Light scalar meson in Ds decays

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arXiv:1909.07327

Outline:
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2. Formalism
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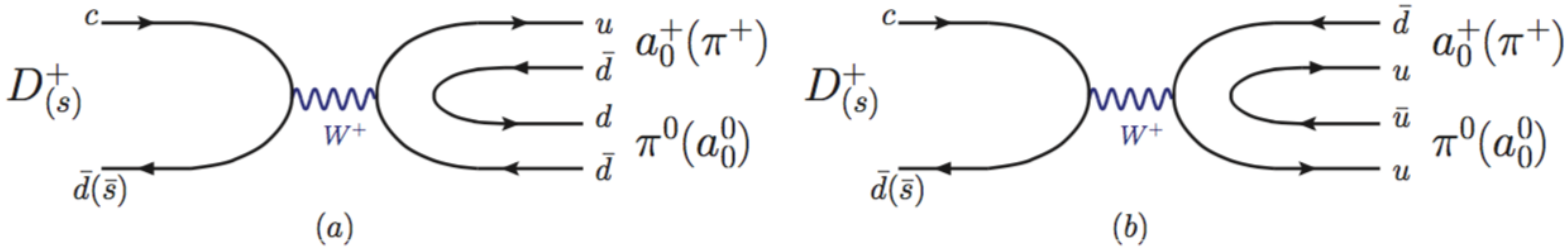
Motivation

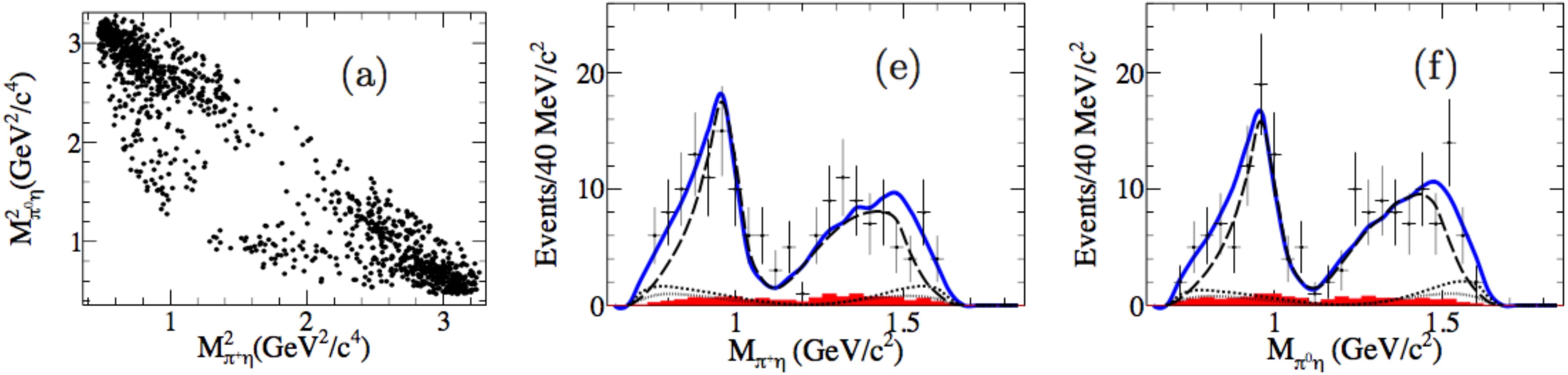
• Observation (BESIII, PRL112001 (2019), arXiv:1903.04118 [hep-ex])

$\mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta) = (1.46 \pm 0.15 \pm 0.23) \times 10^{-2}$,

$a_0 \equiv a_0(980)$, claimed as the W-annihilation process.



with the assumption that a_0 is a p-wave scalar meson.



• Theoretical difficulties

The spectator quark $\bar{s}$ in D_s^+ needs elimination.

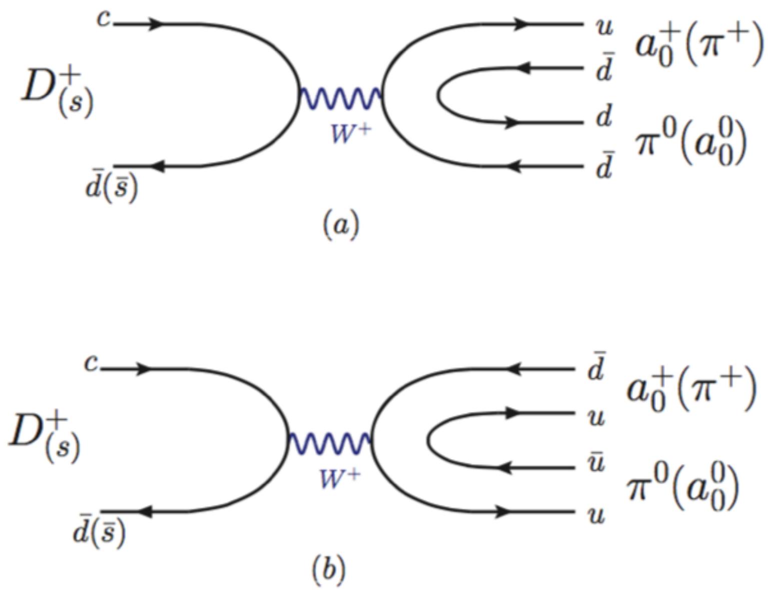
The productions of $a_0^{+,0}$, equal sizes.

$\mathcal{B}(D_s^+ \to \pi^+\rho^0) = (2.0 \pm 1.2) \times 10^{-4}$

$\mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta) = 1.46 \times 10^{-2}$

$\mathcal{B}(D_s^+ \to \pi^+\eta) = (1.70 \pm 0.09) \times 10^{-2}$

$\mathcal{B}(D_s^+ \to \pi^+ f_0(980)) \sim O(10^{-2})$



• Estimation

$$\mathcal{B}(D^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta)$$
$$\simeq \left(\frac{f_D}{f_{D_s}}\right)^2 \left(\frac{|V_{cd}|}{|V_{cs}|}\right)^2 \frac{\tau_D}{\tau_{D_s}} \left(\frac{m_{D_s}}{m_D}\right)^3 \times \mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta)$$
$$\simeq 1.2 \times 10^{-3}$$

disapproved by data: $\mathcal{B}(D^+ \to \pi^+\pi^0\eta) = (1.38 \pm 0.35) \times 10^{-3}$

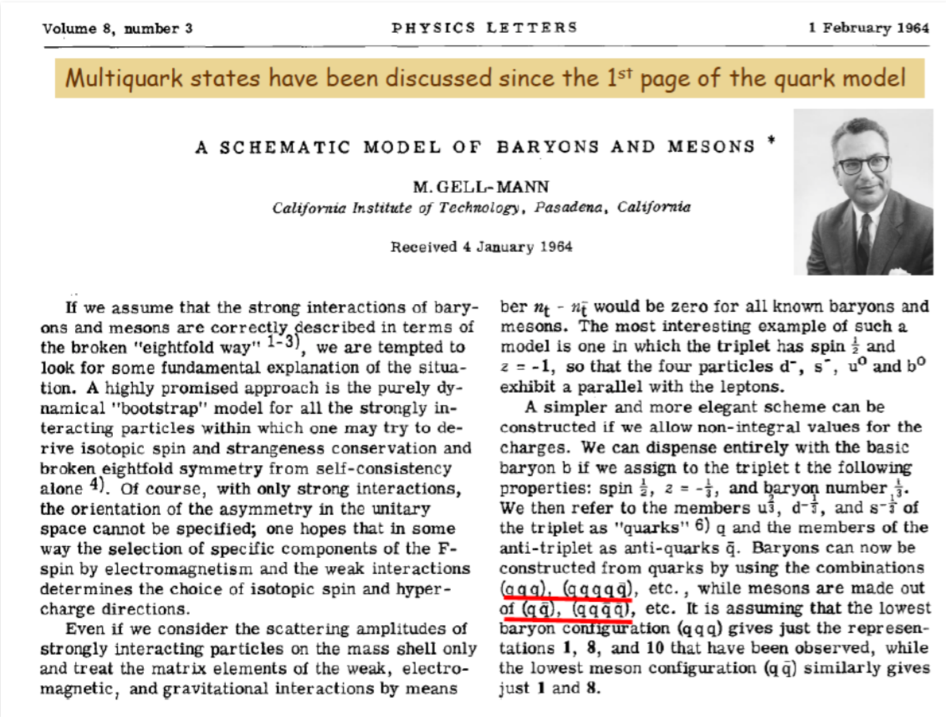
a0, tetraquark?

- meson, baryon, tetraquark, pentaqurak, hexaquark.

unicycle (1-wheel), bicycle (2-wheel), ...

- multi-quark bound state besides M, $\mathcal{B}$

proposed by Murray Gell-Mann and George Zweig.



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

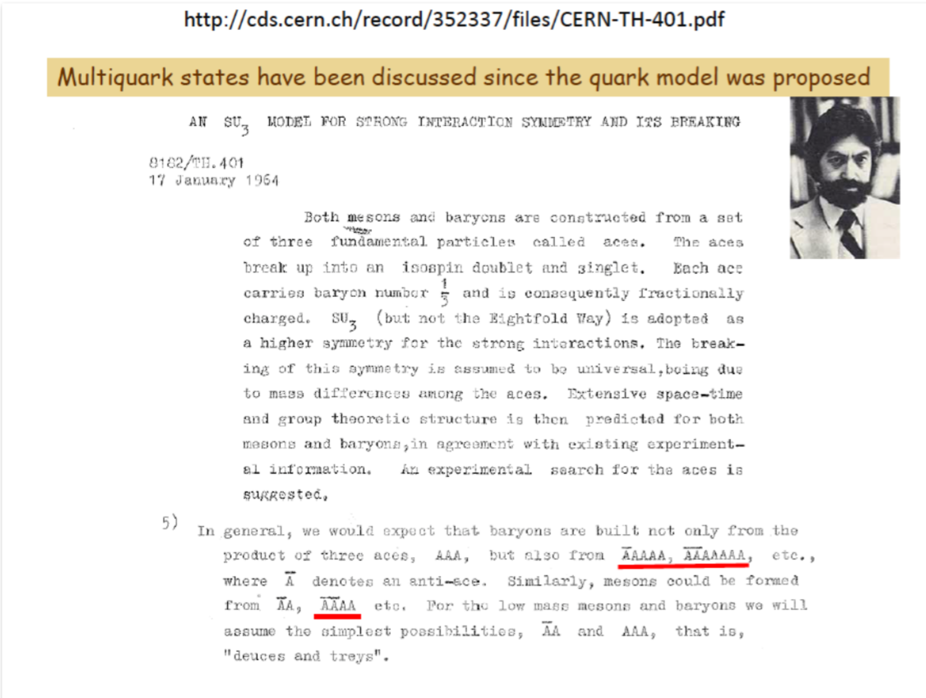
Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.



http://cds.cern.ch/record/352337/files/CERN-TH-401.pdf

Multiquark states have been discussed since the quark model was proposed

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. An experimental search for the aces is suggested.

5) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

Scalar mesons below 1 GeV

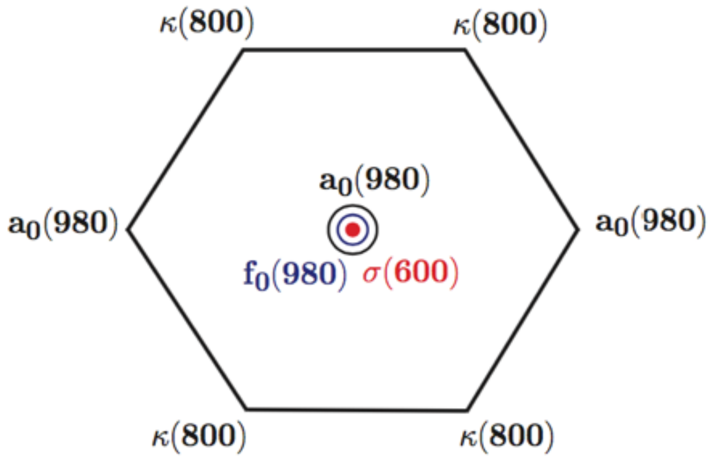
- Controversial identifications

a_0^+, $a_0^{0,+}$, $f_0(980)$

p-wave $(u\bar{d})$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $s\bar{s}$

compact $s\bar{s}(u\bar{d})$, $s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}$,

$s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2}$ tetraquarks



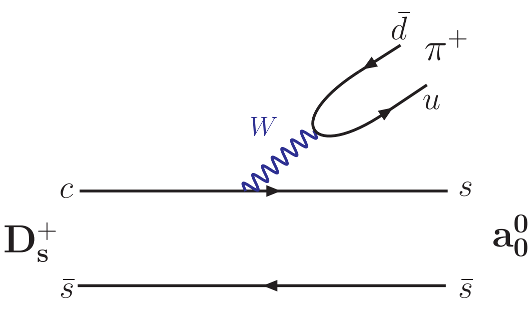
- tetraquark, promising

$f_0(600)$, $ud\bar{u}\bar{d}$; $f_0(980)$, $us\bar{u}\bar{s}$;

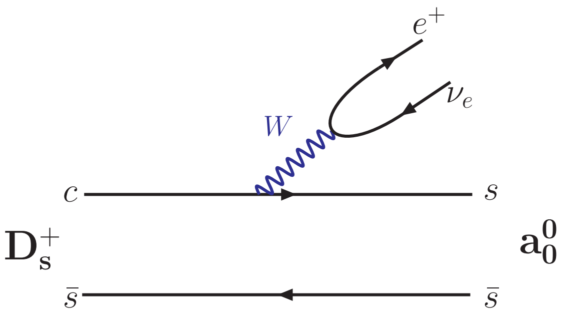
lighter than 1 GeV

PRL110, 261601 (2013), Steven Weinberg

Since you have eliminated the impossible, whatever remains, however improbable, must be the truth.

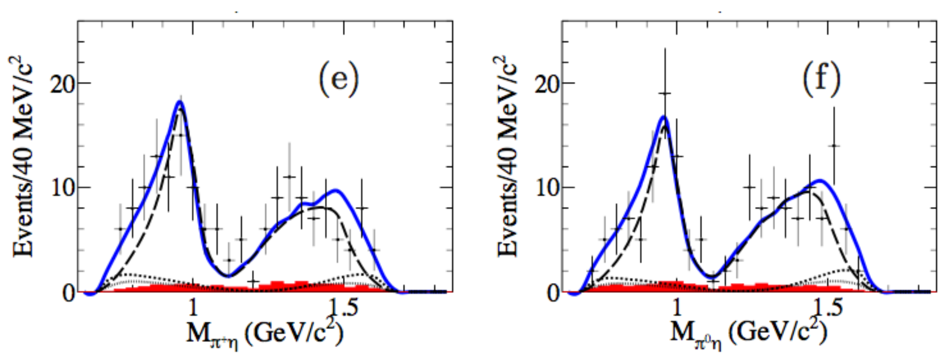


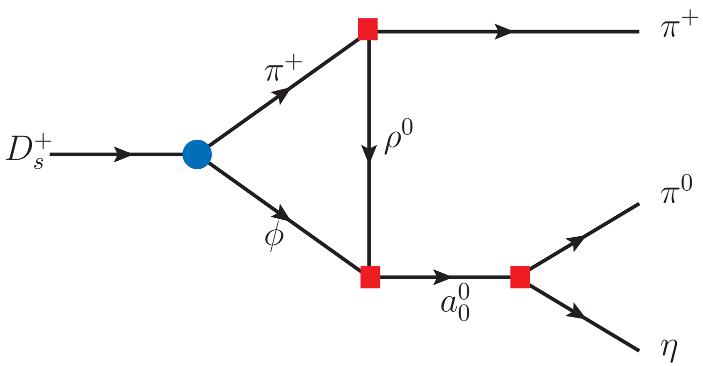
(a)



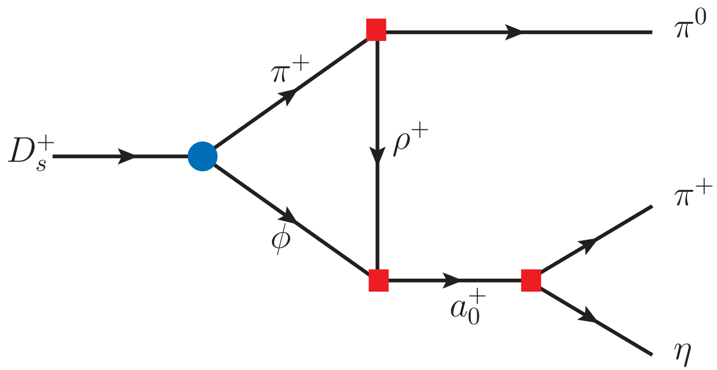
(b)

- not for a_0^+
- constraint from $D_s^+ \to a_0^0 e^+ \nu_e$
- $\phi \to a_0 \gamma$



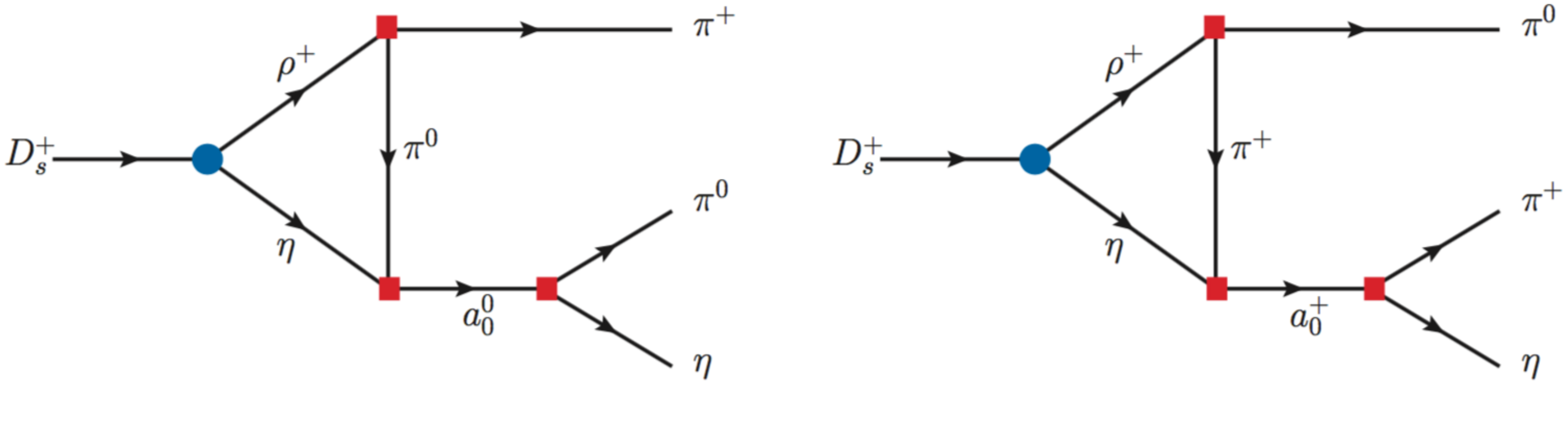


(a)

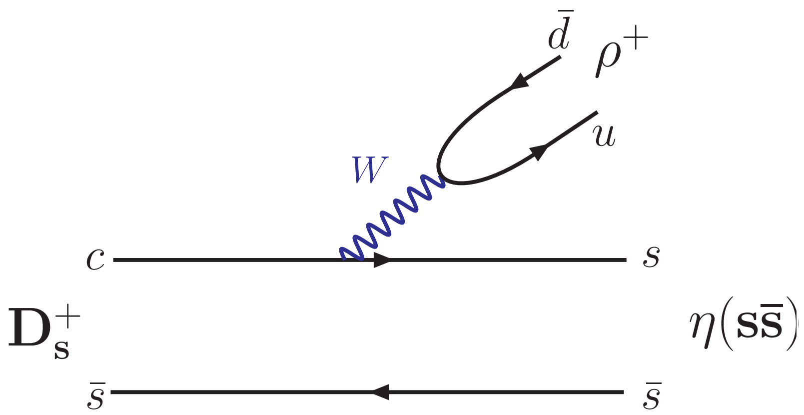


(b)

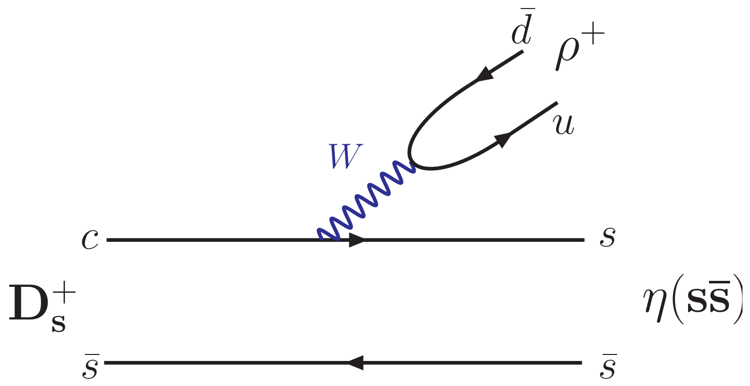
- $\mathcal{B}(D_s^+ \to \eta\rho^+) = (8.9 \pm 0.8)\%$
- Is a_0 still a tetraquark?



(a) (b)



$(D_s^+ \to \eta\rho^+)$



$(D_s^+ \to \eta\rho^+)$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud} [c_1^{eff} (\bar{u}d)(\bar{s}c) + c_2^{eff} (\bar{s}d)(\bar{u}c)]$$

$$\mathcal{A}(D_s^+ \to \eta\rho^+) = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud} a_1 \langle \rho^+ | (\bar{u}d) | 0 \rangle \langle \eta | (\bar{s}c) | D_s^+ \rangle$$

$$\langle \eta | (\bar{s}c) | D_s^+ \rangle = (p_{D_s} + p_\eta)_\mu F_+(t) + q_\mu F_-(t)$$

$$\langle \rho^+ | (\bar{u}d) | 0 \rangle = m_\rho f_\rho \epsilon_\mu^*$$

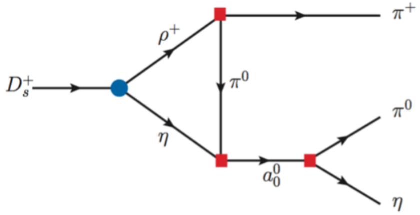
$$F(t) = \frac{F(0)}{1 - a(t/m_{D_s}^2) + b(t^2/m_{D_s}^4)}$$

$$a_1 = 1.02 \pm 0.05$$

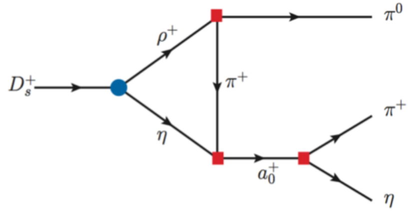
- $\mathcal{B}(D_s^+ \to \eta\rho^+) = (8.9 \pm 0.8)\%$

$$\mathcal{A}(a_0 \to \eta\pi) = g_{a_0\eta\pi}$$

$$\mathcal{A}(\rho^+ \to \pi^+\pi^0) = g_{\rho\pi\pi} \epsilon \cdot (p_{\pi^+} - p_{\pi^0})$$



(a)



(b)

$$\mathcal{A}_{a+b} \equiv \mathcal{A}(D_s^+ \to \pi^+(a_0^0 \to)\pi^0\eta + \pi^0(a_0^+ \to)\pi^+\eta) = \mathcal{A}_a + \mathcal{A}_b \,,$$

$$\mathcal{A}_a \equiv \mathcal{A}(D_s^+ \to \pi^+(a_0^0 \to)\pi^0\eta) = \frac{1}{m_{12}^2 - m_{a_0^0}^2 + i m_{a_0^0}\Gamma_{a_0^0}}$$

$$\times\, i \int \frac{d^4 q_3}{(2\pi)^4} \frac{\hat{A}_a}{(q_1^2 - m_{\rho^+}^2 + i\epsilon)(q_2^2 - m_\eta^2 + i\epsilon)(q_3^2 - m_{\pi^0}^2)} F_a^2(q_3^2) \,,$$

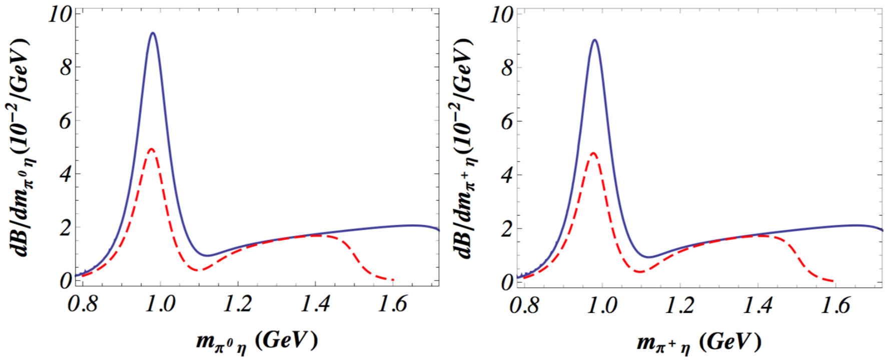
$$\mathcal{A}_b \equiv \mathcal{A}(D_s^+ \to \pi^0(a_0^+ \to)\pi^+\eta) = \frac{1}{m_{23}^2 - m_{a_0^+}^2 + i m_{a_0^+}\Gamma_{a_0^+}}$$

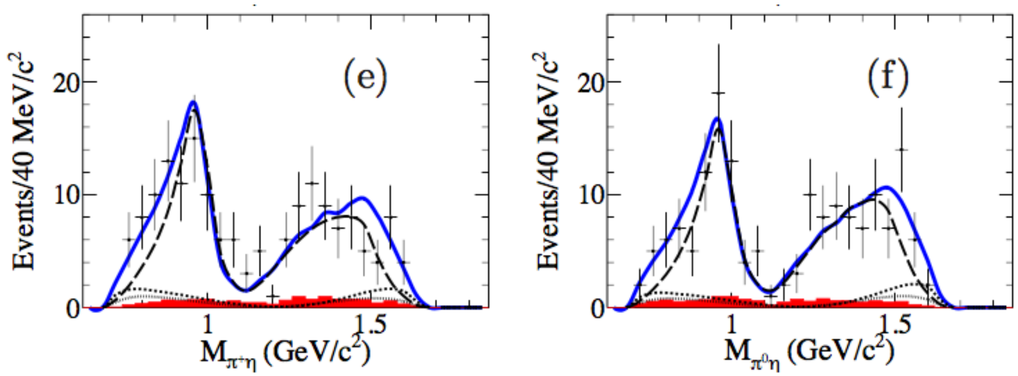
$$\times\, i \int \frac{d^4 q_3}{(2\pi)^4} \frac{\hat{A}_b}{(q_1^2 - m_{\rho^+}^2 + i\epsilon)(q_2^2 - m_\eta^2 + i\epsilon)(q_3^2 - m_{\pi^+}^2)} F_b^2(q_3^2) \,,$$

$$\hat{A}_{a(b)} = \mathcal{A}(D_s^+ \to \eta\rho^+)\mathcal{A}(\eta\pi^{0(+)} \to a_0^{0(+)})\mathcal{A}_{a(b)}(\rho^+ \to \pi^{+(0)}\pi^{0(+)})\mathcal{A}(a_0^{0(+)} \to \eta\pi^{0(+)}) \,,$$

$$F_{a(b)}(q_3^2) = (m_{\pi^{0(+)}}^2 - \Lambda^2)/(q_3^2 - \Lambda^2) \,,$$

$$\Lambda = (1.6 \pm 0.2)\ \mathrm{GeV}$$





$$\mathcal{B}(D_s^+ \to a_0^{0(+)}\pi^{+(0)}) = (1.7 \pm 0.4) \times 10^{-2}\,,$$

$$\mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta) = (1.5 \pm 0.3) \times 10^{-2}\,,$$

$$\mathcal{B}(D_s^+ \to \pi^{+(0)}(a_0^{0(+)} \to)\pi^{0(+)}\eta) = (1.46 \pm 0.15 \pm 0.23) \times 10^{-2}$$

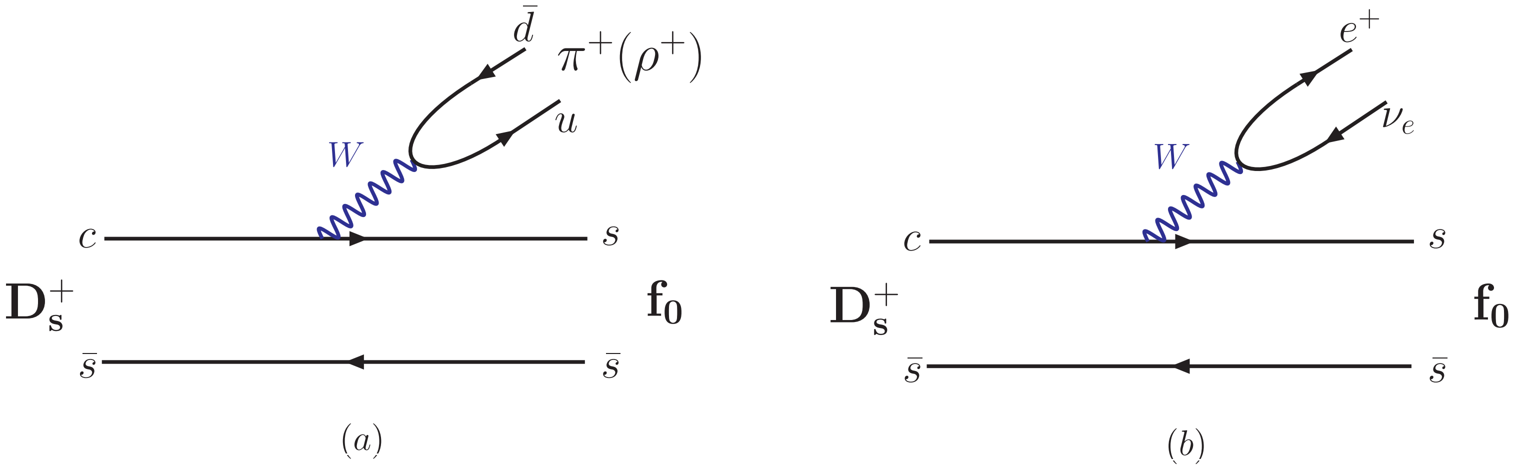
- $D_s^+ \to \pi^+(a_0^0 \to)\pi^0\eta$ and $D_s^+ \to \pi^0(a_0^+ \to)\pi^+\eta$

large interference with a relative phase of 180°

$\rho^+(q_4) \to \pi^0(q_3)\pi^+(q_4 - q_3)$, $\rho^+(q_4) \to \pi^+(q_3)\pi^0(q_4 - q_3)$

$\mathcal{A}_a(\rho^+ \to \pi^+\pi^0) = -\mathcal{A}_b(\rho^+ \to \pi^0\pi^+)$

30% cancellation to the total branching ratio.



	our result (preliminary)	data
$10^2\mathcal{B}(D_s^+ \to \pi^+ f_0)$	0.9	—
$10^2\mathcal{B}(D_s^+ \to \rho^+ f_0)$	2.6	—
$10^2\mathcal{B}(D_s^+ \to \pi^+(f_0 \to)\pi^+\pi^-)$	0.8	0.63 ± 0.08
$10^2\mathcal{B}(D_s^+ \to \pi^+(f_0 \to)K^+K^-)$	0.2	1.15 ± 0.32
$10^3\mathcal{B}(D_s^+ \to f_0 e^+\nu_e)$	2.8	—
$10^3\mathcal{B}(D_s^+ \to e^+\nu_e(f_0 \to)\pi^+\pi^-)$	1.3	$1.3 \pm 0.3 \pm 0.1$
$10^4\mathcal{B}(D_s^+ \to e^+\nu_e(f_0 \to)K^+K^-)$	5.9	—

Summary

- By explaining $\mathcal{B}(D_s^+ \to \pi^+(a_0^0 \to)\pi^0\eta, \pi^0(a_0^+ \to)\pi^+\eta)$

as large as 10^{-2},

we have provided the evidence that a_0 is a tetraquark.

- Apart from $\phi \to a_0\gamma$, there rarely exists the decay

for a_0 in association with $s\bar{s}$ and $q\bar{q}$ both,

which makes the observation by BESIII important.

Thank You