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

[J. J. Xie, M. Albaladejo, E. Oset, Phys.Lett.,B728,319(2014)]

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

[J. J. Xie, L. R. Dai, E. Oset, Phys.Lett.,B742,363(2015)]

Miguel Albaladejo (IFIC, Valencia)

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CSIC Consejo Superior de Investigaciones Científicas
IFIC Institut de Física Corpuscular
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Ministerio de Economía y Competitividad

Part I

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Introduction

About the experiments

- BES studied the decay $J/\psi \to \eta K^{*0}\bar{K}^{*0}$ 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/ψ is $0^-(1^{--})$ and η 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...

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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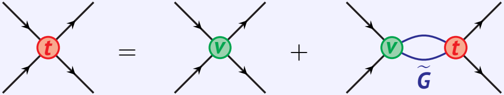
$K^*\bar{K}^*$ interaction

- The amplitude for $K^*\bar{K}^*$ can be written as:

$$t(s) = \frac{v(s)}{1 - v(s)\widetilde{G}(s)} \iff$$



- $v(s)$ is the **potential** (to be discussed later)
- $\tilde{G}(s)$ the **loop function** for the $K^*\bar{K}^*$ pair,

$$\widetilde{G}(s) = \int_{m_-^2}^{m_+^2} \mathrm{d}m_1^2 \mathrm{d}m_2^2\, \omega(m_1^2)\omega(m_2^2) G(s, m_1^2, m_2^2)\ ,$$

- 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^* ($\Gamma_{K^*} \simeq 50$ MeV). The range is taken to be $m_\pm = m_{K^*} \pm 2\Gamma_{K^*}$.

$$\omega(m_1^2) \propto \mathrm{Im} \frac{1}{m_1^2 - m_{K^*}^2 + i\Gamma(m_1^2) m_1} \qquad \Gamma(m_1^2) = \Gamma_{K^*} \frac{p^3(m_1^2)}{p^3(m_{K^*}^2)}$$

Two forms for the potential

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

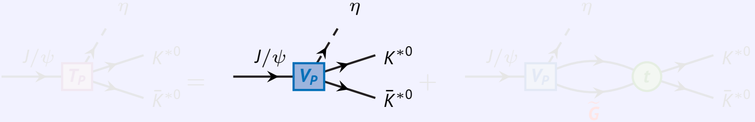
$$v(s) = \left(9 + b\left(1 - \frac{3s}{4m_{K^*}^2}\right)\right) g^2$$

- $g = m_\rho/2f_\pi \simeq 4$. 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 (ρ, ω, ϕ 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 $v \Longrightarrow$ Fix $a(\mu) = -0.8$.

$K^{*0}\bar{K}^{*0}$ 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 $K^*\bar{K}^*$

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

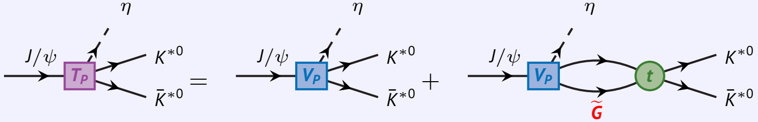
- The invariant mass spectrum is (C is a normalization constant, absorbing V_P):

$$\frac{d\Gamma}{d\sqrt{s}} = \frac{C}{M_{J/\psi}} p_1 \tilde{p}_2 \frac{|t(s)|^2}{|v(s)|^2}$$

- Momenta:

$$\tilde{p}_2(s) = \int_{m_-^2}^{m_+^2} dm_1^2 dm_2^2 \omega(m_1^2)\omega(m_2^2) \frac{\lambda^{1/2}(s, m_1^2, m_2^2)}{2\sqrt{s}}, \qquad p_1(s) = \frac{\lambda^{1/2}(M_{J/\psi}^2, s, m_\eta^2)}{2\sqrt{s}}$$

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



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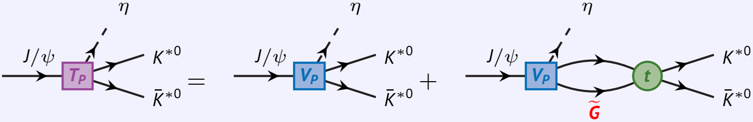
$K^{*0}\bar{K}^{*0}$ spectrum in $J/\psi \to \eta K^{*0}\bar{K}^{*0}$



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Part I

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

[J. J. Xie, M. Albaladejo, E. Oset, Phys.Lett.,B728,319(2014)]

Results

Constant potential

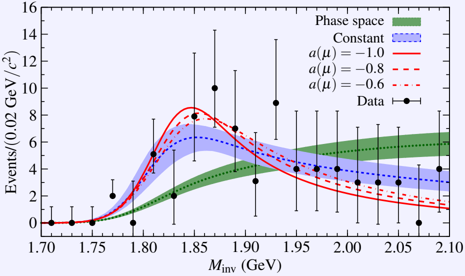
- Error bands $\chi^2 \leqslant \chi^2_{\text{min}} + 1$
- **Good reproduction** of the data
- Rather **model independent** (no underlying model)

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 $t = v = 1$
- χ^2/d.o.f. $= 0.9$ (good, but larger than in our fits)
- But systematically wrong, does not follow the trend of the data



Potential	C (GeV^{-1})	a_μ	v/g^2	χ^2/d.o.f.
Constant	42 ± 6	-0.8	-6.2 ± 1.2	0.45
Hidden gauge	42 ± 6	-1.0	fixed	0.56
Hidden gauge	53 ± 7	-0.8	fixed	0.47
Hidden gauge	67 ± 9	-0.6	fixed	0.42

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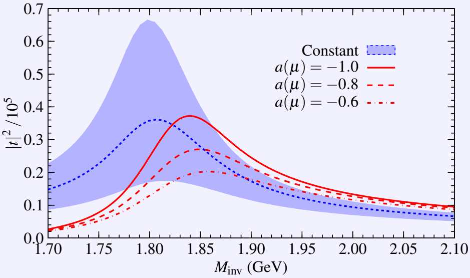

- Constant: $M \simeq 1810$ MeV, $\Gamma \simeq 100$ MeV
- Dynamical: $M \simeq 1850$ MeV, $\Gamma \simeq 120$ MeV

Results

Constant potential

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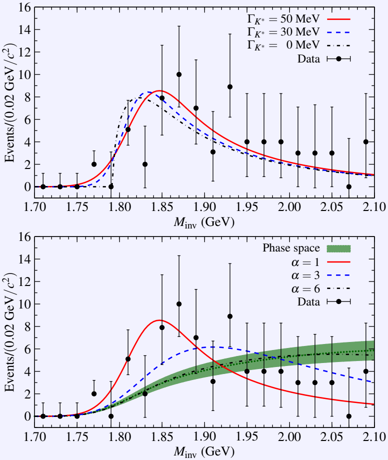
Conclusions

- 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 $v \to v/\alpha$ ($\alpha = 1$ physical case, $\alpha \to \infty$ no interaction)
- A small or zero interaction cannot describe the spectrum

Part I

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Summary and conclusions

- In the BES data regarding $J/\psi \to \eta K^{*0}\bar{K}^{*0}$ 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 ($\eta_c \to \phi K^*\bar{K}^*$) proposed to look for this elusive state [Ren,Geng,Oset,Meng, Eur.Phys.J.,A50,133(2014)].

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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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 σ 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_S^0 and a scalar resonance ($D^0 \to K_S^0\, S$) as a novel test of the nature of $f_0(500)$, $f_0(980)$, $a_0(980)$

1. **Experimental data** from CLEO collaboration
   [PRL89(2002)251802;PRL90(2003)059901;PRL93(2004)111801;also PRD86(2012)010001]
2. Theoretical work is **scarce**:
   - mostly devoted to issues related to CP violation or $D^0 - D^{*0}$ mixing
   - A thorough study for the $D^0 \to K_s^0 \pi^+\pi^-$ 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
     $D^0 \to K_s^0 a_0(980)$ Cabibbo-allowed
     $\bar{B}_s^0 \to J/\psi a_0(980)$ 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

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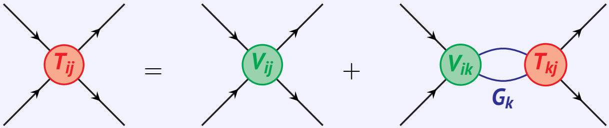
Chiral unitary approach



- Bethe-Salpeter equation: $T = V + VGT \Longrightarrow T = (\mathbb{I} - VG)^{-1}\, V$

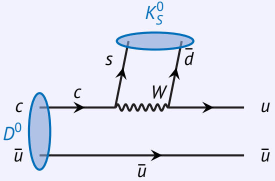
$I = 0$ $\pi^+\pi^-, \pi^0\pi^0, K^+K^-, K^0\bar{K}^0$ and $\eta\eta$ T, V, G: 5×5

$I = 1$ $K^+K^-, K^0\bar{K}^0$ and $\pi^0\eta$ T, V, G: 3×3

- 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:

$$G_k(s) = i \int_{|q|<q_{\max}} \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - m_1^2 + i\varepsilon} \frac{1}{q^2 - m_2^2 + i\varepsilon}$$

$D^0 \to K^0_S\, S$: general idea



Goal: $D^0 \to K^0_s R$. At the quark level:

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

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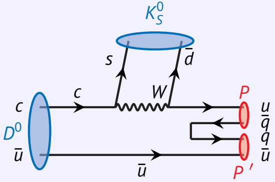

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$D^0 \to K_S^0 S$: hadronization

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

$$M = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{pmatrix}, \text{ satisfying } M \cdot M = M \times \underbrace{(\bar{u}u + \bar{d}d + \bar{s}s)}_{\bar{q}q \text{ pair from vacuum}}$$

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

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

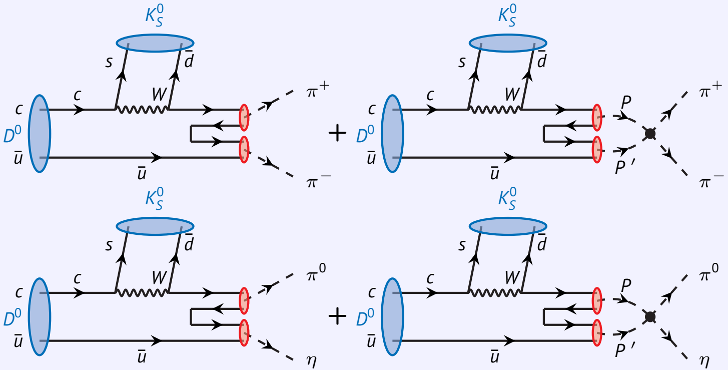
- **Hadronization** proceeds via $M \cdot M \Rightarrow \phi \cdot \phi$. For the $u\bar{u}$ pair,

$$u\bar{u}\underbrace{(\bar{u}u + \bar{d}d + \bar{s}s)}_{\bar{q}q \text{ pair from vacuum}} = (M \cdot M)_{11} \Rightarrow (\phi \cdot \phi)_{11}$$

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

$$(M \cdot M)_{11} \Rightarrow (\phi \cdot \phi)_{11} = \frac{1}{2}\pi^0\pi^0 + \frac{1}{3}\eta\eta + \frac{2}{\sqrt{6}}\pi^0\eta + \pi^+\pi^- + K^+K^-$$

$D^0 \to K^0_S\, S$: 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**

$D^0 \to K^0_S\, S$: amplitudes for $\pi^+\pi^-$ and $\pi^0\eta$

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

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

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

- 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_{max}.
- T_{ij} are the PP' **scattering matrices** (seen before).

Part II

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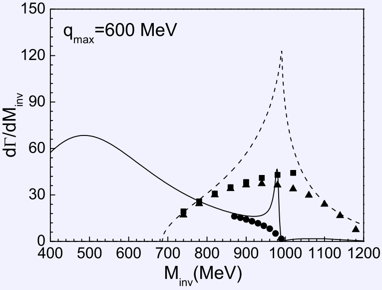
[J. J. Xie, L. R. Dai, E. Oset, Phys.Lett.,B742,363(2015)]

Results: distribution (shapes)

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

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.



1. solid line: $\pi^+\pi^-$ in $D^0\to\bar{K}^0\pi^+\pi^-$
2. dashed line: $\pi^0\eta$ in $D^0\to\bar{K}^0\pi^0\eta$
3. **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**:

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

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

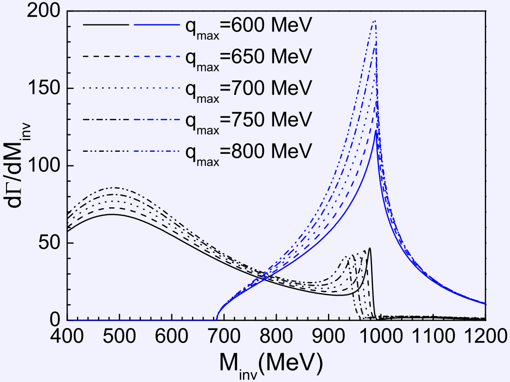
$$\text{BR}(D^0 \to \bar{K}^0 a_0(980), a_0(980) \to \pi^0\eta) = (6.5 \pm 2.0) \times 10^{-3},$$
$$\text{BR}(D^0 \to \bar{K}^0 f_0(980), f_0(980) \to \pi^+\pi^-) = (1.22^{+0.40}_{-0.24}) \times 10^{-3}.$$

- The **experimental ratio** that one obtains from there is:

$$R_{\text{exp}} = \mathbf{5.3^{+2.4}_{-1.9}}$$

- 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_{max}**

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

By performing a similar estimate of the background, even within this broad range of $q_{\rm max}$, the theoretical value $R_{\rm th}$ remains within the errors ⇒ **a solid prediction**

Part II

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

[J. J. Xie, L. R. Dai, E. Oset, Phys.Lett.,B742,363(2015)]

Summary and conclusions

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 $D^0 \to K_S^0\, S$
- 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

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

[J. J. Xie, M. Albaladejo, E. Oset, Phys.Lett.,B728,319(2014)]

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

[J. J. Xie, L. R. Dai, E. Oset, Phys.Lett.,B742,363(2015)]

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Newport News, Sept. 13-18, 2015

Thanks for your attention

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