Study light scalar mesons from heavy quark decays

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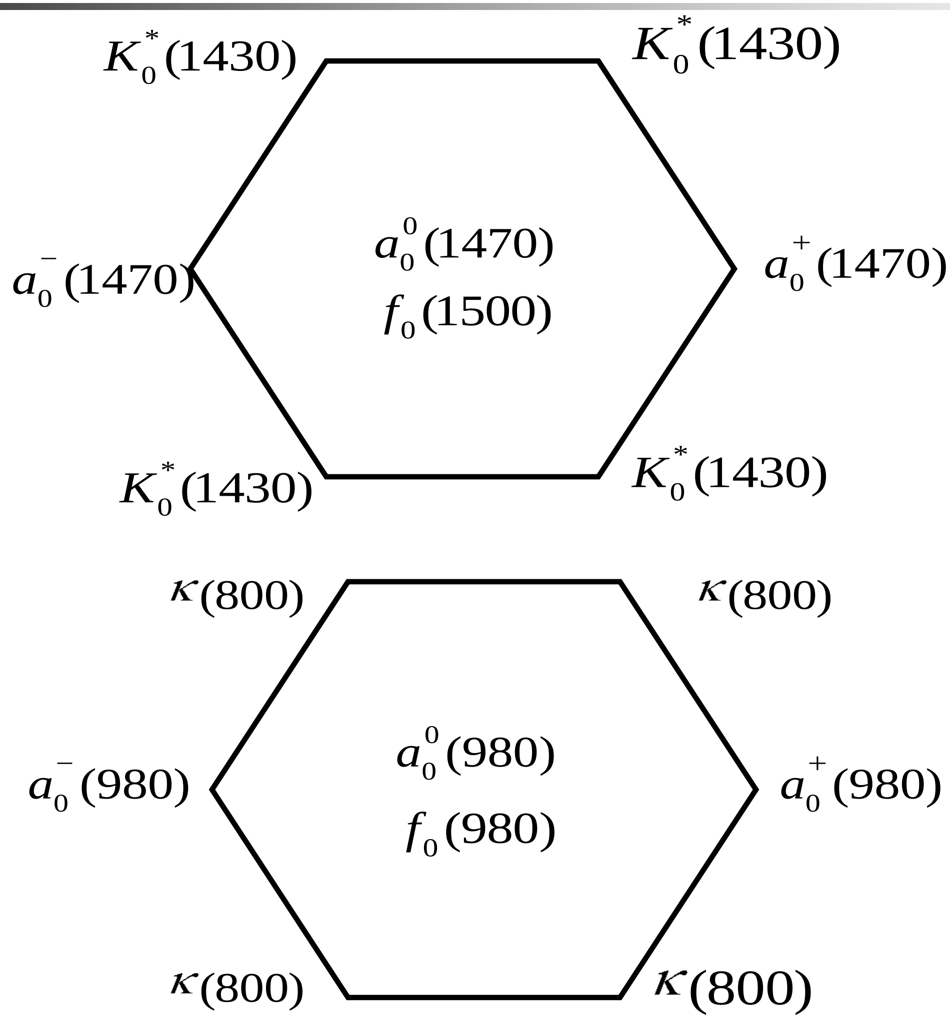
Outline

- **Scalar meson study status**
- **Four quark states or two-quark states: semileptonic decays**
- **Non-leptonic decays**
- **Summary**

Scalar Mesons ($J^P=0^+$)

$q\bar{q}$



$+$ $f_0(1370)$ $f_0(1710)$

$q^2\bar{q}^2$

or $q\bar{q}$

$+$ $\sigma(600)$

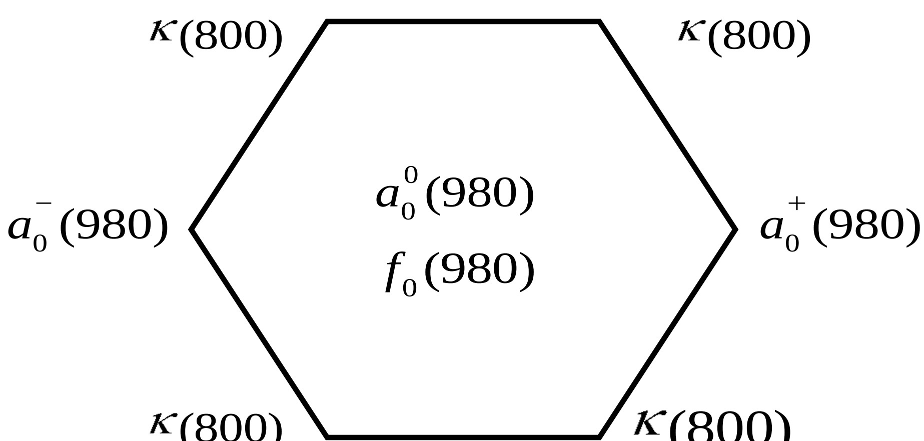
Scalar Mesons around 1GeV ($J^P=0^+$)

σ exist or not for many years

Mass too light to be $q\bar{q}$

Because 0^{++} states are S=1, L=1, should be heavier than 1^{--}(ρ, ϕ K^*)

$q^2\bar{q}^2$

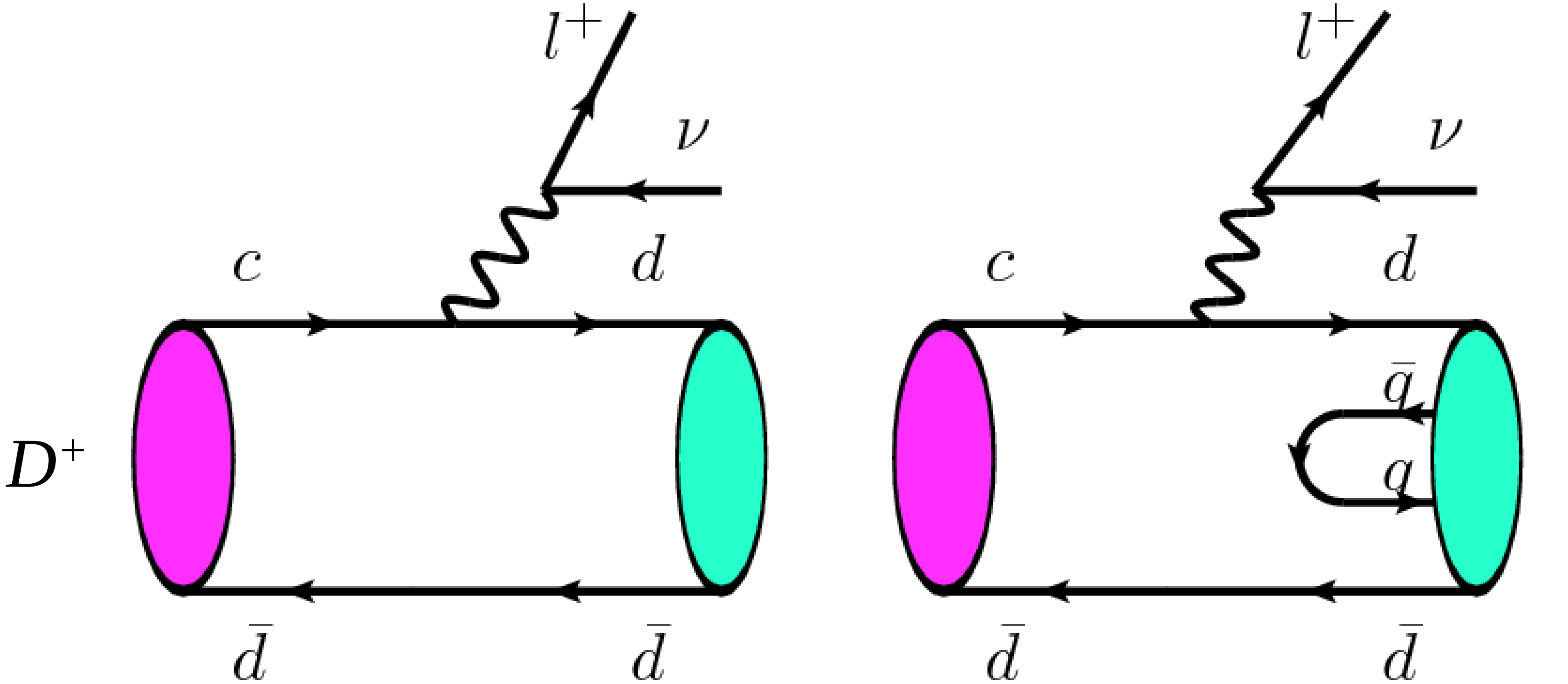


$+ \quad \sigma(600)$

the neutral scalar meson 0^{++} has the same quantum number with vacuum

- They can mix with vacuum, glueball, even molecular states
- So a lot of explanations on the market— tetra quark states
- Most study focus on the decay property of the scalar mesons
- The production of scalar mesons from heavy quark decays are more interesting

Feynman diagrams of semi-leptonic decays of D to Scalar Mesons



$D^+ \to f_0\, \pi^+$, $D^+ \to \sigma\, \pi^+$ **have been measured**

Isospin relation

$$\mathcal{B}(D^+ \to a_0^0 l^+ \nu) = \mathcal{B}(D^+ \to \sigma l^+ \nu)$$

- Isospin 0 and isospin 1 contribution should be 1:1, derived from the Clebsch-Gordan coefficients
- Isospin conserved by strong interaction, no matter perturbative or non-perturbative

--model independent

similarly, $B^+ / D^+ \to \rho^0 e^+ \nu_e = B^+ / D^+ \to \omega e^+ \nu_e$

already verified by exp.

2-quark picture of ordinary light Scalar Mesons

$$|\sigma\rangle = \frac{1}{\sqrt{2}}(|\bar{u}u\rangle + |\bar{d}d\rangle) \equiv |\bar{n}n\rangle, \quad |f_0\rangle = |\bar{s}s\rangle, \qquad (1$$

$$|a_0^0\rangle = \frac{1}{\sqrt{2}}(|\bar{u}u\rangle - |\bar{d}d\rangle), \quad |a_0^-\rangle = |\bar{u}d\rangle, \quad |a_0^+\rangle = |\bar{d}u\rangle$$

σ - f_0 mixing:

$$\left|\begin{matrix} f_0 \\ \sigma \end{matrix}\right\rangle = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \left|\begin{matrix} \bar{s}s \\ \bar{n}n \end{matrix}\right\rangle$$

with

$$25^\circ < \theta < 40^\circ, \quad 140^\circ < \theta < 165^\circ$$

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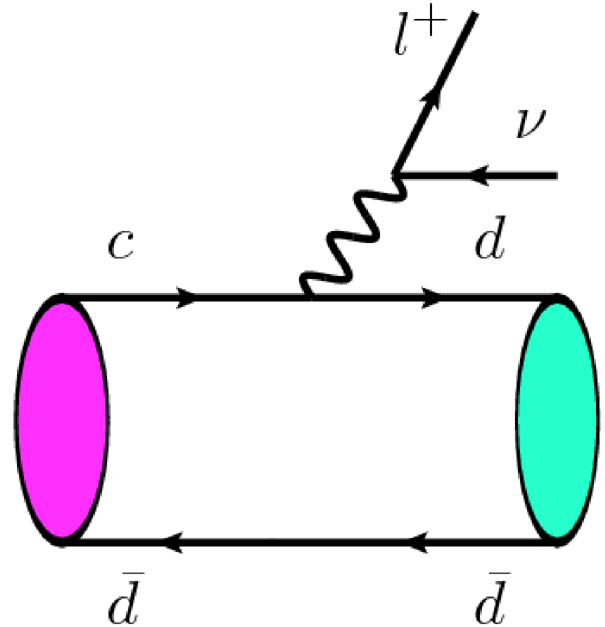

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Sum rule independent of mixing

only $d\bar{d}$ component contributes, in isospin symmetry, we have

$$\mathcal{A}(D^+ \to f_0 l^+ \nu) \;=\; -\sin\theta\hat{\mathcal{A}},$$
$$\mathcal{A}(D^+ \to \sigma l^+ \nu) \;=\; -\cos\theta\hat{\mathcal{A}}$$

where

$$\hat{\mathcal{A}} \equiv \mathcal{A}(D^+ \to a_0^0 l^+ \nu)$$

Br ~ |✌|², **We can get sum rule as**

$$\mathcal{B}(D^+ \to a_0^0 l^+ \nu) = \mathcal{B}(D^+ \to f_0 l^+ \nu) + \mathcal{B}(D^+ \to \sigma l^+ \nu)$$

4-quark picture of ordinary light Scalar Mesons

Group theory assignment

$$|\sigma\rangle = \bar{u}u\bar{d}d, \quad |f_0\rangle = |\bar{n}n\bar{s}s\rangle, \qquad (5)$$

$$a_0^0\rangle = \frac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d)\bar{s}s, \quad |a_0^+\rangle = |\bar{d}u\bar{s}s\rangle, \quad |a_0^-\rangle = |\bar{u}d\bar{s}s\rangle$$

σ - f_0 mixing:

$$\begin{vmatrix} f_0 \\ \sigma \end{vmatrix}\Big\rangle = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \begin{vmatrix} \overline{n}n\overline{s}s \\ \overline{u}u\overline{d}d \end{vmatrix}\Big\rangle$$

with

$$\phi = (174.6^{+3.4}_{-3.2})^\circ$$

$$n\bar{n} = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$$

4-quark picture of ordinary light Scalar Mesons

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$$|\sigma\rangle = \bar{u}u\bar{d}d, \quad |f_0\rangle = |\bar{n}n\bar{s}s\rangle,$$

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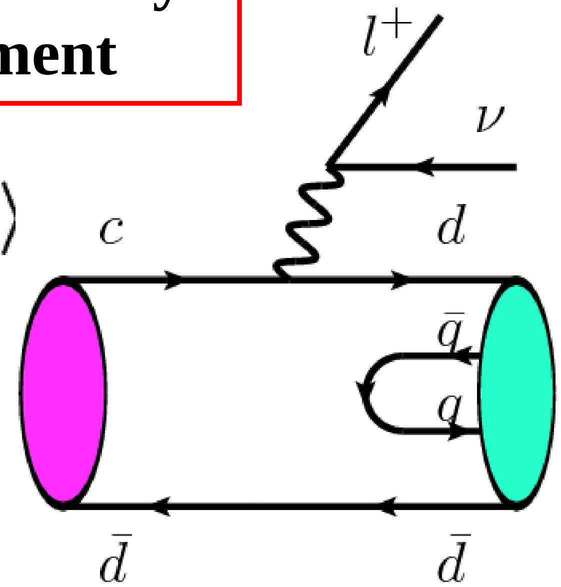


σ - f$_0$ mixing:

$$\left| \begin{matrix} f_0 \\ \sigma \end{matrix} \right\rangle = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \left| \begin{matrix} n\bar{n}s\bar{s} \\ u\bar{u}d\bar{d} \end{matrix} \right\rangle$$

with

$$\phi = (174.6^{+3.4}_{-3.2})^\circ$$

$$n\bar{n} = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$$

4-quark picture of Scalar Mesons

$$\mathcal{A}(D^+ \to f_0 l^+ \nu) = -(\cos\phi + \sqrt{2}\sin\phi)\hat{\mathcal{A}}$$
$$\mathcal{A}(D^+ \to \sigma l^+ \nu) = (\sin\phi - \sqrt{2}\cos\phi)\hat{\mathcal{A}},$$

where

$$\hat{\mathcal{A}} \equiv \mathcal{A}(D^+ \to a_0^0 l^+ \nu)$$

We can get sum rule as

$$\mathcal{B}(D^+ \to a_0^0 l^+ \nu) = \frac{1}{3}[\mathcal{B}(D^+ \to f_0 l^+ \nu) + \mathcal{B}(D^+ \to \sigma l^+ \nu)]$$

Define a ratio R

$$R = \frac{\mathcal{B}(D^+ \to f_0 l^+ \nu) + \mathcal{B}(D^+ \to \sigma l^+ \nu)}{\mathcal{B}(D^+ \to a_0^0 l^+ \nu)}.$$

It is one for 2-quark picture, while 3 for 4-quark picture

Similarly, for B meson decays, we have

$$\begin{aligned} R &= \frac{\mathcal{B}(B^+ \to f_0 l^+ \nu) + \mathcal{B}(B^+ \to \sigma l^+ \nu)}{\mathcal{B}(B^+ \to a_0^0 l^+ \nu)} \\ &= \begin{cases} 1 & \text{two} \quad \text{quark} \\ 3 & \text{tetra-quark} \end{cases}. \end{aligned}$$

These channels have large enough BRs to be measurable

If the mixing angle is modest, all three $D^+ \to S l^+ \nu$ have similar branching ratios. The branching ratio of the semileptonic $D_s \to f_0$ decay is measured [9] as

$$\begin{aligned} &\mathcal{B}(D_s \to f_0 l \bar{\nu}) \times \mathcal{B}(f_0 \to \pi^+\pi^-) \\ &= (2.0 \pm 0.3 \pm 0.1) \times 10^{-3}. \end{aligned} \tag{16}$$

Thus as an estimation, branching ratios for the cascade $D^+ \to S l^+ \nu$ decays are expected to have the order

$$\frac{V_{cd}^2}{V_{cs}^2} \times 2 \times 10^{-3} \sim 1 \times 10^{-4}. \tag{17}$$

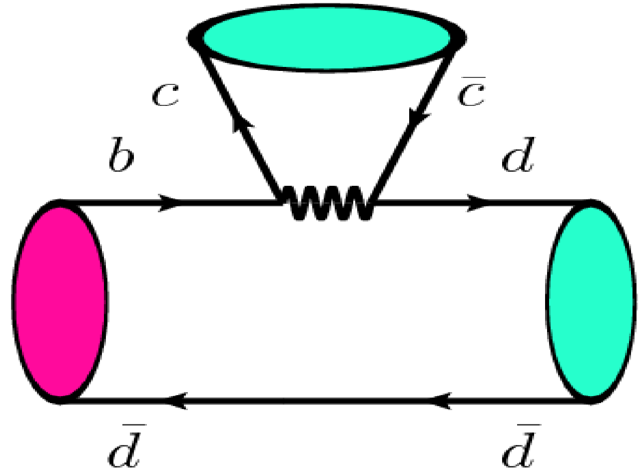
As for the B decays, the branching ratio of $B \to Sl\bar{\nu}$ can be estimated utilizing the $B \to \rho l\bar{\nu}$ and $D_s^+ \to \phi l^+ \nu$ decays. If the mixing angle is moderate, the branching ratio can be estimated as

$$\mathcal{B}(B \to f_0 l\bar{\nu}) \;\sim\; \mathcal{B}(B \to \rho l\bar{\nu}) \frac{\mathcal{B}(D_s \to f_0 l\bar{\nu})}{\mathcal{B}(D_s \to \phi l\bar{\nu})}$$
$$\sim\; 10^{-4} \times \frac{10^{-3}}{10^{-2}} = 10^{-5}. \qquad (18)$$

Compared with the recently measured semileptonic $B \to \eta$ decay [11]

$$\mathcal{B}(B^- \to \eta l^- \bar{\nu}) \;=\; (3.1 \pm 0.6 \pm 0.8) \times 10^{-5}, \qquad (19)$$

B→ J/ψ (η_c) f_0



- **Semileptonic B decays $B^+ \to f_0 l^+ \nu_l$ are clean, but the neutrino is identified as missing energy, thus the efficiency is limited**
- **The lepton pair can also be replaced by a charmonium state such as J/ψ, since J/ψ does not carry any light flavor either.**
- ***B→ J/ψ f_0* decays may provide another ideal probe to detect the internal structure of the scalar mesons.**

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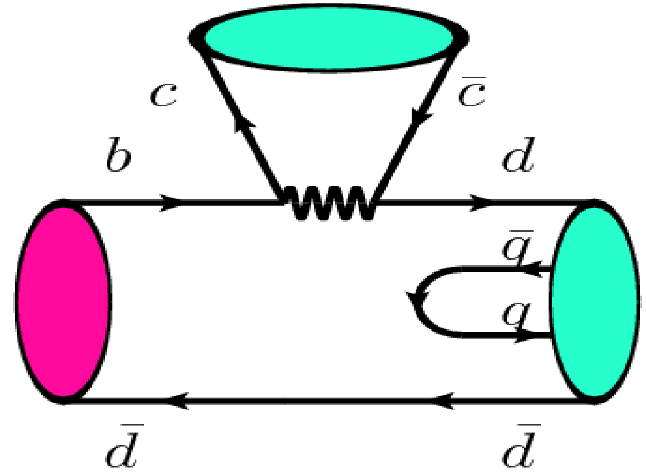

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$B \to J/\psi(\eta_c)$ S

$$R = \frac{\mathcal{B}(\bar{B}^0 \to f_0 J/\psi) + \mathcal{B}(\bar{B}^0 \to \sigma J/\psi)}{\mathcal{B}(\bar{B}^0 \to a_0^0 J/\psi)} = 1 \quad (20)$$

in the $\bar{q}q$ picture, and

$$R = \frac{\mathcal{B}(\bar{B}^0 \to f_0 J/\psi) + \mathcal{B}(\bar{B}^0 \to \sigma J/\psi)}{\mathcal{B}(\bar{B}^0 \to a_0^0 J/\psi)} = 3 \quad (21)$$

in the $\bar{q}q\bar{q}q$ picture. Although these are hadronic decays

The branching fraction is expected to have the order

$$\begin{aligned} \mathcal{B}(B \to f_0 J/\psi) &\sim \mathcal{B}(\bar{B}^0 \to \rho^0 J/\psi) \frac{\mathcal{B}(D_s \to f_0 l\bar{\nu})}{\mathcal{B}(D_s \to \phi l\bar{\nu})} \\ &\sim 10^{-5} \times \frac{10^{-3}}{10^{-2}} = 10^{-6}. \end{aligned} \tag{22}$$

On experimental side, the J/ψ is easily detected through a lepton pair l^+l^- and thus this mode may be more useful. If the J/ψ meson is replaced by η_c in eq.(20,21), one can get the similar sum rules.

Uncertainties mainly from SU(3) breaking

- Form factor difference – no problem, since it makes the R for 4-quark picture even larger than 3
- Mostly by mass difference, only problem:
  m_σ = (0.4~1.2) GeV, but any way phase space is easy to calculate
- Relatively large uncertainty in D decays. But in B decays, there is no problem, since m_σ negligible
- Governed by heavy quark effective theory, the SU(3) breaking is suppressed by $1/m_Q$

Summary

- **The semi-leptonic decays of D and/or B mesons to scalar mesons can provide a theoretically clean way to distinguish the 2-quark and 4-quark picture of light scalar mesons**
- **So as the non-leptonic decays of $B \to J/\psi(\eta_c)\ S$**

Thank you!

$$R_{f_0} = \frac{\mathcal{B}(D/B \to f_0 l\nu)}{\mathcal{B}(D/B \to a_0^0 l\nu)} \quad \left(R_{f_0} = \frac{\mathcal{B}(B \to f_0 J/\psi)}{\mathcal{B}(B \to a_0^0 J/\psi)}\right)$$

The measurement of ratio R can determine the mixing angle of f_0 and σ