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Reinvestigation of $pp \to pp\pi^0$ and $pp \to pp\eta$ at threshold *

FRIEDER KLEEFELD AND MANFRED DILLIG

Inst. f. Theoretical Physics III, University of Erlangen-Nürnberg, Staudtstr. 7, 91058 Erlangen, Germany
kleefeld@theorie3.physik.uni-erlangen.de, mdillig@theorie3.physik.uni-erlangen.de

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$pp \to pp\pi^0$ and $pp \to pp\eta$ were considered close to threshold. The pion production was found not only to be dominated by IA and rescattering contributions, but also strongly by box-diagrams, resonances and heavy-meson exchanges. New relevant contributions for the IA were found. The role of the offshell behaviour of nucleon-resonance couplings ($P_{11}(1440), S_{11}(1535)$) and of interference effects for the eta production was investigated. The results opened a large door for microsopic understanding of short range physics. A covariant model for $pp \to pp\eta$ being under construction is going to be finished.

1. Reinvestigation of $pp \to pp\pi^0$ at threshold

Following Watson-Migdal we multiplicatively can separate the short-ranged production part of the matrix elements from the long-ranged part belonging to (initial and) final state interactions (ISI, FSI). Under the assumtion that the short range part approximately is a slowly variing function of the phasespace integration variables the total production cross section of $pp \to pp\pi^0$ at threshold can be calculated in the following way:

$$\sigma^{\mathrm{SFSA}}_{pp\to pp\,\pi^0}(s) = \frac{1}{2\sqrt{\lambda(s,m_p^2,m_p^2)}}\,\frac{1}{(2\,\pi)^5}\;R_3^{\mathrm{FSI}}(s\;;\,m_p^2,m_p^2,m_{\pi^0}^2)\cdot$$

$$\cdot\;\Big|<00,11|\,\Big(\,\mathcal{M}^{(\mathrm{a})}_{\mathrm{IA}}(\vec{p}\,)+\mathcal{M}^{(\mathrm{b})}_{\mathrm{IA}}(\vec{p}\,)+\mathcal{M}_{\mathrm{Rescatt.}}(\vec{p}\,)+\mathcal{M}_{S_{11}}(\vec{p}\,)+\mathcal{M}_{P_{11}}(\vec{p}\,)$$

$$+\,\mathcal{M}^{HMEC}_{\sigma+\omega}(\vec{p}\,)+\sum_{B''B'B}\Big[\,\mathcal{M}^{NC}_{B''B',B}\,(\vec{p}\,)+\mathcal{M}^{C}_{B''B',B}\,(\vec{p}\,)\Big]\,\Big)\,|10,11>\Big|^2 \qquad (1)$$

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while $R_3^{\rm FSI}(s)$ is a FSI-modified three body phasespace integral and s the square of the CM-energy ($2\,|\vec{p}| = \sqrt{s - 4\,m_p^2}$; $B, B', B'' = N, \Delta$, C="Crossed Box", NC="Noncrossed Box"). The different contributions are shown in Fig. 4. The resulting matrix elements are shown in Fig. 5 (Q_{cm} = excess energy)(For couplings and cutoffs used see [1], p. 56 !). Noticable is the large role of the (usually neglected) irreducible IA contribution (b) with one exchange pion present when the produced pion is radiated off. The other remarkable point is the opposite sign of the heavy meson exchanges compared to previous publications ($< \mathcal{M}_\sigma > \simeq -208.7$ fm and $< \mathcal{M}_\omega > \simeq 406.7$ fm at threshold), and the nonvanishing contribution of the box-diagrams. Using FSI-corrections due to the Reid-Soft-Core- and the Coulomb-potential the resulting total cross section is about a factor 0.042 smaller then the experiment at $\eta_\pi = 0.31$, which is mostly due to the large HMEC contribution. It should be noted, that from their branching ratios the following onshell meson-nucleon-resonance couplings were calculated:

$$|f_{\pi N P_{11}}| = 0.17\ , \quad |f_{\eta N P_{11}}| = 0.66\ , \quad |f_{\rho N P_{11}}| = 0.13\ ,$$
$$|g_{\pi N S_{11}}| = 0.77\ , \quad |g_{\eta N S_{11}}| = 2.08\ , \quad |g_{\rho N S_{11}}| = 0.22$$

while for the calculation above we use the couplings used by Moalem et al. [2] listed at the Figures. Using the offshell couplings of the following η-production model we mention, that all the above $S_{11}(1535)$ resonance contributions to π^0-production will vanish! As a result we state that the complex production mechanism of $pp \to pp\,\pi^0$ is still not clearly understood.

2. Reinvestigation of $pp \to pp\eta$ at threshold

It is well known for the proton induced η-production process at threshold that in resonant meson-exchange models the interference and the relative sign between the different meson-exchange amplitudes controls the absolute magnitude of the total cross-section compared to — by isospin invariance connected — processes like $pn \to pn\eta$ and $pn \to d\eta$. By now people fix the relative signs of amplitudes by hand in order to obtain and understand the nature of the total cross section. To avoid this arbitrariness we tried to calculate the real parts of the relevant meson-nucleon-resonance couplings $g_{\lambda N N^*}(\vec{p}\,', \vec{p})$ by a model, in which the mesons couple to quarks in the proton and the respecting resonances (which are considered to be Harmonic Oscillators described by one unique range parameter a. The mixing angle between spin 1/2 and 3/2 components in the $S_{11}(1535)$-resonance is denoted by θ, the polarization vector of the exchanged ρ-meson by $\vec{\varepsilon}_\rho$). The resulting couplings are ($g_{\lambda N N^*}(\vec{0}, \vec{p})$):

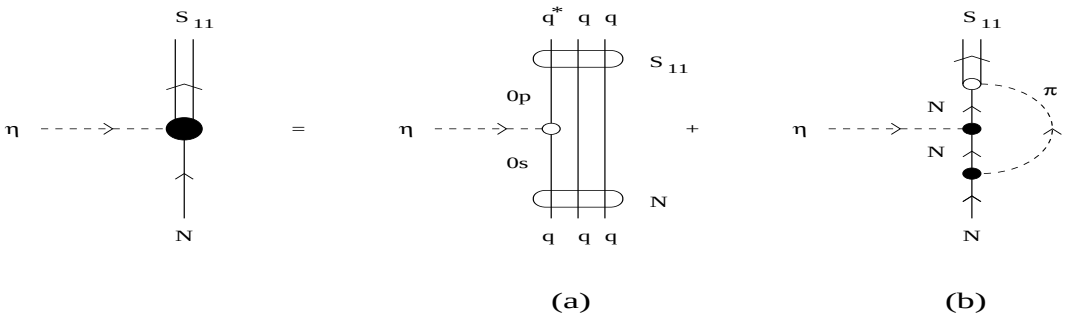

Fig. 1. Relevant contributions to the $\eta N S_{11}$–coupling at the η–threshold.

$$g^{(a)}_{\pi N S_{11}} = \frac{\sqrt{2}}{3}\,\frac{f_{\pi qq}}{m_\pi}\,\cos\left(\theta - \arcsin\frac{1}{3}\right)\,\frac{|\vec{p}\,|^2}{a}\,\exp(-\frac{|\vec{p}\,|^2}{6a^2})$$

$$g^{(a)}_{\eta N S_{11}} = \frac{\sqrt{2}}{3}\,\frac{f_{\eta qq}}{m_\eta}\,\cos\left(\theta - \arcsin\frac{1}{3}\right)\,\frac{|\vec{p}\,|^2}{a}\,\exp(-\frac{|\vec{p}\,|^2}{6a^2})$$

$$g^{(a)}_{\rho N S_{11}} = -\frac{1}{3}\sqrt{\frac{11}{6}}\,\frac{f_{\rho qq}}{m_\rho}\,\cos\left(\theta - \arcsin\frac{1}{\sqrt{33}}\right)\,\frac{|\vec{p}\,|^2}{a}\,\exp(-\frac{|\vec{p}\,|^2}{6a^2})\,\left(1 - \frac{(\vec{\varepsilon}_\rho\cdot\vec{p}\,)^2}{|\vec{p}\,|^2}\right)$$

The imaginary parts of the couplings we calculate by nonrelativistic lowest order meson loop corrections to the vertices considered. The considered diagrams are shown in Figs. 1, 2, 3 for the $S_{11}(1535)$ resonance. The Roper resonance can be treated analogously. Obviously the real part of the couplings is still not fixed, but seems to be dominated by the quark contributions. The couplings strongly depend on the mixing angle θ which can be measured by this method, if the model takes care for the complete real part of the couplings. At the moment the value $\theta = -5^0$ is favoured compared to larger values. The range parameter a shows up to be about $(0.5\,\mathrm{fm})^{-1}$. As a general result the observations of Moalem et al. [2] are confirmed, but the mechanisms which lead to the absolute magnitude of the total cross section are very nontrivial. The couplings at the vertex of the produced η-meson are in general very small, but the coupling constants at the internal vertices of the exchanged meson show up to be very large and to have imaginary part! Putting together all these effects the results of Moalem on average are obtained. A detailed discussion will be given in [3].

[1] R. Machleidt et al., Phys. Rep. **149** (1987) 1
[2] A. Moalem et al., hep–ph/9505264; Nucl. Phys. **A 589** (1995) 649; Nucl. Phys. **A 600** (1996) 445
[3] F. Kleefeld, Doctoral Thesis (Univ. Erlangen-Nürnberg, Germany)

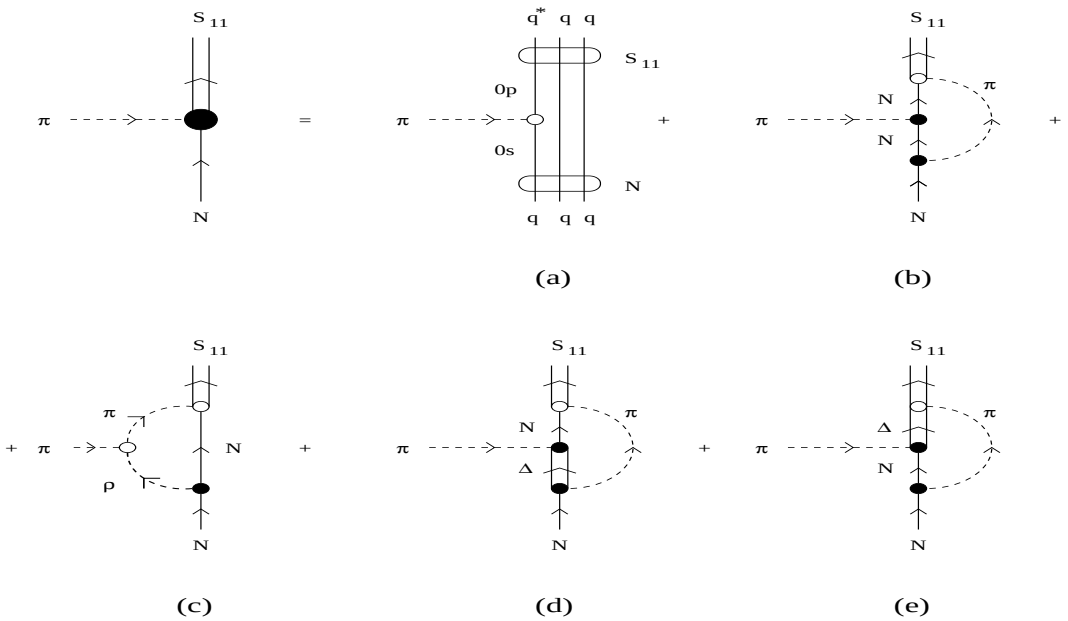

Fig. 2. Relevant contributions to the $\pi N S_{11}$–coupling at the π–threshold.

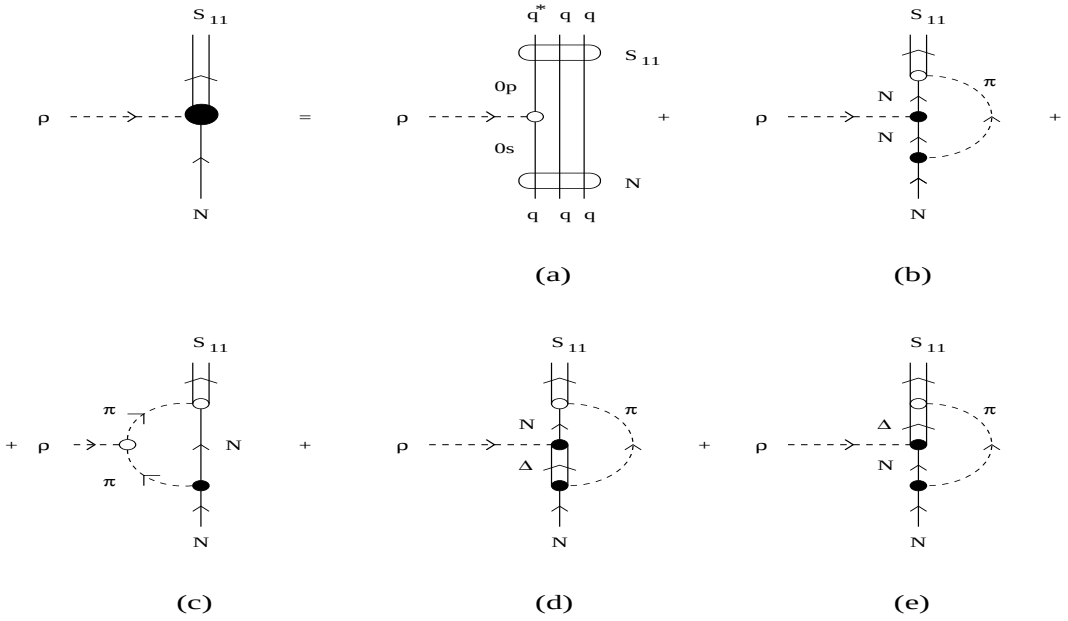

Fig. 3. Relevant contributions to the $\rho N S_{11}$–coupling at ρ–threshold.

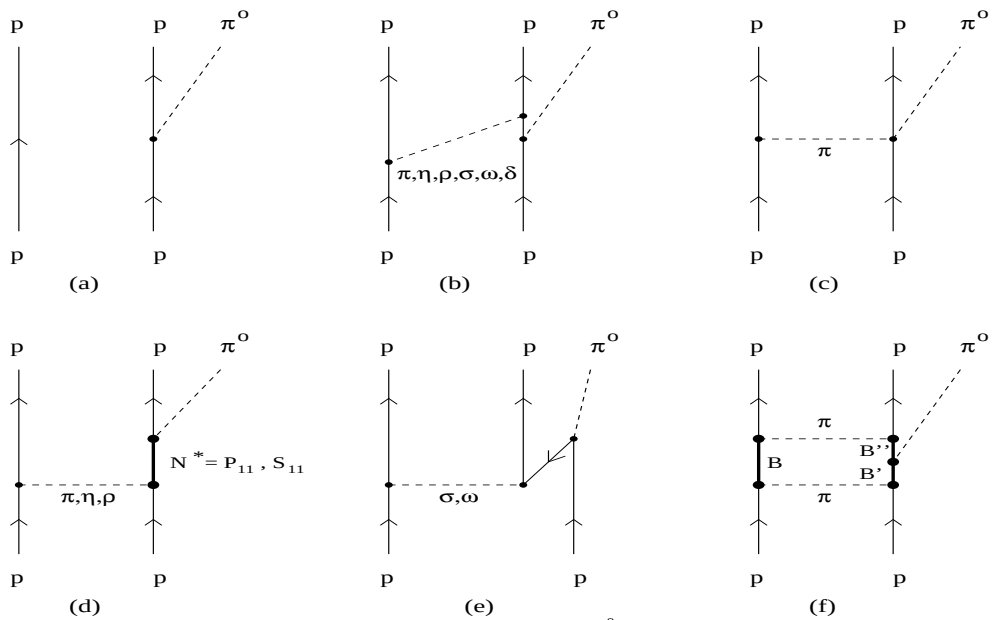

Fig. 4. Diagrammatic contributions for $pp \to pp\,\pi^0$ at threshold: IA (a), leading irreducible correction to IA (b), non-resonant S–wave-rescattering (c), resonant S– and P–wave contributions (d), Heavy meson exchange (e), $\pi\pi$ box-diagrams (f).

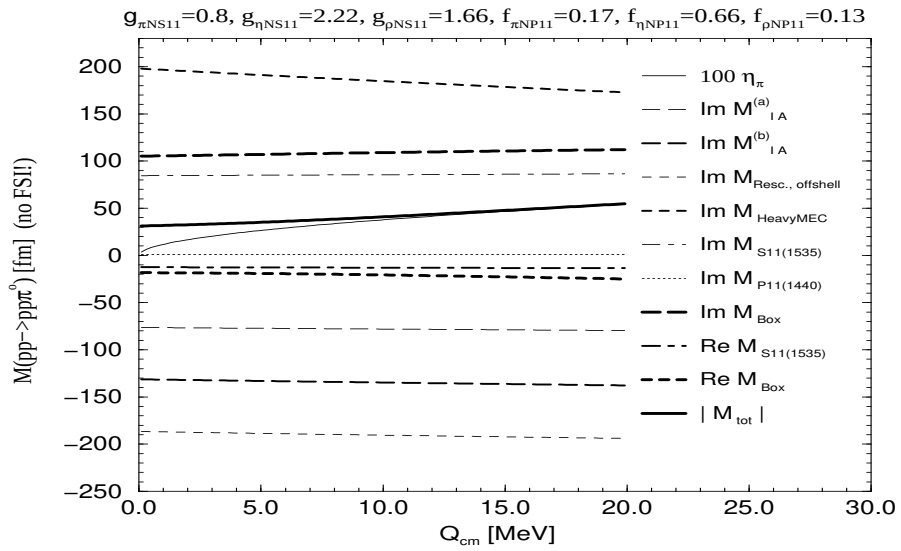

Fig. 5. Nonvanishing real– and imaginary parts of $<\mathcal{M}\,(Q_{cm})>$.