Theoretical interpretation of the $D_s^+ \to \pi^+\pi^0\eta$ decay and the nature of $a_0(980)$

Raquel Molina, Ju-Jun Xie, Wei-Hong Liang, Lisheng Geng and E. Oset

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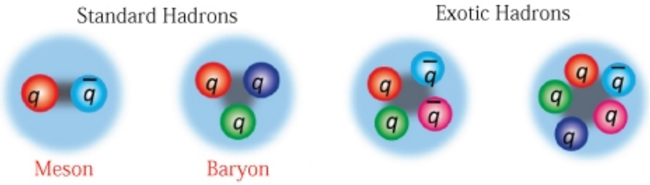
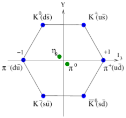
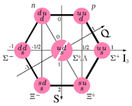
Introduction

Hadrons



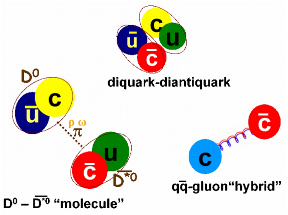
- 'Regular' hadrons: $q\bar{q}$, qqq



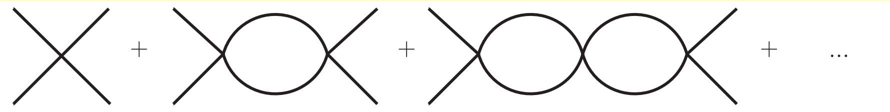


- Exotics: $q\bar{q}q\bar{q}$, $qqqq\bar{q}$, qqg,...

  Not $q\bar{q}$: $J^{PC} = 0^{+-}$, 1^{-+}, 2^{+-}, 3^{-+},...



Dynamically Generated Resonances



Examples

- σ, $a_0(980)$, $f_0(980)$... `Oller, Oset, Pelaez, PRL80(1998)`
- $N(1440)$ `Krehl, Hanhart, Krewald and Speth, PRC62(2000)`
- $\Lambda(1405)$ `Ramos, Oset, NPA635(1998); Jido, Meissner, Oller NPA725(2003); Hyodo, Weise PRC77(2008)`
- $P_c(4450)$ `Wu, Molina, Zou, Oset, PRL105(2010)`
- **New** **state** $X_0(2900)$ `Molina, Branz, Oset PRD82(2010)`

How to test the nature of a ...

Dynamically Generated Resonance?

- Production $B_0 \to D_0\sigma(a_0(980))$ Liang, Xie, Oset PRD92(2015)

  Triangle singularity $D^{*0}\bar{D}^{*0} \to \gamma X(3872)$ F.K. Guo, PRL122(2019)
- Decays $Y \to \gamma\gamma$ Branz, Gutsche, Lyubovitskij PRD82(2010)
- Study of N_c behavior Pelaez, Phys. Rep. 658(2016)
- Nuclear medium $X(3872)$ Nieves et al., 2102.08589(2020)
- Weinberg compositeness condition and generalizations Weinberg PR137(1965), Hyodo, Oset, Oller
- Chiral trajectories (EFT) + LatticeQCD data,

  Molina, Ruiz de Elvira JHEP2011(2020)

The $D_s^+ \to \pi^+\pi^0\eta$ decay and the nature of the $a_0(980)$

Is the $a_0(980)$ a threshold effect or a true resonance?

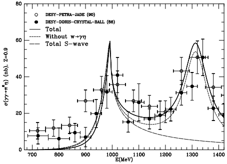


Figure 1: Integrated cross section for $\gamma\gamma \to \pi^0\eta$. Data: Oest(1990), Antreasyan(1986).

UChPT predictions

Channels: $K\bar{K}$, $\pi\eta$
Oller, Oset, NPA629(1998)
Guo, Liu, Oller, Rusetski, Meissner PRD95(2017)

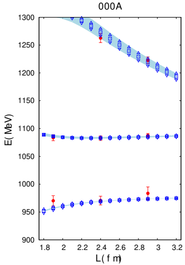


Figure 2: Fit to HadSpec data.

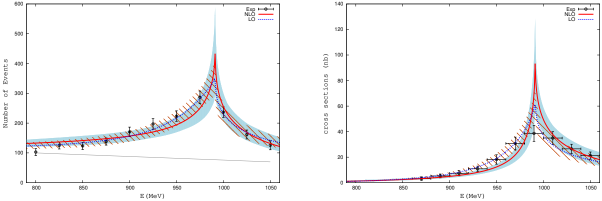


Figure 3: Left: $\pi\eta$ distribution. Data: WA76(1991). Right. Cross section $\gamma\gamma \to \pi\eta$. Data: Belle(2009).

Is the $a_0(980)$ a threshold effect or a true resonance?

Large N_c behaviour

“In particular, we have shown that the QCD large N_c scaling of the unitarized meson-meson amplitudes of chiral perturbation theory is in conflict with a $\bar{q}q$ nature for the lightest scalars [not so conclusively for the $a_0(980)$. The $a_0(980)$ behavior is more complicated. We cannot rule out a possible $\bar{q}q$ nature, or a sizable mixing], and strongly suggests a $\bar{q}\bar{q}qq$ or two-meson main component, maybe with some mixing with glue- balls, when possible.”

Pelaez, PRL92(2004)

Amplitude analysis of $\chi_{c1} \to \eta\pi^+\pi^-$

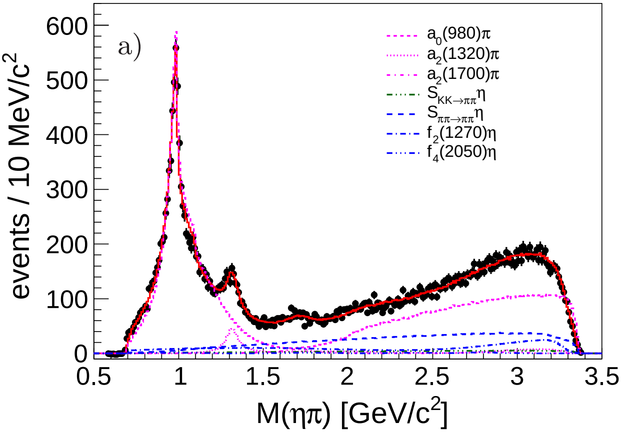


Figure 4: Projections in the (a)$\eta\pi$-invariant mass from data, compared with a base-line fit (solid curve) and corresponding amplitudes (various dashed and dotted lines) from PRD95(2017), BESIII.

BESIII: $D_s^+ \to \pi^+\pi^0\eta$

2019. BESIII has reported the so-called first observation of a pure W-annihilation decays $D_s^+ \to a_0^+(980)\pi^0$ and $D_s^+ \to a_0^0(980)\pi^+$

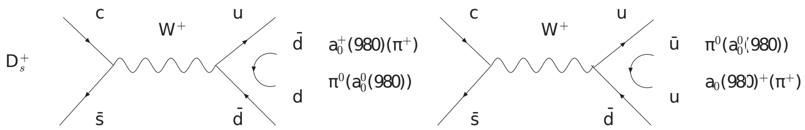


Figure 5: Annihilation mechanisms assumed in Ref.for the $D_s^+ \to \pi^0 a_0^+(980)$, $\pi^+ a_0^0(980)$. $\mathcal{B}[D_s^+ \to a_0(980)^+\pi^0,\ a_0(980)^+ \to \pi^+\eta] = (1.46 \pm 0.15 \pm 0.23)\%$

Topological classification of Weak decays

1. W-external emission
2. W-internal emission
3. W-exchange
4. W-annhilation
5. Horizontal W-loop
6. Vertical W-loop

L.L.Chau. PR(1983),PRD36(1987), PRD39(1989)

(Cabibbo favored) W-external emission? $D_s^+ \to \pi^+\bar{s}s$, but $\bar{s}s$ has $I = 0$. Requires $f_0(980)$ upon hadronization. Not good

$D_s^+ \to \pi^+\pi^0\eta$: W-internal emission PLB803(2020)

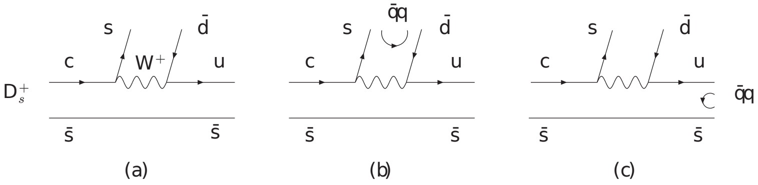


Figure 6: $D_s^+ \to \pi^0 a_0^+(980)$, $\pi^+ a_0^0(980)$: W internal emission mechanisms, (a) Primary step; (b) hadronization of the $s\bar{d}$ pair; (c) hadronization of the $u\bar{s}$ pair.

Hadronization

$$M = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{pmatrix},$$

$$\sum_i s\bar{q}_i q_i \bar{d} = \sum_i M_{3i} \qquad M_{i2} = (M^2)_{32},$$

$$\sum_i u\bar{q}_i q_i \bar{s} = \sum_i M_{1i} \qquad M_{i3} = (M^2)_{13},$$

$$(M^2)_{32} = \pi^+ K^- - \frac{1}{\sqrt{2}}\pi^0 \bar{K}^0,$$

$$(M^2)_{13} = \frac{1}{\sqrt{2}}\pi^0 K^+ + \pi^+ K^0,$$

$$H_1 = (\pi^+ K^- - \frac{1}{\sqrt{2}}\pi^0 \bar{K}^0) K^+,$$

$$H_2 = (\frac{1}{\sqrt{2}}\pi^0 K^+ + \pi^+ K^0) \bar{K}^0.$$

$D_s^+ \to \pi^0 a_0^+(980),\ \pi^+ a_0^0(980)$

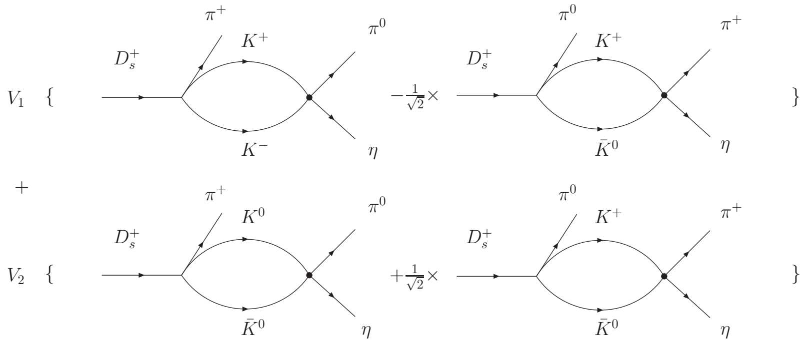


Figure 7: Diagrammatic representation of the $K\bar{K}$ final state interaction of the states H_1 and H_2 leading to $\pi^+\pi^0\eta$ in the final states.

$$
\begin{aligned}
t = \quad & V_1[G_{K\bar{K}}(M_{\pi^0\eta})t_{K^+K^-\to\pi^0\eta}(M_{\pi^0\eta}) - \frac{1}{\sqrt{2}}G_{K\bar{K}}(M_{\pi^+\eta})t_{K^+\bar{K}^0\to\pi^+\eta}(M_{\pi^+\eta})] \\
& +V_2[G_{K\bar{K}}(M_{\pi^0\eta})t_{K^0\bar{K}^0\to\pi^0\eta}(M_{\pi^0\eta}) + \frac{1}{\sqrt{2}}G_{K\bar{K}}(M_{\pi^+\eta})t_{K^+\bar{K}^0\to\pi^+\eta}(M_{\pi^+\eta})]\ ,
\end{aligned}
$$

$D_s^+ \to \pi^0 a_0^+(980)$, $\pi^+ a_0^0(980)$

Chiral Unitary approach

$$\boxed{T = [1 - VG]^{-1} V}$$

Oller, Oset, Pelaez, PRL80(1998)

Xie, Dai, Oset, PLB742(2015)

$q_{\rm max} = 600$ MeV

Isospin

$$t_{K^+K^-\to\pi^0\eta} = -\frac{1}{\sqrt{2}} t^{I=1}_{K\bar{K}\to\pi\eta},$$

$$t_{K^0\bar{K}^0\to\pi^0\eta} = \frac{1}{\sqrt{2}} t^{I=1}_{K\bar{K}\to\pi\eta},$$

$$t_{K^+\bar{K}^0\to\pi^+\eta} = -t^{I=1}_{K\bar{K}\to\pi\eta},$$

We obtain,

$$\boxed{t = \bar{V}\left[G_{K\bar{K}}(M_{\pi^0\eta}) t^{I=1}_{K\bar{K}\to\pi\eta}(M_{\pi^0\eta}) - G_{K\bar{K}}(M_{\pi^+\eta}) t^{I=1}_{K\bar{K}\to\pi\eta}(M_{\pi^+\eta})\right]}$$

with $\bar{V} = (V_2 - V_1)/\sqrt{2}$.

Note that, with the isospin multiplets (u, d), $(-\bar{d}, \bar{u})$,

$$|s\bar{d}> = -|1/2, 1/2> \qquad |s\bar{d}, u\bar{s}> = -|1,1>$$

$$|u\bar{s}> = |1/2, 1/2> \qquad |\pi a_0; I = 1, I_3 = 1> = \frac{1}{\sqrt{2}}|\pi^0 a_0^+ - \pi^+ a_0^0>$$

$D_s^+ \to \pi^0 a_0^+(980),\ \pi^+ a_0^0(980)$

Invariant mass distribution

$$\frac{d^2\Gamma}{dM_{\pi^0\eta}dM_{\pi^+\eta}} = \frac{1}{(2\pi)^3}\frac{M_{\pi^0\eta}M_{\pi^+\eta}}{8M_{D_s^+}^2}|t|^2$$

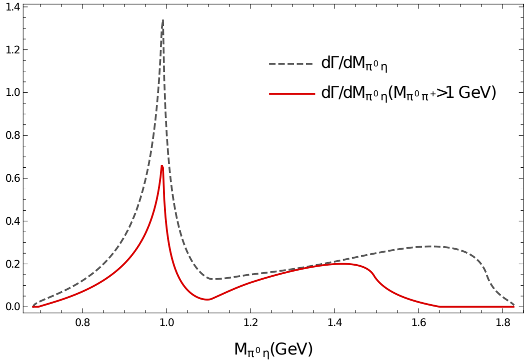


Figure 8: $d\Gamma/dM_{\pi^0\eta}$ as a function of $M_{\pi^0\eta}$. Dashed line with no $M_{\pi^+\pi^0}$ restriction. Solid line with the restriction of $M_{\pi^+\pi^0} > 1$ GeV.

$D_s^+ \to \pi^0 a_0^+(980),\ \pi^+ a_0^0(980)$

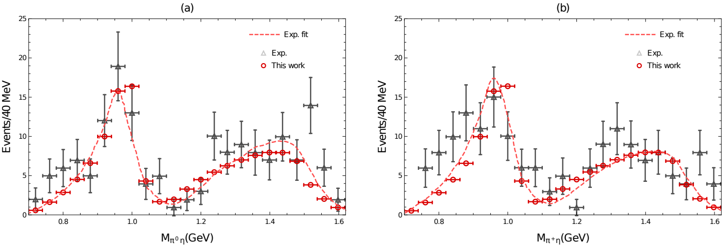


Figure 9: Event distribution in 40 MeV bins of $d\Gamma/dM_{\pi\eta}$ compared with experiment with $M_{\pi^+\pi^0} > 1$ GeV. (a) for $\pi^0\eta$ distribution; (b) for $\pi^+\eta$ distribution. The dashed lines are taken from [1] after the non πa_0 events are removed. Molina, Xie, Liang, Geng and Oset, PLB803(2020)

[1] BESIII Collaboration, PRL123(2019)

But...this is not the end of the story!

$D_s^+ \to \pi^0 a_0^+(980)$, $\pi^+ a_0^0(980)$

Arxiv: 2102.0534, Ling, Liu, Lu, Geng and Xie

Inspired in the work of Hsiao et al., EPJC80(895), the authors find that both mechanisms, internal and external-W emission through triangle diagrams are relevant.

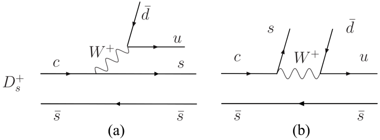


Figure 10: a) External W-emission mechanism for $D_s^+ \to \rho^+\eta$ and b) internal W-conversion mechanisms.

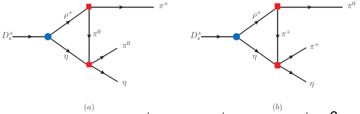


Figure 11: $D_s^+ \to (\rho^+\eta \to)\pi^+\pi^0\eta$.

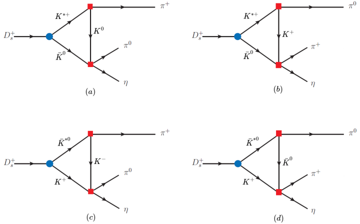


Figure 12: Triangle rescattering diagrams for $D_s^+ \to (K^{*0}\bar{K}^0 \to)\pi^+\pi^0\eta$ and $D_s^+ \to (K^+\bar{K}^{*0} \to)\pi^+\pi^0\eta$.

$D_s^+ \to \pi^0 a_0^+(980)$, $\pi^+ a_0^0(980)$

Arxiv: 2102.0534, Ling, Liu, Lu, Geng and Xie

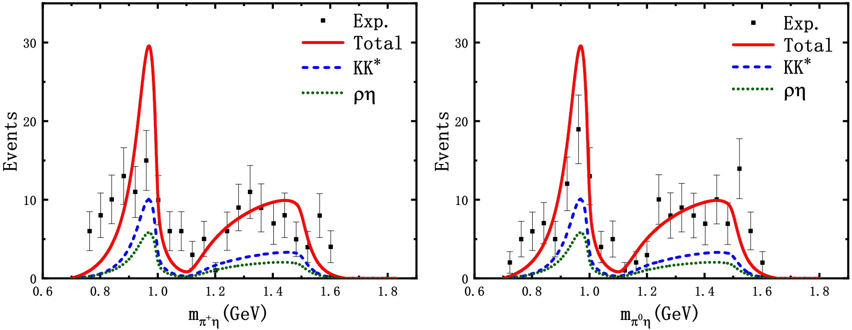


Figure 13: Invariant mass distributions of $\pi\eta$ with the cut of $m_{\pi^+\pi^0} > 1$ GeV for the decay $D_s^+ \to \pi(a_0(980) \to)\pi^0\pi^+\eta$, in comparison with the BESIII data.

Conclusions

Conclusions

- The $D_s^+ \to \pi^+\pi^-\eta$ through the $a_0(980)$ proceeds via W-internal/external emission and not W-annhilation.
- The new BESIII data and the analysis shown here supports the $a_0(980)$ as a dynamically generated resonance from the $\pi\eta$ and $K\bar{K}$ channels.