Isospin symmetry breaking in double-pion production in the region of d*(2380) and the scalar σ meson

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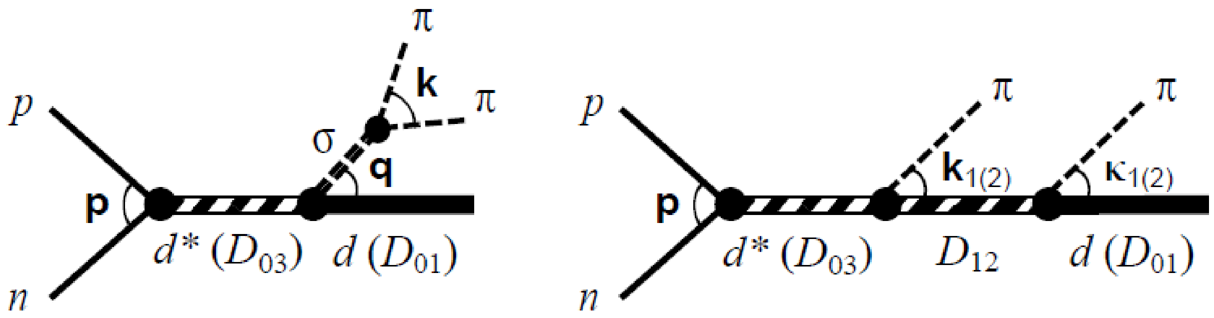
Introduction

The first attempt is made to provide a quantitative theoretical interpretation of the WASA at-COSY experimental data on the basic double-pion production reactions pn->dπ0π0 and pn->dπ+π− in the energy region Tp = 1–1.3GeV **[P. Adlarson et al., Phys. Lett. B 721, 229 (2013)].**

These measurements have revealed the significant isospin symmetry violation in the invariant-mass spectra in the near-threshold region,i.e., a suppression of the ABC enhancement by about 25% for charged dipion production as compared to neutral dipion production.

N.E. Booth, A. Abashian, and K.M. Crowe, Phys. Rev.Lett. 7, 35 (1961); A. Abashian, N.E. Booth, and K.M.Crowe, ibid. 5, 258 (1960).

M.N. Platonova and V.I. Kukuin, Phys. Rev. C 87, 025202 (2013)



(a) (b)

Mass	$\pi^{\pm}$: 139.570 39(18) MeV/c^2[1] π^0: 134.9768(5) MeV/c^2[1]

Formalism for the double-pion production reactions pn->d(ππ)0 in the region of d*(2380)

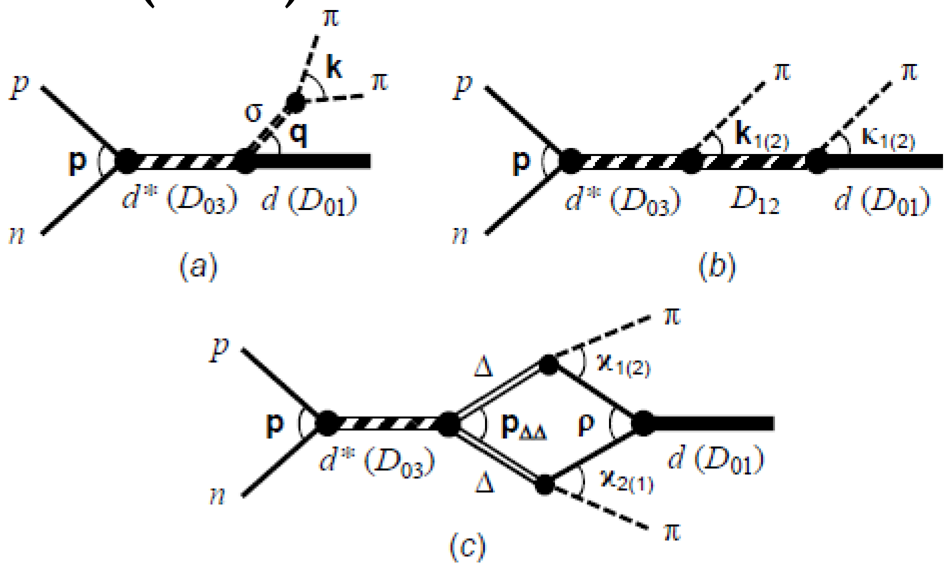


FIG. 1: Diagrams of different mechanisms for double-pion production in the region of the $\mathcal{D}_{03}$ (or $d^*(2380)$) resonance formation. The 3-momenta in the pair center-of-mass frames are indicated between the respective lines.

$$\mathcal{M}_{\lambda_p,\lambda_n,\lambda_d} = \frac{\sum\limits_{\lambda_3} \mathcal{M}^{(D_{03})}_{\lambda_p,\lambda_n,\lambda_3}\left[\mathcal{M}^{(\sigma)}_{\lambda_3,\lambda_d} + \mathcal{M}^{(D_{12})}_{\lambda_3,\lambda_d} + \mathcal{M}^{(\Delta\Delta)}_{\lambda_3,\lambda_d}\right]}{s - M^2_{D_{03}} + i\sqrt{s}\,\Gamma_{D_{03}}(s)}$$

$$\mathcal{M}^{(D_{03})}_{\lambda_p,\lambda_n,\lambda_3} = F_{pn\to D_{03}}(p)\, C^{3\lambda_3}_{1\lambda_3 20}\, C^{1\lambda_3}_{\frac{1}{2}\lambda_p \frac{1}{2}\lambda_n}\, Y_{20}(\hat{p}),$$

$$\mathcal{M}^{(\sigma)}_{\lambda_3,\lambda_d} = \frac{F_{D_{03}\to d\sigma}(q) F_{\sigma\to\pi\pi}(k)}{M^2_{\pi\pi} - m^2_\sigma + iM_{\pi\pi}\Gamma_\sigma(M^2_{\pi\pi})}\, C^{3\lambda_3}_{1\lambda_d 2\mu}\, Y_{2\mu}(\hat{q}),$$

$$\mathcal{M}^{(D_{12})}_{\lambda_3,\lambda_d} = \frac{F_{D_{03}\to D_{12}\pi_1}(k_1) F_{D_{12}\to d\pi_2}(\kappa_1)}{M^2_{d\pi_2} - M^2_{D_{12}} + iM_{d\pi_2}\Gamma_{D_{12}}(M^2_{d\pi_2})}$$

$$\times \sum_{\lambda_2} C^{3\lambda_3}_{2\lambda_2 1\mu_2}\, C^{2\lambda_2}_{1\lambda_d 1\mu_1}\, Y_{1\mu_2}(\hat{k}_1) Y_{1\mu_1}(\hat{\kappa}_1) + (\pi_1 \leftrightarrow \pi_2),$$

$$\mathcal{M}^{(\Delta\Delta)}_{\lambda_3,\lambda_d} = \int \frac{d^3\rho}{(2\pi)^3}\, \varphi_d(\rho) F_{D_{03}\to\Delta\Delta}(p_{\Delta\Delta})$$

$$\times G_\Delta(M_{N_1\pi_1}) G_\Delta(M_{N_2\pi_2}) F_{\Delta\to N_1\pi_1}(\varkappa_1) F_{\Delta\to N_2\pi_2}(\varkappa_2)$$

$$\times \sum_{\lambda_{\Delta_1}\lambda_{N_1}} C^{3\lambda_3}_{\frac{3}{2}\lambda_{\Delta_1} \frac{3}{2}\lambda_{\Delta_2}}\, C^{\frac{3}{2}\lambda_{\Delta_1}}_{\frac{1}{2}\lambda_{N_1} 1\mu_1}\, C^{\frac{3}{2}\lambda_{\Delta_2}}_{\frac{1}{2}\lambda_{N_2} 1\mu_2}\, C^{1\lambda_d}_{\frac{1}{2}\lambda_{N_1} \frac{1}{2}\lambda_{N_2}}$$

$$\times Y_{1\mu_1}(\hat{\varkappa}_1) Y_{1\mu_2}(\hat{\varkappa}_2) + (\pi_1 \leftrightarrow \pi_2), \qquad (5)$$

Neutral and charged dipion production via the intermediate D12 and Δ Δ excitation

TABLE I: Parameters of resonances R and their decay channels $R \to a + b$. For the parameter p_0, the given interval corresponds to all possible isospin channels.

R	M_R (MeV)	$\Gamma_R^{(0)}$ (MeV)	ab	l	p_0 (MeV)	$\Gamma_{R\to ab}^{(0)}$ (MeV)	Λ_{ab} (GeV)
			np	2	730	9	0.35
$\mathcal{D}_{03}$	2376	77	σd	2	350	2	0.18
			$\pi\mathcal{D}_{12}$	1	173–176	31	0.12
$\mathcal{D}_{12}$	2150	110	πd	1	221–223	33	0.15
Δ	1232	117	πN	1	226–229	117	0.16
σ	303	126	$\pi\pi$	0	72–80	126	0.09

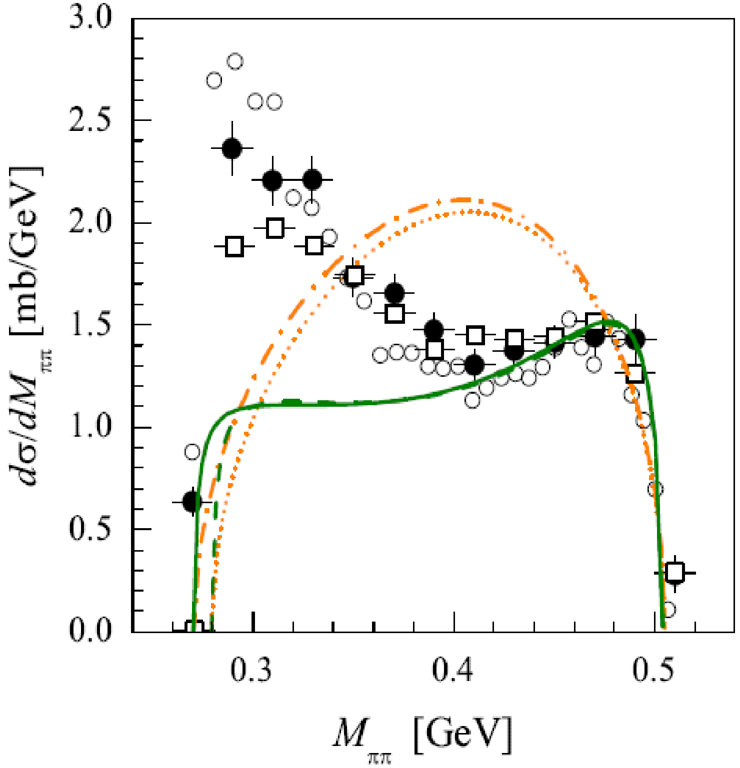


FIG. 2: (Color online) The $\pi\pi$ invariant-mass distributions in the reactions $pn \to d\pi^0\pi^0$ (multiplied by 2, solid line) and $pn \to d(\pi^+\pi^-)_0$ (dashed line) at $\sqrt{s} = 2.38$ GeV resulted from the $\mathcal{D}_{03} \to \mathcal{D}_{12}\pi$ decay in the intermediate state. The theoretical calculations are compared to the experimental data on $2d\sigma/dM_{\pi^0\pi^0}$ (filled circles) and $d\sigma/dM_{\pi^+\pi^-} - \frac{1}{2}d\sigma/dM_{\pi^+\pi^0}$ (open squares) from Ref. [9], as well as the data on $2d\sigma/dM_{\pi^0\pi^0}$ from Ref. [8] (open circles). The latter data have been multiplied by 0.45 (see Appendix). The model parameters are those listed in Tab. I, except for the parameter $\Gamma^{(0)}_{\mathcal{D}_{03}\to\mathcal{D}_{12}\pi}$, which has been adjusted to reproduce the experimental data at high invariant masses. Also shown are the pure phase-space distributions for $\pi^0\pi^0$ (dash-dotted line) and $\pi^+\pi^-$ (dotted line) production normalized to the respective total cross sections.

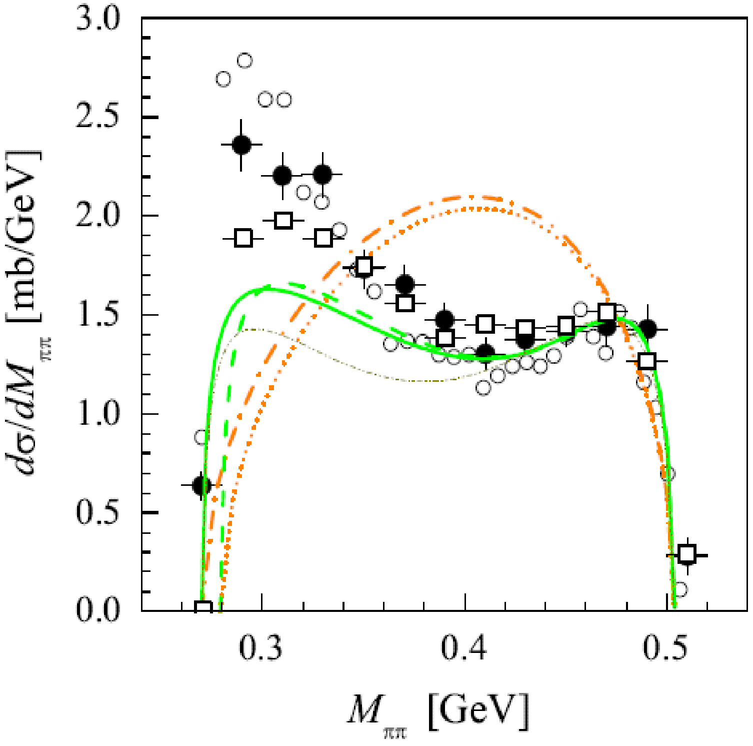


FIG. 3: (Color online) The same as in Fig. 2, but for the $\mathcal{D}_{03} \to \Delta\Delta$ decay in the intermediate state. The coupling constant $g_{\Delta\Delta}$ has been adjusted to reproduce the experimental data at high invariant masses. The thin dash-dot-dotted line shows the result of the calculation for $\pi^0\pi^0$ production without account for the nucleon recoil in the $\Delta \to \pi N$ decay (as in Ref. [17]).

Inclusion of the intermediate σ-meson production

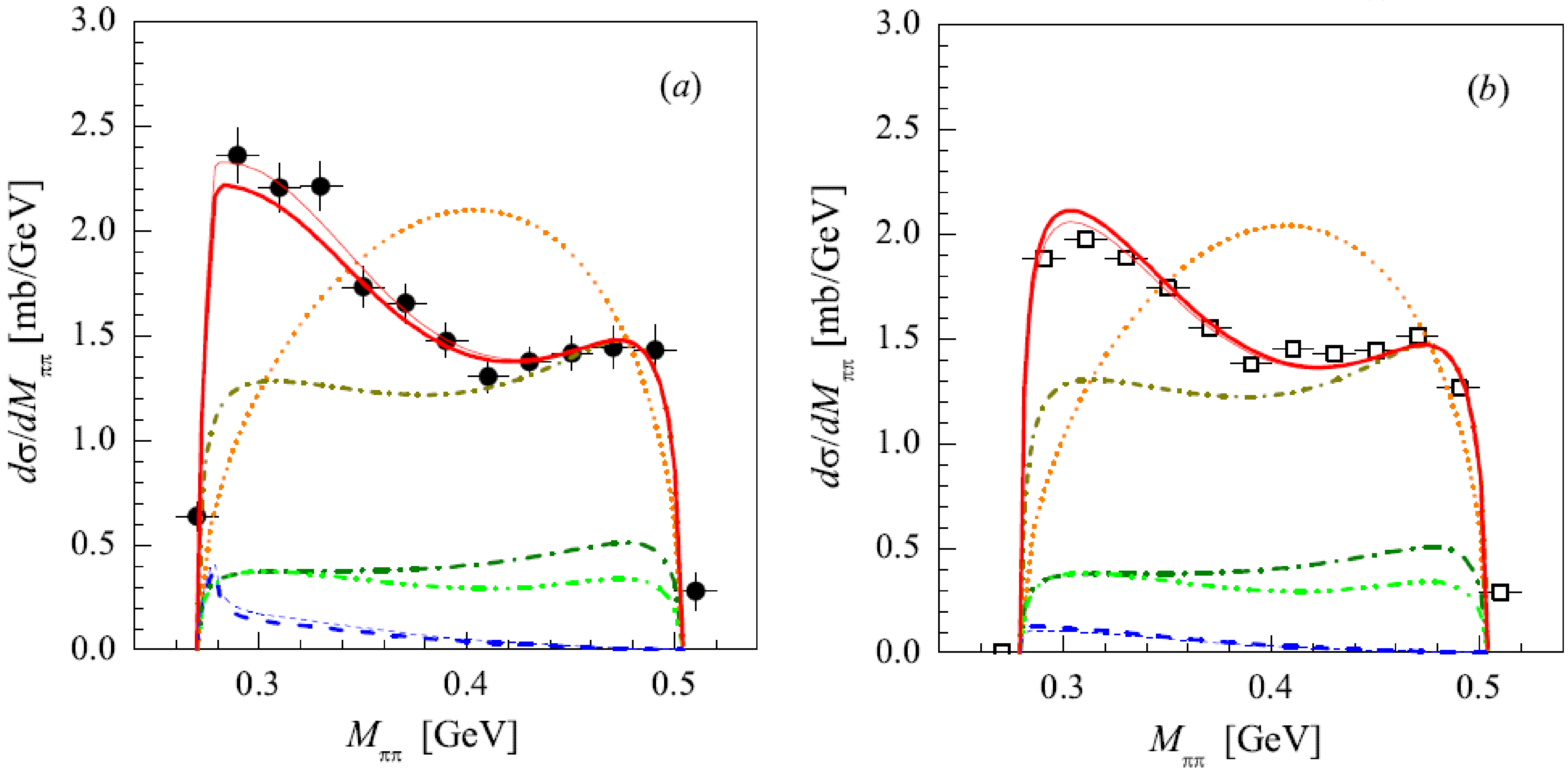


FIG. 6: (Color online) The $\pi\pi$ invariant-mass distributions in the reactions (a) $pn \to d\pi^0\pi^0$ (multiplied by 2) and (b) $pn \to d(\pi^+\pi^-)_0$ at $\sqrt{s} = 2.38$ GeV calculated with the model parameters from Tab. I. Shown are the distributions resulted from the $\mathcal{D}_{03} \to \mathcal{D}_{12} + \pi$ decay (dash-dotted lines), the $\mathcal{D}_{03} \to \Delta + \Delta$ decay (dash-dot-dotted lines), the $\mathcal{D}_{03} \to d + \sigma$ decay (dashed lines), and the coherent sum of these three $\mathcal{D}_{03}$ decay routes (solid lines). Upper dash-dotted lines (with short dashes) show the summed contribution of the $\mathcal{D}_{12} + \pi$ and $\Delta + \Delta$ excitation mechanisms. Dotted lines correspond to the pure phase-space distributions. Thin dashed and solid lines correspond to the σ-excitation mechanism and the total distributions with $\alpha = 0.23$ (see Eq. (15)). The theoretical calculations are compared to the experimental data on $2d\sigma/dM_{\pi^0\pi^0}$ (filled circles) and $d\sigma/dM_{\pi^+\pi^-} - \frac{1}{2}d\sigma/dM_{\pi^+\pi^0}$ (open squares) taken from Ref. [9].

Energy dependence of the double-pion production cross sections

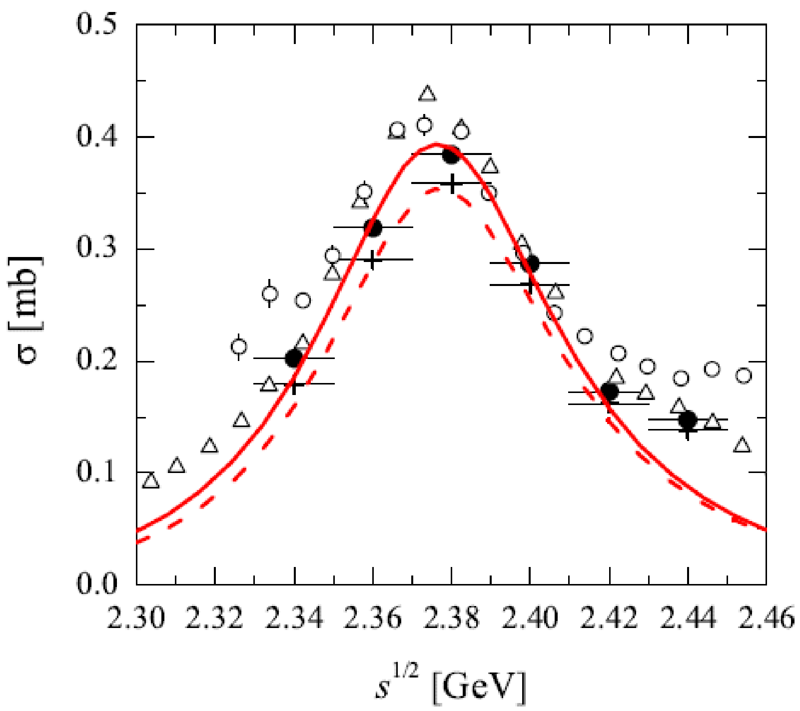


FIG. 7: (Color online) The total cross sections in the reactions $pn \to d\pi^0\pi^0$ (multiplied by 2) and $pn \to d(\pi^+\pi^-)_0$ as functions of the invariant energy $\sqrt{s}$. The solid and dashed lines correspond to the model calculations for $\pi^0\pi^0$ and $\pi^+\pi^-$ production, respectively, including the $\mathcal{D}_{03} \to \mathcal{D}_{12}+\pi$, $\mathcal{D}_{03} \to \Delta+\Delta$, and $\mathcal{D}_{03} \to d+\sigma$ decay routes with parameters from Tab. 1 and $\alpha = 0.23$ (see Eq. (15)). The theoretical calculations are compared to the experimental data on $2\sigma(pn \to d\pi^0\pi^0)$ (filled circles) and $\sigma(pn \to d\pi^+\pi^-) - \frac{1}{2}\sigma(pp \to d\pi^+\pi^0)$ (crosses) obtained by an integration of the respective $M_{\pi\pi}$ distributions measured in Ref. [9]. Also shown are the total cross section data on $2\sigma(pn \to d\pi^0\pi^0)$ from Ref. [9] multiplied by a factor of 0.83 (open circles) and from Ref. [8] multiplied by a factor of 0.5 (open triangles) — see Appendix.

VI. SUMMARY AND OUTLOOK

We have shown that the observed suppression of the near-threshold enhancement (the so-called ABC effect) in the $\pi\pi$ invariant-mass spectrum in the reaction $pn \to d\pi^+\pi^-$ compared to that in the reaction $pn \to d\pi^0\pi^0$ can be at least partially explained by the intermediate $\mathcal{D}_{03}(2380)$ (denoted also as $d^*(2380)$) dibaryon decay with the scalar σ-meson emission. The same mechanism is capable to explain the appearance of the ABC effect itself [18], provided the σ mass and width are shifted downwards to the values of about m_σ = 290–320 MeV and Γ_σ = 75–150 MeV due the partial chiral symmetry restoration in the excited $\mathcal{D}_{03}$ dibaryon. Being a near-threshold resonance, such a renormalized σ meson produces a cusp in the $\pi^0\pi^0$ production cross section at the $\pi^+\pi^-$ threshold, thus giving the visible splitting between the neutral and charged dipion production cross sections in the near-threshold region. The free-space σ meson with the parameters $m_\sigma \simeq \Gamma_\sigma \simeq 500$ MeV produces a similar (though less prominent) cusp but a different shape of the $M_{\pi\pi}$ distribution, which peaks at the nominal σ mass.

THANK YOU!