Part I: Signature of an $h_1$ state in the $J/\psi \rightarrow \eta h_1 \rightarrow \eta K^*0 \bar{K}^*0$ decay


Part II: The low lying scalar resonances in the $D^0$ decays into $K_S^0$ and $f_0(500), f_0(980), a_0(980)$


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Hadron 2015
Part I

Signature of an $h_1$ state in the $J/\psi \rightarrow \eta h_1 \rightarrow \eta K^0 \bar{K}^0$ decay


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Introduction

About the experiments

- BES studied the decay $J/\psi \rightarrow \eta K^{*0} \bar{K}^{*0}$ in search of $Y(2175)$. “No evidence of a signal is seen” [BES Collab., Phys. Lett., B685, 27(2010)]
- $Y(2175)$, now $\phi(2170)$, has $0^{-}(1^{--})$, and does not couple to $K^{*0} \bar{K}^{*0}$
- Since $J/\psi$ is $0^{-}(1^{--})$ and $\eta$ is $0^{+}(0^{-+})$, the reaction is ideal to study $h_1$ states, $0^{-}(1^{+-})$, coupling to $S$-wave $K^* \bar{K}^*$.
- Experimental information is scarce (see PDG)

Meanwhile, in the theory side...

- A $h_1$ state around 1.8 GeV is predicted in the $K^* \bar{K}^*$ interaction predicted by an approach using unitarity and the hidden gauge lagrangian [Geng, Oset, Phys. Rev., D79, 074009 (2009)]
- Elusive states: Do not couple to most $VV$ ($\rho \rho$, $\omega \omega$, $\omega \phi$, ... ) or $PP$. It can decay to $VP$, but thresholds are far, far away...
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**$K^*\bar{K}^*$ interaction**

- The amplitude for $K^*\bar{K}^*$ can be written as:
  
  $$ t(s) = \frac{\nu(s)}{1 - \nu(s)\tilde{G}(s)} $$

- $\nu(s)$ is the **potential** (to be discussed later)

- $\tilde{G}(s)$ the **loop function** for the $K^*\bar{K}^*$ pair,

  $$ \tilde{G}(s) = \int_{m_{\bar{K}^*}^2}^{m_{K^*}^2} dm_1^2 dm_2^2 \omega(m_1^2)\omega(m_2^2)G(s, m_1^2, m_2^2) $$

- The loop function $G(s)$ is **convoluted** with the mass distribution functions $\omega(m_{1,2}^2)$ to take into account the large width of $K^*$ ($\Gamma_{K^*} \simeq 50 \text{ MeV}$). The range is taken to be $m_\pm = m_{K^*} \pm 2\Gamma_{K^*}$.

  $$ \omega(m_1^2) \propto \text{Im} \frac{1}{m_1^2 - m_{K^*}^2 + i\Gamma(m_1^2)m_1} \quad \Gamma(m_1^2) = \Gamma_{K^*} \frac{p^3(m_1^2)}{p^3(m_{K^*}^2)} $$
Two forms for the potential

1. **Hidden gauge potential**: completely fixed (no new free parameters):

\[ v(s) = \left( 9 + b \left( 1 - \frac{3s}{4m_{K^*}^2} \right) \right) g^2 \]

- \( g = m_\rho / 2f_\pi \approx 4 \). The term \( 9g^2 \) comes from the four vector contact term.
- The term proportional to \( b \) comes from the exchange of vector mesons.
- \( b \) is determined by the masses of the vector mesons (\( \rho, \omega, \phi \) and \( K^* \)), \( b = 6.8 \).
- We use the values \( a(\mu) = (-1.0, -0.8, -0.6) \).
  - \( a(\mu) = -1.7 \) is used in [Geng, Oset, Phys.Rev., D79, 074009 (2009)]

2. **Constant potential**:

- Reasonable in the small range of energies we are using.
- Quite model independent.
- In the amplitude there appears the linear combination \( 1/v - a(\mu) \), so any shift in \( a(\mu) \) can be reabsorbed in \( v \) \( \Rightarrow \) Fix \( a(\mu) = -0.8 \).
Let us denote with $V_P$ the bare production vertex for $J/\psi \to \eta K^* \bar{K}^*$.

The full amplitude $T_P$ for the process takes into account the FSI of $K^* \bar{K}^*$:

$$T_P = V_P (1 + \tilde{G}(s)t(s)) = V_P \frac{t(s)}{v(s)}$$

The invariant mass spectrum is ($C$ is a normalization constant, absorbing $V_P$):

$$\frac{d\Gamma}{d\sqrt{s}} = \frac{C}{M_{J/\psi}} \rho_1 \tilde{p}_2 \frac{|t(s)|^2}{|v(s)|^2}$$

Momenta:

$$\tilde{p}_2(s) = \int_{m^2_1}^{m^2_2} dm^2_1 dm^2_2 \omega(m^2_1) \omega(m^2_2) \lambda^{1/2}(s, m^2_1, m^2_2) \frac{\lambda^{1/2}(s, m^2_{\eta}, m^2_2)}{2\sqrt{s}}$$

$$p_1(s) = \frac{\lambda^{1/2}(M_{J/\psi}^2, s, m^2_{\eta})}{2\sqrt{s}}$$
\( K^0 \bar{K}^0 \) spectrum in \( J/\psi \rightarrow \eta K^0 \bar{K}^0 \)

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\]

Momenta:

\[
\bar{p}_2(s) = \int_{m_1^2}^{m_2^2} dm_1^2 dm_2^2 \omega(m_1^2)\omega(m_2^2) \frac{\lambda^{1/2}(s, m_1^2, m_2^2)}{2\sqrt{s}}, \quad p_1(s) = \frac{\lambda^{1/2}(M_{J/\psi}^2, s, m_\eta^2)}{2\sqrt{s}}
\]

---

**K^*0\bar{K}^*0** spectrum in \( J/\psi \to \eta K^*0 \bar{K}^*0 \)**

Let us denote with \( V_P \) the bare production vertex for \( J/\psi \to \eta K^* \bar{K}^* \).

The full amplitude \( T_P \) for the process takes into account the FSI of \( K^* \bar{K}^* \):

\[
T_P = V_P (1 + \tilde{G}(s) t(s)) = V_P \frac{t(s)}{\nu(s)}
\]

The invariant mass spectrum is (\( C \) is a normalization constant, absorbing \( V_P \)):

\[
\frac{d\Gamma}{d\sqrt{s}} = \frac{C}{M_{J/\psi} \rho_1 \tilde{\rho}_2} \frac{|t(s)|^2}{|\nu(s)|^2}
\]

Momenta:

\[
\tilde{\rho}_2(s) = \int_{m_-^2}^{m_+^2} dm_1^2 dm_2^2 \omega(m_1^2) \omega(m_2^2) \frac{\lambda^{1/2}(s, m_1^2, m_2^2)}{2\sqrt{s}}, \quad p_1(s) = \frac{\lambda^{1/2}(M_{J/\psi}^2, s, m_\eta^2)}{2\sqrt{s}}
\]
Part I

Signature of an $h_1$ state in the $J/\psi \to \eta h_1 \to \eta K^*0 \bar{K}^*0$ decay


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**Results**

**Constant potential**
- Error bands $\chi^2 \leq \chi^2_{\text{min}} + 1$
- **Good reproduction** of the data
- Rather **model independent** (no underlying model)

**Hidden gauge potential**
- Three values for $a(\mu) = (-1.0, -0.8, -0.6)$
  ([Geng,Oset,PR,D70,074009] take $-1.7$)

**Phase space**
- Can pure phase space distribution explain the data? Set $t = \nu = 1$
- $\chi^2 / \text{d.o.f.} = 0.9$ (good, but larger than in our fits)
- But systematically wrong, does not follow the trend of the data
**Results**

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---

- Constant: $M \simeq 1810$ MeV, $\Gamma \simeq 100$ MeV
- Dynamical: $M \simeq 1850$ MeV, $\Gamma \simeq 120$ MeV
Results
Constant potential
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Phase space
• Can pure phase space distribution explain the data? Set $t = \nu = 1$
• $\chi^2 / \text{d.o.f.} = 0.9$ (good, but larger than in our fits)
• But systematically wrong, does not follow the trend of the data

Conclusions
• The inclusion of a $h_1$ state, generated by $K^* \bar{K}^*$ dynamics, is crucial to reproduce the data (phase space is not enough)
• Definitely, an experimental study with more statistics is needed
Some checks

Width
- Vary the $K^*$ width ($\Gamma_{K^*} = 50, 30, 0$ MeV)
- The effect and the state still persist: it is not due to a threshold effect, softened by the large $K^*$ width.

FSI
- Even without considering whether there is a resonance or not, it can be shown that the enhancement is due to the strong final state interactions in the $K^*\bar{K}^*$ pair
- Change $v \rightarrow v/\alpha$ ($\alpha = 1$ physical case, $\alpha \rightarrow \infty$ no interaction)
- A small or zero interaction cannot describe the spectrum
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Summary and conclusions

- In the BES data regarding $J/\psi \rightarrow \eta K^0\bar{K}^0$ there is an enhancement in the $K^0\bar{K}^0$ distribution [BES Collab., Phys. Lett., B685, 27(2010)].
- In the hidden gauge approach to $K^*\bar{K}^*$ [Geng, Oset, Phys. Rev., D79, 074009(2009)] a dynamically generated $h_1$ state $[0^-(1^{+-})]$ is predicted around 1.8 GeV with a width 80 MeV.
- **Idea!** [Xie, Albaladejo, Oset, Phys. Lett., B728, 319(2014)] Put both pieces together. We show in our work that:
  1. The enhancement is due to a state with mass (1810, 1850) MeV, and a width (100, 120) MeV (two different “models”)
  2. Experimental studies with more statistics would be appreciated
- There is another reaction ($\eta_c \rightarrow \phi K^*\bar{K}^*$) proposed to look for this elusive state [Ren, Geng, Oset, Meng, Eur. Phys. J., A50, 133(2014)].
The low lying scalar resonances in the $D^0$ decays into $K^0_S$ and $f_0(500)$, $f_0(980)$, $a_0(980)$

Part II

The low lying scalar resonances in the $D^0$ decays into $K^0_S$ and $f_0(500)$, $f_0(980)$, $a_0(980)$


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Introduction

The nature of the light scalar mesons ($0^{++}$) is a topic of long-standing debate

- Scalar mesons below 1 GeV: $f_0(500), f_0(980), a_0(980), \kappa(800)$
- Possible structures of quark model:
  normal meson[$q\bar{q}$], tetraquark[$q^2\bar{q}^2$], molecule[($q\bar{q}$)($q\bar{q}$)], glueball[$gg, ggg$], hybrid[$q\bar{q}g$], . . .
  ([M. Albaladejo, J.A. Oller, Phys.Rev., D86, 034003(2012)] on the nature of $\sigma$ meson)

Chiral unitary approach

1. $f_0(500), f_0(980), a_0(980)$ resonances are dynamically generated from the interaction of pseudoscalar mesons and could be interpreted as a kind of molecular states of meson-meson

2. Test this possibility:
   - Hadronic decay and Radiative decay $\Rightarrow$ successful
   - Weak decay? novel and interesting test $\Rightarrow$ our motivation
Introduction

We study the $D^0$ weak decay to $K^0_S$ and a scalar resonance ($D^0 \to K^0_S S$) as a novel test of the nature of $f_0(500), f_0(980), a_0(980)$

1. **Experimental data** from CLEO collaboration


2. Theoretical work is **scarce**:

   - mostly devoted to issues related to CP violation or $D^0 - D^{*0}$ mixing
   - A thorough study for the $D^0 \to K^0_S \pi^+ \pi^-$ reaction with 33 free parameters is presented in [Dedonder, Kaminski, Lesniak, Loiseau, Phys. Rev. D 89,094018 (2014)]

3. In the **present work**:

   - Rates are large compared to $\bar{B}^0$ decay
     $D^0 \to K^0_S a_0(980)$ Cabibbo-allowed
     $\bar{B}^0_s \to J/\psi a_0(980)$ doubly Cabibbo-suppressed [Liang, Oset, Phys.Lett.,B737,70 (2015)]
   - Isospin non-conservation: same decay for $I = 0$ and $I = 1$.
   - No free parameters, only shapes and relative weight are computed
Part II

The low lying scalar resonances in the $D^0$ decays into $K_S^0$ and $f_0(500)$, $f_0(980)$, $a_0(980)$


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Chiral unitary approach

\[ T_{ij} = V_{ij} + G_k V_{ik} T_{kj} \]

- Bethe-Salpeter equation: \( T = V + VGT \implies T = (I - VG)^{-1} V \)

\[
\begin{align*}
I = 0 & \quad \pi^+\pi^-, \pi^0\pi^0, K^+K^-, K^0\bar{K}^0 \text{ and } \eta\eta \quad T, V, G: 5 \times 5 \\
I = 1 & \quad K^+K^-, K^0\bar{K}^0 \text{ and } \pi^0\eta \quad T, V, G: 3 \times 3
\end{align*}
\]

- Relevant \( V \)-matrix elements computed from Chiral Lagrangians (references: [Liang, Oset, Phys.Lett.B,737,70])

- \( G \)-function is the two-meson \((m_1, m_2)\) propagator for the \( k \)-channel:

\[
G_k(s) = i \int_{|q|<q_{\text{max}}} \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - m_1^2 + i\varepsilon} \frac{1}{q^2 - m_2^2 + i\varepsilon}
\]
\( D^0 \rightarrow K_S^0 \): general idea

**Goal:** \( D^0 \rightarrow K_S^0 R \). At the quark level:

- Start from the dominant diagram for \( D^0 \rightarrow \bar{K}^0 u\bar{u} \)
- The process is **Cabibbo allowed**
- The \( s\bar{d} \) pair produces the \( \bar{K}^0 \), which will convert to the observed \( K_S^0 \)
- **Hadronization** of the \( u\bar{u} \) through an extra \( \bar{q}q \) with vacuum quantum numbers gives two mesons
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- **Hadronization** of the \( u\bar{u} \) through an extra \( q\bar{q} \) with vacuum quantum numbers gives two mesons
**$D^0 \to K_S^0 S$: hadronization**

- Let us introduce the following $q\bar{q}$ matrix, $M$:

\[
M = \begin{pmatrix}
  u\bar{u} & u\bar{d} & u\bar{s} \\
  d\bar{u} & d\bar{d} & d\bar{s} \\
  s\bar{u} & s\bar{d} & s\bar{s}
\end{pmatrix}, \text{ satisfying } M \cdot M = M \times (\bar{u}u + \bar{d}d + \bar{s}s)
\]

- There is a relation between $q\bar{q}$ $M$-matrix and the meson $\phi$-matrix:

\[
\phi = \begin{pmatrix}
  \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{3}} \eta + \frac{1}{\sqrt{6}} \eta' & \pi^+ & K^+ \\
  \pi^- & -\frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{3}} \eta + \frac{1}{\sqrt{6}} \eta' & K^0 \\
  K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}} \eta + \sqrt{\frac{2}{3}} \eta'
\end{pmatrix}
\]

- **Hadronization** proceeds via $M \cdot M \Rightarrow \phi \cdot \phi$. For the $u\bar{u}$ pair,

\[
u\bar{u} (\bar{u}u + \bar{d}d + \bar{s}s) = (M \cdot M)_{11} \Rightarrow (\phi \cdot \phi)_{11}
\]

- Hence upon hadronization of the $u\bar{u}$ ($M$) component, in terms of mesons ($\phi$), we shall have:

\[
(M \cdot M)_{11} \Rightarrow (\phi \cdot \phi)_{11} = \frac{1}{2} \pi^0 \pi^0 + \frac{1}{3} \eta \eta + \frac{2}{\sqrt{6}} \pi^0 \eta + \pi^+ \pi^- + K^+ K^-
\]
$D^0 \rightarrow K_S^0 S$: diagrams for $\pi^+\pi^-$ and $\pi^0\eta$

- Top: **direct** $\pi^+\pi^-$ production + $\pi^+\pi^-$ production through primary production of a $PP'$ pair and **rescattering**
- Bottom: **direct** $\pi^0\eta$ production + $\pi^0\eta$ production through primary production of a $PP'$ pair and **rescattering**
$D^0 \rightarrow K^0_S S$: amplitudes for $\pi^+\pi^-$ and $\pi^0\eta$

The **production amplitudes** of the mesons taking into account rescattering are:

$$t(D^0 \rightarrow \bar{K}^0 \pi^+\pi^-) = V_P \left( 1 + G_{\pi^+\pi^-} T_{\pi^+\pi^- \rightarrow \pi^+\pi^-} + \frac{1}{2} \frac{1}{2} G_{\pi^0\pi^0} T_{\pi^0\pi^0 \rightarrow \pi^+\pi^-} 
+ \frac{1}{3} \frac{1}{2} G_{\eta\eta} T_{\eta\eta \rightarrow \pi^+\pi^-} + G_{K^+K^-} T_{K^+K^- \rightarrow \pi^+\pi^-} \right)$$

$$t(D^0 \rightarrow \bar{K}^0 \pi^0\eta) = V_P \left( \sqrt{\frac{2}{3}} + \sqrt{\frac{2}{3}} G_{\pi^0\eta} T_{\pi^0\eta \rightarrow \pi^0\eta} + G_{K^+K^-} T_{K^+K^- \rightarrow \pi^0\eta} \right)$$

- **$V_P$** is an unknown **production vertex**, containing the quark-level dynamics which is **common** to both amplitudes.
- **$G$** is the loop function of two mesons, and regularized by a **cutoff $q_{\text{max}}$**.
- **$T_{ij}$** are the **PP’ scattering matrices** (seen before).
Part II

The low lying scalar resonances in the $D^0$ decays into $K_S^0$ and $f_0(500)$, $f_0(980)$, $a_0(980)$


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Results: distribution (shapes)

\[ \frac{d\Gamma}{dM_{\text{inv}}} = \frac{1}{(2\pi)^3} \frac{p_{\bar{K}^0} \tilde{p}_\pi}{4M_{D^0}^2} \left| t_{D^0 \rightarrow \bar{K}^0 \pi^+ \pi^-} \right|^2 \quad \text{(for } \pi^+ \pi^- \text{ reaction)} \]

here \( p_{\bar{K}^0} \) is the \( \bar{K}^0 \) momentum in the global CM frame (\( D^0 \) at rest) and \( \tilde{p}_\pi \) is the pion momentum in the \( \pi^+ \pi^- \) rest frame. Similarly for the \( \pi^0 \eta \) production.

- **solid line**: \( \pi^+ \pi^- \) in \( D^0 \rightarrow \bar{K}^0 \pi^+ \pi^- \)
- **dashed line**: \( \pi^0 \eta \) in \( D^0 \rightarrow \bar{K}^0 \pi^0 \eta \)
- **smooth background** (squares, triangles, circles) below the \( a_0(980) \) and \( f_0(980) \) peaks
Results: ratios (relative weights)

- Integrating the area below these structures in the previous figure we obtain the theoretical ratio:

\[
R_{th} = \frac{\Gamma(D^0 \to \bar{K}^0 a_0(980), a_0(980) \to \pi^0 \eta)}{\Gamma(D^0 \to \bar{K}^0 f_0(980), f_0(980) \to \pi^+ \pi^-)} = 6.7 \pm 1.3
\]

- Experimental data from the PDG and [PRL89,251802;PRL93,111801]:

\[
\begin{align*}
\text{BR}(D^0 \to \bar{K}^0 a_0(980), a_0(980) \to \pi^0 \eta) &= (6.5 \pm 2.0) \times 10^{-3}, \\
\text{BR}(D^0 \to \bar{K}^0 f_0(980), f_0(980) \to \pi^+ \pi^-) &= (1.22^{+0.40}_{-0.24}) \times 10^{-3}.
\end{align*}
\]

- The experimental ratio that one obtains from there is:

\[
R_{exp} = 5.3^{+2.4}_{-1.9}
\]

- Good agreement between theoretical value and experimental data (within errors)
- Genuine prediction without any free parameter
Results: checks

Invariant mass distributions with different cutoff $q_{\text{max}}$

- **Black curves:** $D^0 \rightarrow \bar{K}^0 \pi^+ \pi^-$
- **Blue curves:** $D^0 \rightarrow \bar{K}^0 \pi^0 \eta$

By performing a similar estimate of the background, even within this broad range of $q_{\text{max}}$, the theoretical value $R_{\text{th}}$ remains within the errors ⇒ a solid prediction
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The low lying scalar resonances in the $D^0$ decays into $K^0_S$ and $f_0(500)$, $f_0(980)$, $a_0(980)$


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We have studied the decay of the $D^0$ decay into $K_S^0$ and $f_0(500), f_0(980), a_0(980)$:

- These are **weak decays** $\Rightarrow$ (strong) isospin violation $\Rightarrow$ test **simultaneously** the production of the $a_0(980)$ and $f_0(980)$ resonances in the decay $D^0 \rightarrow K_S^0 S$
- New test for the chiral unitary approach
- New and novel test about the nature of the lightest scalar mesons
- **Cabibbo-allowed** $\Rightarrow$ rates of $D^0$ decay are **large** compared to $\bar{B}^0$ decay
- No free parameters $\Rightarrow$ **genuine predictions**
- Only **shapes** and **relative weight** can be computed
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Thanks for your attention