Study of the decay $D^0 \to K^+K^-\eta$

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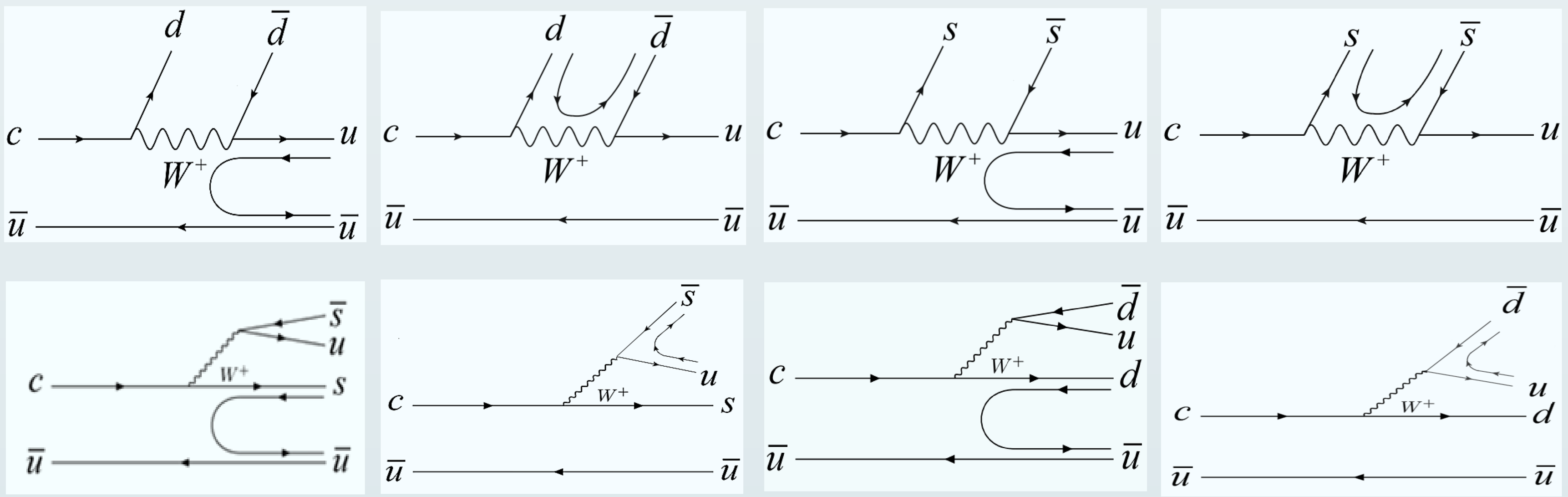
Introduction

Exotic states in the sector of light scalar mesons has been a topic of intense discussions for years. These exotic states cannot be adjusted in the traditional $q\bar{q}$ objects. A successful dynamical picture is known as the chiral unitary approach, incorporating the interaction of pseudoscalar mesons in coupled channels, the constraints of unitarity in coupled channels and the dynamics of the chiral Lagrangians. This approach provides an accurate description in the different reactions, where the scalar resonances are produced. It is beneficial for understanding the internal structures of some lowest-lying exotic states and this approach has been considered the chiral symmetry for low energy hadron dynamics and the general properties of the scattering amplitude such as unitarity and analyticity. Within that methodology, there are different methods to evaluate the T-matrix, where we use the Bethe-Salpeter equation in this work.

Motivated by the recent measurement for the branching fraction of $D^0 \to K^+K^-\eta$ and the Dalitz plot analysis by Belle collaboration [1], we investigate the invariant mass distributions of $K^+K^-, K^-\eta, K^+\eta$ and obtain the parameters of the final state interaction in the Chiral unitary approach.

Methodology

We investigate the decay of $D^0 \to K^+K^-\eta$ based on the chiral unitary approach and takes into account the external and internal W-emission mechanisms at the quark level. The mechanism of the Cabibbo suppressed process includes three steps, weak decay, hadronization, and the final state interactions. The diagrammatic representations for the W-internal and W-external emmissions in D^0 decays are as following



Thus, the total amplitude can be written as

$$
\begin{aligned}
t_{D^0\to K^+K^-\eta} = & \frac{2}{\sqrt{6}} C_1 G_{\pi^+\pi^-}(s_{12}) T_{\pi^+\pi^-\to K^+K^-}(s_{12}) + \frac{1}{\sqrt{6}}(C_1-2C_2) + \frac{1}{\sqrt{6}}(C_1-2C_2) G_{K^+K^-}(s_{12}) T_{K^+K^-\to K^+K^-}(s_{12}) \\
& + \frac{1}{3\sqrt{6}} \beta C_2 G_{\eta\eta}(s_{12}) T_{\eta\eta\to K^+K^-}(s_{12}) - \frac{1}{\sqrt{6}} \beta C_2 G_{\pi^0\pi^0}(s_{12}) T_{\pi^0\pi^0\to K^+K^-}(s_{12}) \\
& + \frac{1}{\sqrt{6}} \beta C_2 G_{K^0\bar{K}^0}(s_{12}) T_{K^0\bar{K}^0\to K^+K^-}(s_{12}) + C_2 G_{\pi^-\bar{K}^0}(s_{23}) T_{\pi^-\bar{K}^0\to K^-\eta}(s_{23}) \\
& - \frac{1}{\sqrt{2}}(C_1-2C_2) G_{K^-\pi^0}(s_{23}) T_{K^-\pi^0\to K^-\eta}(s_{23}) + \frac{1}{\sqrt{6}}(C_1-2C_2) G_{K^-\eta}(s_{23}) T_{K^-\eta\to K^-\eta}(s_{23}) \\
& + C_2 G_{\pi^+K^0}(s_{13}) T_{\pi^+K^0\to K^+\eta}(s_{13}) - \frac{1}{\sqrt{2}}(C_1-2C_2) G_{K^+\pi^0}(s_{13}) T_{K^+\pi^0\to K^+\eta}(s_{13}) \\
& + \frac{1}{\sqrt{6}}(C_1-2C_2) G_{K^+\eta}(s_{13}) T_{K^+\eta\to K^+\eta}(s_{13})
\end{aligned}
$$

considering final state productions at the tree level and rescattering processes of the decay $D^0 \to K^+K^-\eta$. The revealed factors $\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{6}}$ come from the prefactor of the flavor components of the quark structures of mesons, η, π^0. C_1, C_2 absorb the production vertex and CKM matrix elements, and also include the normalization factor used to fit our model to the invariant mass distributions of the experimental data. The energy of the two body system can be defined by

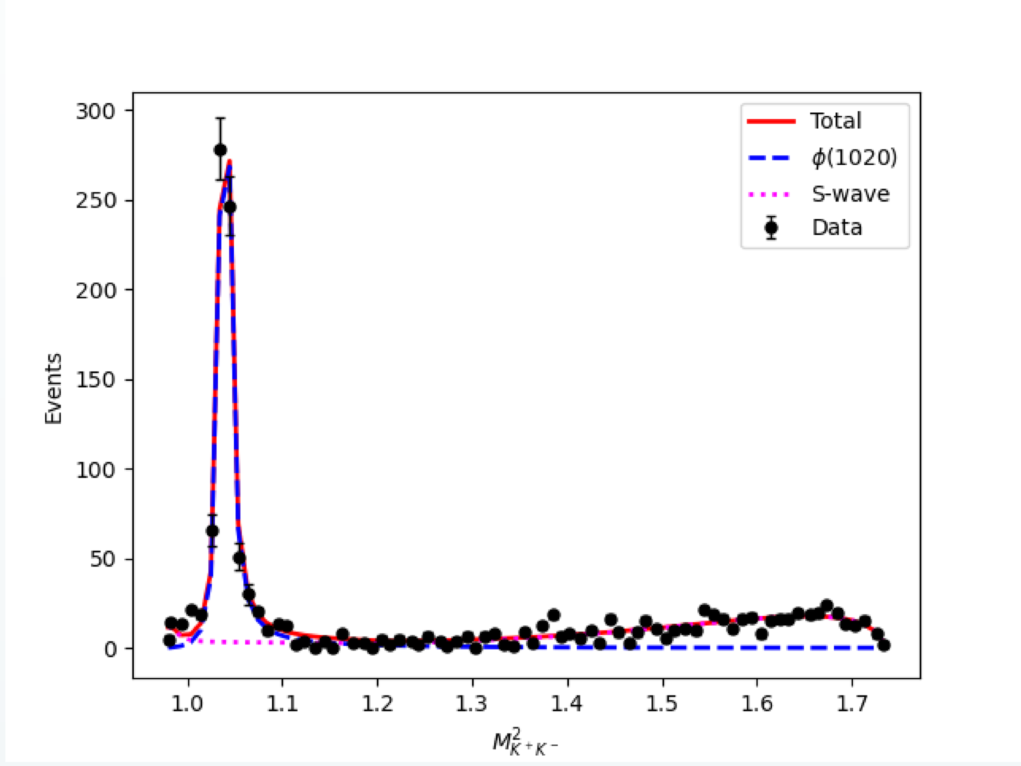
$$s_{12} = (p_1+p_2)^2, s_{23} = (p_2+p_3)^2$$

The two body scattering amplitude can be calculated by the Bethe-Salpeter equation of Chiral Unitary approach [2,3], $T = [1 - VG]^{-1} V$

G is the diagonal matrix of loop functions in terms of interactions of pseudoscalar mesons, which are evaluated by Chiral Lagrangians. In our study, we are dealing with Isospin 0, ½, and 1.

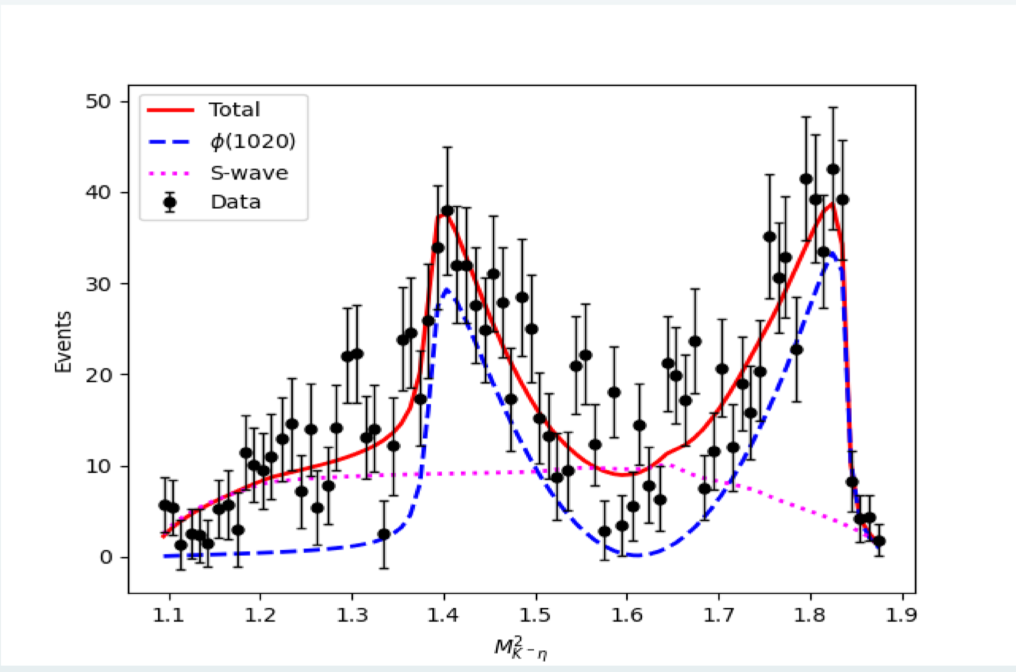
Results

In the three following figures, one can see the $K^+K^-, K^-\eta, K^+\eta$ invariant mass distributions of the decay $D^0 \to K^+K^-\eta$. The parameters are obtained by reduced chi-square. The dot points with error bars are taken from the Belle data.



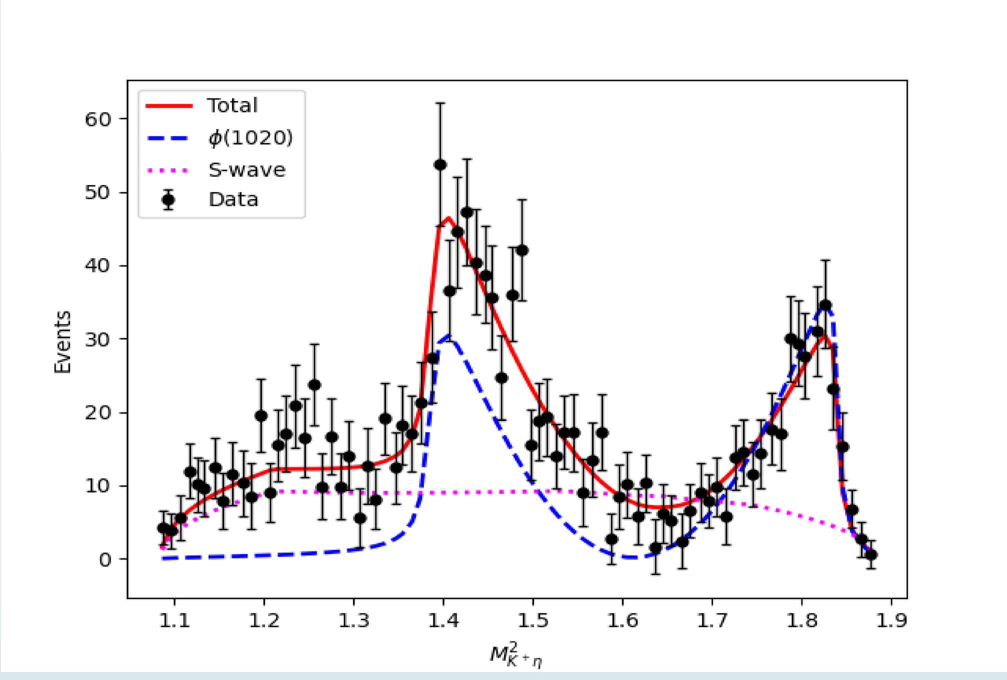
C_1	C_2	β	α	D_ϕ	α_ϕ	χ^2/dof
1243.403 $\pm$ 1.980	393.183 $\pm$ 1.880	1.00 $\pm$ 0.129	-7.112 $\pm$ 0.081	139.738 $\pm$ 1.579	-4.939 $\pm$ 2.000	4.641

The red solid lines are our total fits. The contributions of S-wave are plotted by the dotted pink lines. The dashed blue lines are the contributions of ϕ meson in all figures.



C_1	C_2	β	α	D_ϕ	α_ϕ	χ^2/dof
6210.101 $\pm$ 985.693	2796.120 $\pm$ 296.162	0.534 $\pm$ 0.174	4.394 $\pm$ 5.200	119.795 $\pm$ 4.097	0.078 $\pm$ 0.292	1.285

The P-wave contribution is proportional to the relativistic Breit-Wigner distribution which arises from the propagator of an unstable ϕ meson while S-wave comes from scattering amplitudes.



C_1	C_2	β	α	D_ϕ	α_ϕ	χ^2/dof
4336.324 $\pm$ 3235.540	2293.977 $\pm$ 1081.828	0.628 $\pm$ 0.460	7.487 $\pm$ 4.476	122.299 $\pm$ 4.153	2.415 $\pm$ 0.243	0.884

Conclusion

According to the experimental results [1] the resonance contributions mainly involved $\phi(1020)$ with $I^G J^{PC} = 0^- 1^{--}$ in the P-wave part of decay $D^0 \to K^+K^-\eta$. We expect the contribution of $f_0(980)$ in the interactions of K^+K^- to be located bellow the threshold of $K\bar{K}$, however the contribution of S-wave is small as can be seen from the figures. In addition, with the obtained parameters in the model as well as the contribution of $\phi(1020)$ meson case, the invariant mass distribution are found to be in good agreement with the Belle data.

References

[1] L. K. Li et al., (The Belle collaboration), JHEP 09 (2021) 075.
[2] R. Molina, J. J. Xie, W. H. Liang, L. S. Geng, E. Oset, Phys. Lett. B 803 (2020) 135279.
[3] Z. Y. Wang, J. Y. Yi, Z. F. Sun, C. W. Xiao, Phys. Rev. D 105 (2022) 016025.