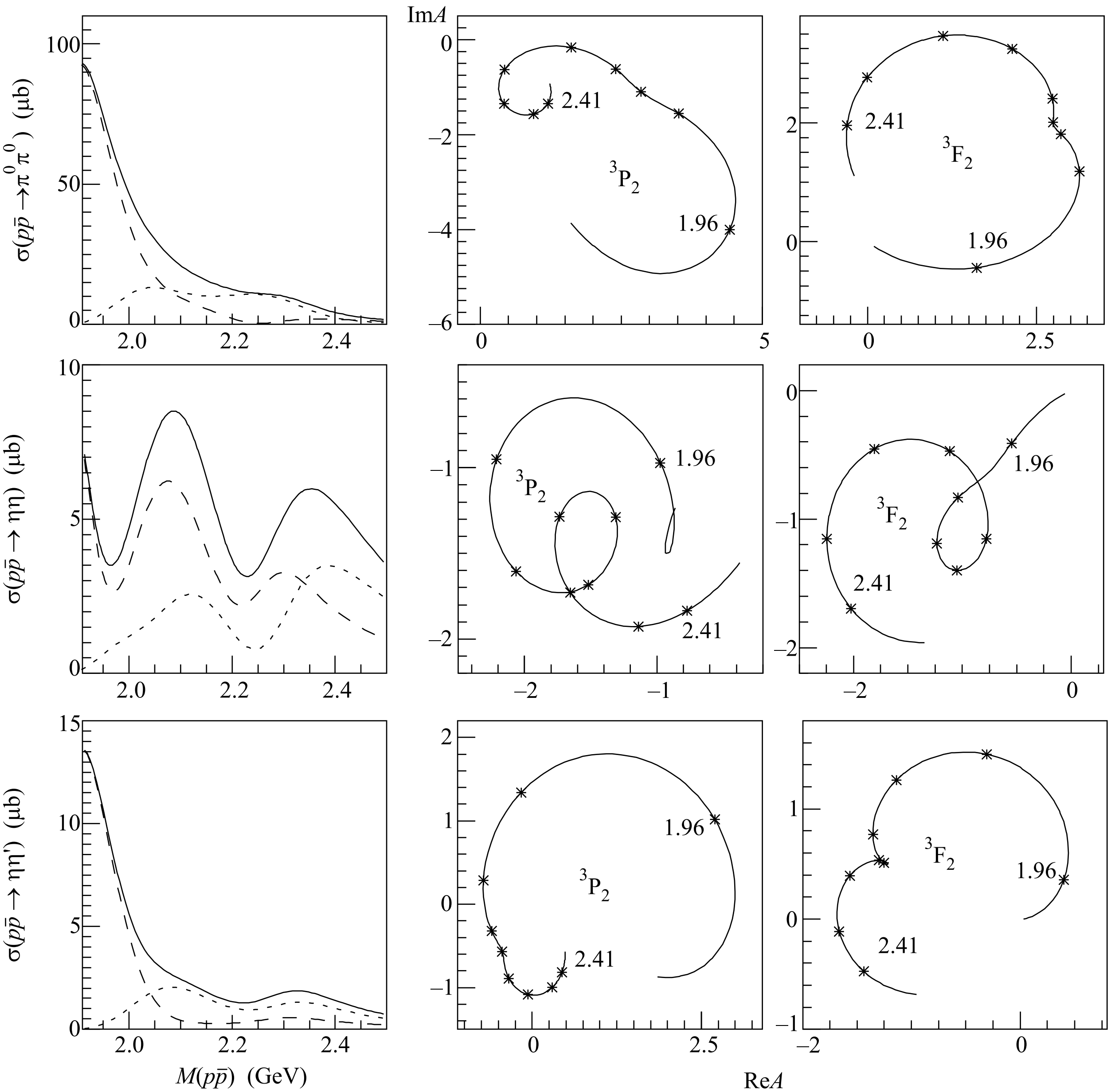

Fig.5. Cross sections and Argand-plots for ${}^3P_2$ and ${}^3F_2$ waves in the reaction $p\bar{p} \to \pi^0\pi^0, \eta\eta, \eta\eta'$. The upper row refers to $p\bar{p} \to \pi^0\pi^0$: we demonstrate the cross sections for ${}^3P_2$ and ${}^3F_2$ waves (dashed and dotted lines, correspondingly) and total $(J = 2)$ cross section (solid line) as well as Argand-plots for the ${}^3P_2$ and ${}^3F_2$ wave amplitudes at invariant masses $M = 1.962$, 2.050, 2.100, 2.150, 2.200, 2.260, 2.304, 2.360, 2.410 GeV. The figures on the second and third rows refer to the reactions $p\bar{p} \to \eta\eta$ and $p\bar{p} \to \eta\eta'$

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