Charmed scalar mesons and related

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§11. Summary on **Part II**

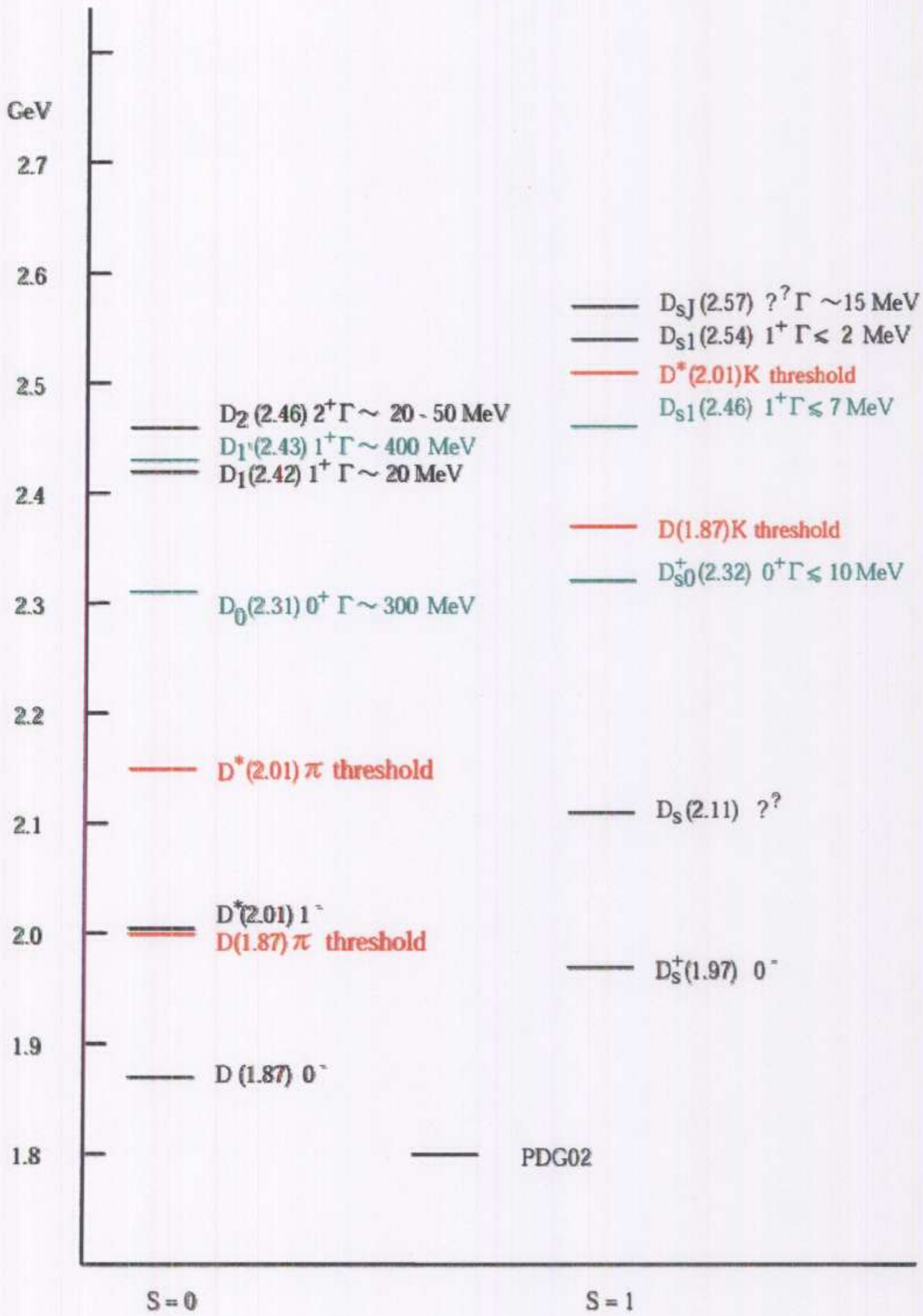
- Motivation to four-quark mesons
  - An important role of four-quark mesons in hadronic weak decays of charm mesons, in particular, in the long standing puzzle,

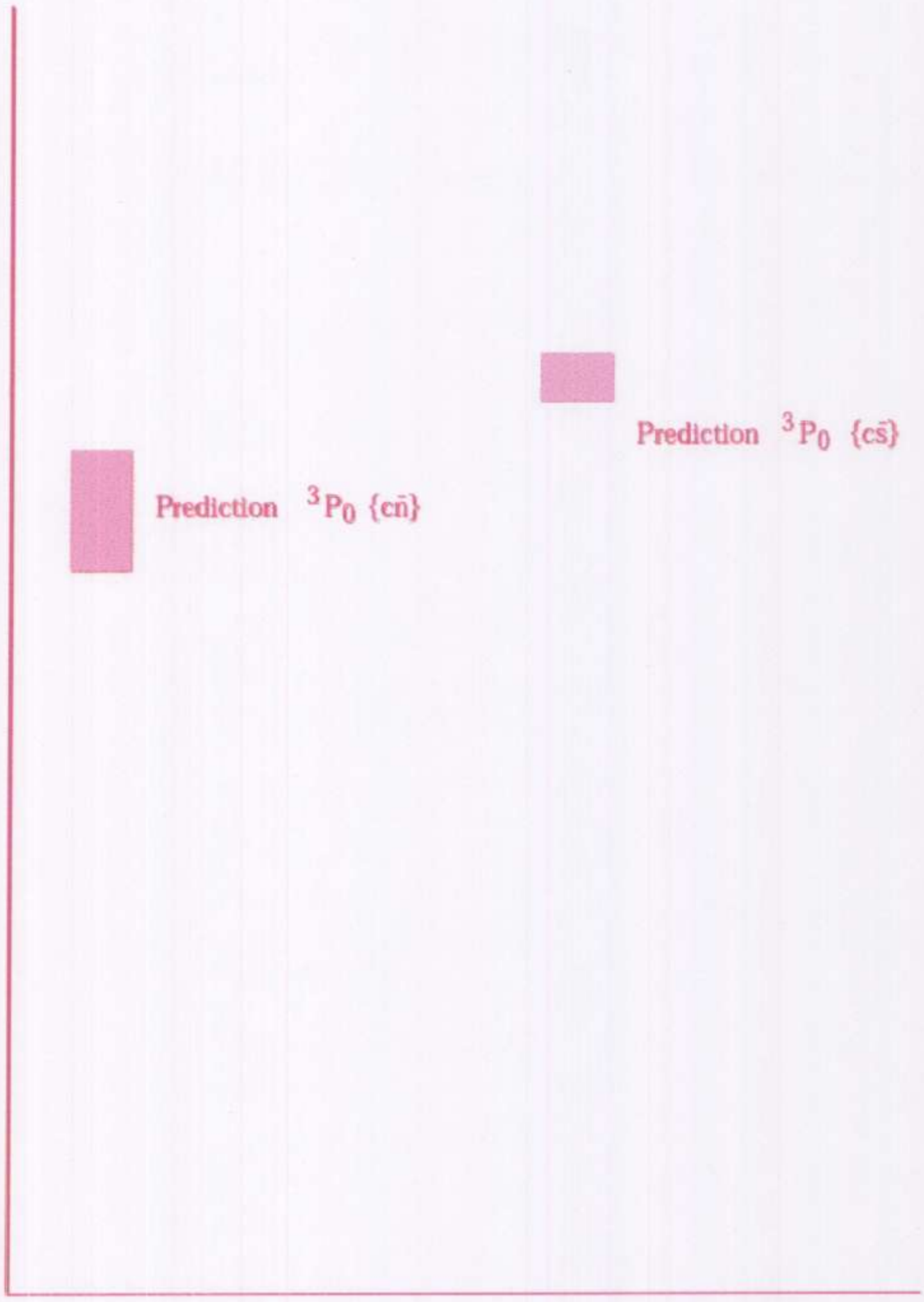
$$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)} = 2.88 \pm 0.15.$$

(PDG02, K. Hagiwara et al., P.R.D **66**, 010001 (2002).)

- The new resonance $D_{s0}^+(2.32)$ as a component of iso-triplet four-quark mesons
  - Extra narrow scalar states

§1. Spectrum of charmed mesons


GeV
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
D2 (2.46) 2+ Γ ~ 20 - 50 MeV
D1' (2.43) 1+ Γ ~ 400 MeV
D1 (2.42) 1+ Γ ~ 20 MeV
D0 (2.31) 0+ Γ ~ 300 MeV
D*(2.01) π threshold
D*(2.01) 1-
D(1.87) π threshold
D (1.87) 0-
PDG02
DsJ (2.57) ?? Γ ~15 MeV
Ds1 (2.54) 1+ Γ ≤ 2 MeV
D*(2.01)K threshold
Ds1 (2.46) 1+ Γ ≤ 7 MeV
D(1.87)K threshold
D+s0 (2.32) 0+ Γ ≤ 10 MeV
Ds (2.11) ??
D+s (1.97) 0-
S = 0
S = 1


Prediction $^3P_0$ $\{c\bar{s}\}$
Prediction $^3P_0$ $\{c\bar{n}\}$

§2. Existing models of $D_{s0}^+(2.32)$ [tentative]

Assignments	Comments
• Scalar $\{c\bar{s}\}$ (a) • χ-partner of D_s^+ (b)	• $m_{\rm pot,\,quench} > 2.4$ GeV • Only one scalar • Production rates ?
• Iso-singlet DK molecule (c) • Mixed state of $\{c\bar{s}\}$ and $\{cq\overline{qs}\}$ (d)	• $\Gamma_{D_{s0}} \ll 10$ MeV (iso-spin violating) • Coupling with the $\{c\bar{s}\}$ • Extra states ? • Color degree of freedom ?
• Iso-singlet $\{cn\bar{n}\bar{s}\}$ (e)	• Narrow $\tilde{D}_{0s}^+$ peak on a broad bump of $\tilde{D}_{1s}^+$ • Exotic : $\tilde{D}_{0\bar{s}}^0$
• A component of iso-triplet $[cn][\overline{sn}]$ (f)	$\Gamma_{\hat{F}_I^+} \simeq \Gamma(\hat{F}_I^+ \to D_s^+\pi^0)$ ~ 10 MeV (input) • Narrow $\hat{F}_I$, $\hat{D}$, $\hat{D}^s$ • $\Gamma_{\hat{F}_0^+} \ll 10$ MeV (iso-spin viol.) • Exotic : $\hat{E}^0$
• Pole of $DK\,(D\pi)$ amplitude (g)	• Unitarized amplitude, • Chiral Lagrangian

References (tentative):

- Assignments:
  (a) A. De Rújula, H. Georgi and S. L. Glashow, P.R.L. **37**, 785 (1976).
  (b) M. A. Nowak, M. Rho and J. Zahed, P.R.D **48**, 4370 (1993); W. A. Bardeen and C. T. Hill, P.R.D **49**, 409 (1994).
  (c) T. Barnes F. E. Close and H. J. Lipkin, P.R.D **68**, 054006 (2003).
  (d) T. Browder, S. Pakvasa ans A. A. Petrov, hep-ph/0307054.
  (e) H.-Y. Chen and W.-S. Hou, P.L. **B566**, 193 (2003).
  (f) K. T., P.R.D **68**, 011501(R) (2003).
  (g) E. van Beveren and G. Rupp, P.R.L. **91**, 012003 (2003);
  A. P. Szczepaniak, Phys. Lett. **B567**, 23 (2003);
  M. F. M. Lutz and E. E. Kolomeitsev, N.P.A **730**, 392 (2004); J. Hofmann and M. F. M. Lutz, hep-ph/0308263.

- Masses of scalar $\{c\bar{s}\}$:
  - Potential model;
    S. Godfrey and N. Isgur, P.R.D **32**,189 (1985);
    S. Godfrey and R. Kokoski, P.R.D **43**,1679(1991);
    M. Di Pierro and E. Eichten, P.R.D 64, 114004 (2001); R. N. Cahn and J. D. Jackson, P.R.D **68**, 037502 (2003); W. Lucha and F. F. Schöberl, M.P.L. A**18**, 2837 (2003).
  - Lattice QCD;
    * Quench
      J. Hein et al., P.R.D **62**, 074503 (2000);P. Boyle, UKQCD, N.P. Proc. Suppl. **63**, 314 (1998).
    * $N_f = 2$
      G. Bali, P.R.D **68**, 071501(R) (2003);
      A. Dougall, R. D. Kenway, C. M. Maynard and C. McNeile, the UKQCD Collaboration, P.L. **B569**, 41 (2003).

- MIT bag model;
  M. Sadzikowski, P.L. **579**,39 (2004).
- Quark-meson model;
  A. Deandrea, G. Nardulli and A. D. Polosa, P.R.D **68**, 097501 (2003).
- QCD sum rule;
  Y.-B. Dai, C.-S. Huang, C. Liu and S.-L. Zhu, P.R.D **68**, 114011 (2003).
- Lightcone oscillator model;
  S. -G. Zhou and H.- C. Pauli, hep-ph/0310330.
- HQET sum rule;
  Y.-B. Dai, C.-S. Huang, C. Liu S.-L. Zhu, hep-ph/0401142.

- Production rates:

  C.-H. Chen and H. Li, hep-ph/0307075;
  A. Datta and P. J. O'Dnnell, P.L. **B572**, 164 (2003); hep-ph/0312160;
  M. Suzuki, hep-ph/0307118.

- Exotic $\hat{E}^0$ (or $\tilde{D}^0_{0\bar{s}}$):

  H. J. Lipkin, P.L. **70B**, 113 (1977);
  M. Suzuki and S. F. Tuan, P.L. **133B**, 125 (1983).

§3. Four-quark mesons

- Potentials mediated by vector mesons with $SU(3)$ "color": S. Hori, P.T.P. **36**, 131 (1966)

$$V_{qq}(\mathbf{r}) = \sum \Lambda_i \Lambda_i v(\mathbf{r}), \quad V_{q\bar{q}}(\mathbf{r}) = -\sum \Lambda_i \Lambda_i v(\mathbf{r}).$$

Their expectation values:

qq / $q\bar{q}$	$\bar{\mathbf{3}}$	$\mathbf{6}$	$\mathbf{8}$	$\mathbf{1}$
$\langle V_{qq} \rangle$	$-\frac{8}{3}\langle v \rangle$	$\frac{4}{3}\langle v \rangle$		
$\langle V_{q\bar{q}} \rangle$			$\frac{2}{3}\langle v \rangle$	$-\frac{16}{3}\langle v \rangle$

- Four-quark meson :
R. L. Jaffe, P.R.D **15**, 267 and 281 (1977)

$$\{qq\bar{q}\bar{q}\} = \underbrace{[qq][\bar{q}\bar{q}] \oplus (qq)(\bar{q}\bar{q})}_{J^P=0^+,1^+,2^+} \oplus \underbrace{\{[qq](\bar{q}\bar{q}) \pm (qq)[\bar{q}\bar{q}]\}}_{J^P=1^+}$$

$\Downarrow$

Two ways to obtain color-singlet states

(dominated by) $\bar{\mathbf{3}} \otimes \mathbf{3}$ $\quad$ $\mathbf{6} \otimes \bar{\mathbf{6}}$ [of $SU_c(3)$]

$\Downarrow$

{lower} $\oplus$ {higher}

(without *) (with *)

Mass difference > 500 MeV ?

Bag potential $\oplus$ spin-spin force:

$$H_g \sim -\frac{\alpha_c}{R} \sum_{a=1}^{8} \sum_{i>j} \vec{\sigma}_i \cdot \vec{\sigma}_j \lambda_i^a \lambda_j^a M\left(\frac{n_s m_s}{N}, \frac{n_s m_s}{N}\right)$$

○ Ideally mixed $\mathbf{9}$ and $\mathbf{9}^*$ of scalar $[qq][\overline{q}\overline{q}]$

S	$I=1$	$I=\frac{1}{2}$	$I=0$	Mass (GeV) $\mathbf{9}$	Mass (GeV) $\mathbf{9}^*$
1		$\widehat{\kappa}$, $\widehat{\kappa}^*$		0.90	1.60
0			$\widehat{\sigma}$, $\widehat{\sigma}^*$	0.65	1.45
0	$\widehat{\delta}^s$, $\widehat{\delta}^{s*}$		$\widehat{\sigma}^s$, $\widehat{\sigma}^{s*}$	1.10	1.80

○ Ideally mixed **36** [and **36***] of scalar $(qq)(\bar{q}\bar{q})$

S	I					Mass (GeV) **36** [**36***]
	2	$\frac{3}{2}$	1	$\frac{1}{2}$	0	
2			E_{KK} [E^*_{KK}]			1.55 [2.10]
1		$E_{\pi K}$ [$E^*_{\pi K}$]		C_K [C^*_K] C^s_K [C^{s*}_K]		1.35 [1.95] 1.75 [2.20]
0	$E_{\pi\pi}$ [$E^*_{\pi\pi}$]		C_π [C^*_π] C^s_π [C^{s*}_π]		C [C^*] C^s [C^{s*}] C^{ss} [C^{ss*}]	1.15 [1.80] 1.55 [2.10] 1.95 [2.35]

○ Ideally mixed $\bar{\mathbf{3}} \oplus \mathbf{6}$ [and $\bar{\mathbf{3}}^* \oplus \mathbf{6}^*$] of charmed scalar $[cq][\bar{q}\bar{q}]$ mesons

S	$I=1$	$I=\frac{1}{2}$	$I=0$	Mass(‡) (GeV)
1	$\hat{F}_I$ $[\hat{F}_I^*]$		$\hat{F}_0^+$ $[\hat{F}_0^{*+}]$	2.32(†) [3.1]
0		$\hat{D}$ $[\hat{D}^*]$ $\hat{D}^s$ $[\hat{D}^{s*}]$		2.22 [3.0] 2.42 [3.2]
-1			$\hat{E}^0$ $[\hat{E}^{*0}]$	2.32 [3.1]

(†) Input data: $D_{s0}^+(2.32) \Rightarrow \hat{F}_I^+(I_z=0)$

(‡) Quark counting with

$$\Delta m_s = m_s - m_n \simeq 0.1 \text{ GeV}$$

$$\left[\begin{array}{l} m_{\hat{\kappa}^*} = 1.6 \text{ GeV as the input data,} \\ \Delta m_c = m_c - m_n \simeq 1.5 \text{ GeV} \end{array} \right]$$

§4. Isospin conserving decays

- Decay rate for $A(\mathbf{p}) \rightarrow B(\mathbf{p}')\pi(\mathbf{q})$:

$$\Gamma(A \rightarrow B\pi) = \Big(\frac{1}{2J_A+1}\Big)\frac{q_c}{8\pi m_A^2}\sum_{\text{spins}} |M(A \rightarrow B\pi)|^2.$$

- Hard pion technique (with PCAC) in the IMF:

$$M(A \rightarrow B\pi) \simeq \lim_{\left(\substack{\mathbf{p}\rightarrow\infty \\ \mathbf{q}\rightarrow 0}\right)} M(A \rightarrow B\pi) \simeq \Big(\frac{m_A^2 - m_B^2}{f_\pi}\Big)\langle B|A_{\bar{\pi}}|A\rangle.$$

where A_π is the axial counterpart of isospin V_π.

$\langle B'|A_\pi|B\rangle$ is given by

$$\langle B'(\mathbf{p}')|A_\pi|B(\mathbf{p})\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}')\langle B'|A_\pi|B\rangle\sqrt{N_{B'}N_B}$$

in the IMF.

- Asymptotic flavor symmetry

  Flavor symmetry of *asymptotic matrix elements* (matrix elements taken between single hadron states with infinite momentum)

- Its breaking:
  Deviations of values of $f_+(0)$ from unity

  – $SU_f(3)$:
    $f_+^{(\pi^- K^0)}(0) = 0.961 \pm 0.008$,
    H. Leutwyler and M. Roos, Z.Phys.C **25**, 91 (1984)

  – $SU_f(4)$:

$$f_+^{(\bar{K}D)}(0) = 0.74 \pm 0.03,$$

[PDG96, PRD**54**, 1(1996)],

$$\left|\frac{f_+^{(\pi D)}(0)}{f_+^{(\bar{K}D)}(0)}\right| = 1.00 \pm 0.13,$$

[E687, PLB**382**, 312(1996)],

$$= 0.99 \pm 0.08,$$

[CLEO, PLB**405**, 373(1997)]

– Example:

Input data;

* $\Gamma(\rho \to \pi\pi) \simeq 149$ MeV, (PDG03)
* $\Gamma_{D^{*+}} = (96 \pm 4 \pm 22)$ keV, (CLEO)
* $\langle \pi^- | A_{\pi^-} | \rho^0 \rangle = 2\sqrt{2} \langle D^+ | A_{\pi^0} | D^{*+} \rangle$
  $= -\sqrt{2} \langle D^0 | A_{\pi^-} | D^{*+} \rangle$

$$\Rightarrow \begin{cases} \Gamma(D^{*+} \to D^0\pi^+)_{as} \simeq 96 \text{ keV} \\ \Gamma(D^{*+} \to D^+\pi^0)_{as} \simeq 42 \text{ keV} \end{cases}$$

$$c.f. \begin{cases} \Gamma(D^{*+} \to D^0\pi^+)_{exp} = 65 \pm 18 \text{ keV} \\ \Gamma(D^{*+} \to D^+\pi^0)_{exp} = 30 \pm \ \ 8 \text{ keV} \end{cases}$$

from (PDG03)

$$Br(D^{*+} \to D^0\pi^+)_{exp} = 67.7 \pm 0.5\ \%$$
$$Br(D^{*+} \to D^+\pi^0)_{exp} = 30.7 \pm 0.5\ \%$$

and $\Gamma_{D^{*+}}$ by CLEO

$$\Rightarrow \quad \sqrt{\frac{\Gamma(D^{*+} \to D^0\pi^+)_{as}}{\Gamma(D^{*+} \to D^0\pi^+)_{exp}}} \simeq 1.2$$

$$\Downarrow$$

$$\left| \frac{\langle D^0 | A_{\pi^-} | D^{*+} \rangle_{as}}{\langle D^0 | A_{\pi^-} | D^{*+} \rangle_{ph}} \right| \simeq 1.2$$

- Parametrization of the asymptotic matrix elements of A_π :

$$\langle D_s^+|A_{\pi^-}|\hat{F}_I^{++}\rangle = \sqrt{2}\langle D_s^+|A_{\pi^0}|\hat{F}_I^+\rangle$$
$$= \langle D_s^+|A_{\pi^+}|\hat{F}_I^0\rangle = -\langle D^0|A_{\pi^-}|\hat{D}^+\rangle$$
$$= 2\langle D^+|A_{\pi^0}|\hat{D}^+\rangle = -2\langle D^0|A_{\pi^0}|\hat{D}^0\rangle$$
$$= -\langle D^+|A_{\pi^+}|\hat{D}^0\rangle.$$

- Input data :

$\Gamma(\hat{F}_I^+) \simeq \Gamma(\hat{F}_I^+ \to D_s^+\pi^0) \sim 10$ MeV

(as an example)

– Why so narrow ?

∗ Small probability to find colorless "D_s^+" and "π^0" in the $\hat{F}_I^+$

$\Uparrow$

(Crossing matrices for color and spin
R. L. Jaffe, P.R.D **15**, 281 (1977).)

TABLE IV. Crossing matrix for color.

	$\vert(Q\bar{Q})^1(Q\bar{Q})^1\rangle^1$	$\vert(Q\bar{Q})^8(Q\bar{Q})^8\rangle^1$
$\vert(Q^2)^6(\bar{Q}^2)^{\bar{6}}\rangle^1$	$(\frac{2}{3})^{1/2}$	$-(\frac{1}{3})^{1/2}$
$\vert(Q^2)^{\bar{3}}(\bar{Q}^2)^3\rangle^1$	$(\frac{1}{3})^{1/2}$	$+(\frac{2}{3})^{1/2}$

TABLE V. Crossing matrices for spin.

	$\vert(Q\bar{Q})^3(Q\bar{Q})^3\rangle^1$	$\vert(Q\bar{Q})^1(Q\bar{Q})^1\rangle^1$
$\vert(Q^2)^3(\bar{Q}^2)^3\rangle^1$	$(\frac{1}{4})^{1/2}$	$(\frac{3}{4})^{1/2}$
$\vert(Q^2)^1(\bar{Q}^2)^1\rangle^1$	$(\frac{3}{4})^{1/2}$	$-(\frac{1}{4})^{1/2}$

	$\vert(Q\bar{Q})^3(Q\bar{Q})^3\rangle^3$	$\vert(Q\bar{Q})^3(Q\bar{Q})^1\rangle^3$	$\vert(Q\bar{Q})^1(Q\bar{Q})^3\rangle^3$
$\vert(Q^2)^3(\bar{Q}^2)^3\rangle^3$	0	$(\frac{1}{2})^{1/2}$	$-(\frac{1}{2})^{1/2}$
$\vert(Q^2)^3(\bar{Q}^2)^1\rangle^3$	$(\frac{1}{2})^{1/2}$	$-\frac{1}{2}$	$-\frac{1}{2}$
$\vert(Q^2)^1(\bar{Q}^2)^3\rangle^3$	$(\frac{1}{2})^{1/2}$	$\frac{1}{2}$	$\frac{1}{2}$

	$\vert(Q\bar{Q})^3(Q\bar{Q})^3\rangle^5$
$\vert(Q^2)^3(\bar{Q}^2)^3\rangle^5$	(1)

R. L. Jaffe, P.R.D **15**, 281 (1977).

Dominant decays of scalar $[cq][\overline{q}\overline{q}]$ mesons and their estimated widths.
$\Gamma(\hat{F}_I^+) \simeq \Gamma(\hat{F}_I^+ \to D_s^+\pi^0) \sim 10$ MeV is used as the input data.

Parent (Mass in GeV)	Final State	Width (MeV)
$\hat{F}_I^{++}(2.32)$	$D_s^+\pi^+$	
$\hat{F}_I^+(2.32)$	$D_s^+\pi^0$	~ 10
$\hat{F}_I^0(2.32)$	$D_s^+\pi^-$	
$\hat{D}^+(2.22)$	$D^0\pi^+$	~ 10
	$D^+\pi^0$	~ 5
$\hat{D}^0(2.22)$	$D^+\pi^-$	~ 10
	$D^0\pi^0$	~ 5
$\hat{D}^s(2.42)$	$D\eta$	$(\ll 10)$
$\hat{F}_0^+(2.32)$	$D_s^+\pi^0$	(isospin viol.)
$\hat{E}^0(2.32)$	$\langle D_s\bar{K}\rangle$	(weak int.)

§5. Ordinary charmed scalar mesons

Ordinary charmed scalar mesons:

$$D_0^* \sim \{c\bar{n}\}, \quad D_{s0}^* \sim \{c\bar{s}\}$$

Compare with the $K_0^*(1.43) \sim {}^3P_0\ \{n\bar{s}\}$:

$$m_{K_0^*} = 1412 \pm 6 \text{ MeV},$$
$$\Gamma_{K_0^*} = 294 \pm 23 \text{ MeV},$$
$$\text{Br}(K_0^* \to K\pi) = 93 \pm 10\ \%$$

$$\Rightarrow \quad |\langle K^+|A_{\pi^+}|K_0^{*0}\rangle| \simeq 0.29.$$

Asymptotic $SU_f(4)$ symmetry breaking:

Input data;

- $\Gamma(\rho \to \pi\pi) \simeq 149$ MeV, (PDG03)
- $\Gamma_{D^{*+}} = (96 \pm 4 \pm 22)$ keV, (CLEO)

$\Downarrow$ Asymptotic $SU_f(4)$ symmetry

$$\begin{cases} \Gamma(D^{*+} \to D^0\pi^+)_{as} \simeq 96 \text{ keV} \\ \Gamma(D^{*+} \to D^+\pi^0)_{as} \simeq 42 \text{ keV} \end{cases}$$

$$c.f. \begin{cases} \Gamma(D^{*+} \to D^0\pi^+)_{exp} = 65 \pm 18 \text{ keV} \\ \Gamma(D^{*+} \to D^+\pi^0)_{exp} = 30 \pm 8 \text{ keV} \end{cases}$$

$$\Rightarrow \quad \sqrt{\frac{\Gamma(D^{*+} \to D^0\pi^+)_{as}}{\Gamma(D^{*+} \to D^0\pi^+)_{exp}}} \simeq 1.2$$

- $D_0^* \sim \{c\bar{n}\}$
  - Mass: $m_{D_0^*} \simeq 2.35$ GeV
    $\left(\begin{array}{l}\text{tentative but in the region}\\ \text{of the predicted values}\end{array}\right)$
  - Width:
    Asymptotic $SU_f(4)$ symmetry:
    $$|\langle D^+|A_{\pi^+}|D_0^{*0}\rangle| = |\langle K^+|A_{\pi^+}|K_0^{*0}\rangle|\,(\times 0.8)$$
    $$\simeq 0.29\ (\times 0.8)$$
    $\Rightarrow \Gamma_{D_0^*} \sim 90\ (\times 0.8^2)$ MeV
- $D_{s0}^* \sim \{c\bar{s}\}$
  - Mass: $m_{D_{s0}^*} \simeq 2.45$ GeV
    $\left(\begin{array}{l}\text{Quark counting with } \Delta_s \simeq 0.1 \text{ GeV}\\ \text{and } m_{D_0^*} \simeq 2.35 \text{ MeV}\end{array}\right)$
  - Width ($D_{s0}^{*+} \to DK$):
    Asymptotic $SU_f(4)$ symmetry:
    $$|\langle D^0|A_{K^-}|D_{s0}^{*0}\rangle| = |\langle D^+|A_{\bar{K}^0}|D_{s0}^{*+}\rangle|$$
    $$= |\langle K^+|A_{\pi^+}|K_0^{*0}\rangle|(\times 0.8) \simeq 0.29(\times 0.8)$$
    $\Rightarrow \Gamma_{D_{s0}^*} \simeq 70\ (\times 0.8^2)$ MeV

Mini-summary on the scalar mesons:

- Ordinary $\{c\bar{q}\}$

  K_0^*: $m_{K_0^*} \simeq 1.43$ GeV, $\Gamma_{K_0^*} \simeq 290$ MeV (input)

D_0^*:	$m_{D_0^*} \simeq 2.35$ GeV,	$\Gamma_{D_0^*} \simeq 90(\times 0.8^2)$ MeV
D_{s0}^*:	$m_{D_{s0}^*} \simeq 2.45$ GeV,	$\Gamma_{D_{s0}^*} \simeq 70(\times 0.8^2)$ MeV

- Salar $[cq][\bar{q}\bar{q}]$:

$\hat{F}_I^+$:	$m_{\hat{F}_I} \simeq 2.32$ GeV,	$\Gamma_{\hat{F}_I} \simeq 10$ MeV (input)
$\hat{D}$:	$m_{\hat{D}} \simeq 2.22$ GeV,	$\Gamma_{\hat{D}} \simeq 15$ MeV
$\hat{D}^s$:	$m_{\hat{D}^s} \simeq 2.42$ GeV,	$\Gamma_{\hat{D}^s} \ll 15$ MeV
$\hat{F}_I$:	$m_{\hat{F}_I} \simeq 2.32$ GeV,	$\Gamma_{\hat{F}_I} \simeq 10$ MeV
$\hat{F}_0$:	$m_{\hat{F}_0} \simeq 2.32$ GeV,	(iso-spin viol.)
$\hat{E}^0$:	$m_{\hat{E}^0} \simeq 2.32$ GeV,	(weak decay)

- Results by the BELLE Collaboration

  BELLE Collaboration, hep-ex/0307021

  - From $D\pi$ mass distribution (Fig. 3),

    $$m_{D_0^0} = (2308 \pm 17 \pm 15 \pm 28)\ \mathrm{MeV}/c^2,$$
    $$\Gamma_{D_0^0} = (276 \pm 21 \pm 18 \pm 60)\ \mathrm{MeV},$$

    $$m_{D_2^0} = (2461.6 \pm 2.1 \pm 0.5 \pm 3.3)\ \mathrm{MeV}/c^2,$$
    $$\Gamma_{D_2^0} = (45.6 \pm 4.4 \pm 6.5 \pm 1.6)\ \mathrm{MeV},$$

    (See also Table I.)

  - From $D^*\pi$ mass distribution (Fig. 8),

    $$m_{D_1^0} = (2421.4 \pm 1.5 \pm 0.4 \pm 0.8)\ \mathrm{MeV}/c^2,$$
    $$\Gamma_{D_1^0} = (23.7 \pm 2.7 \pm 0.2 \pm 4.0)\ \mathrm{MeV},$$
    $$m_{D_1'^0} = (2427 \pm 26 \pm 20 \pm 15)\ \mathrm{MeV}/c^2,$$
    $$\Gamma_{D_1'^0} = (384^{+107}_{-\ 75} \pm 24 \pm 70)\ \mathrm{MeV},$$

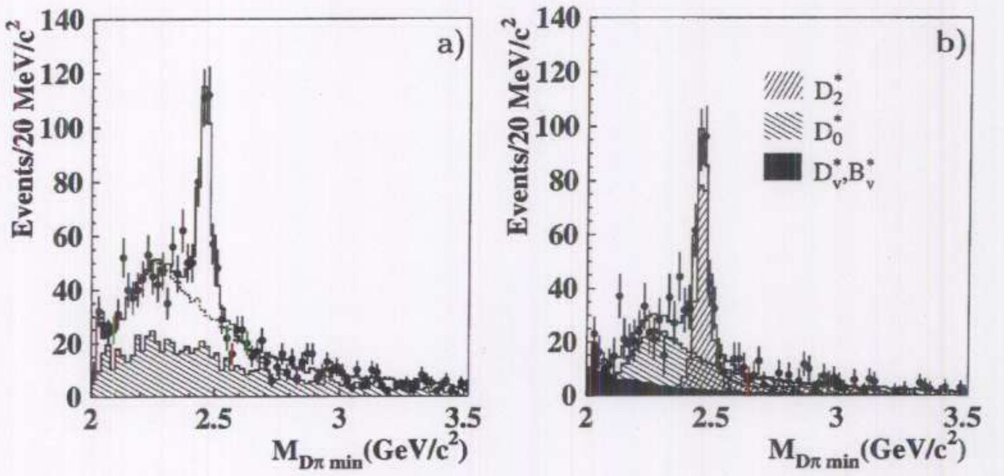


FIG. 3: a)The minimal $D\pi$ mass distribution of $B^- \to D^+\pi^-\pi^-$ candidates. The points with error bars correspond to the signal box events, while the hatched histogram shows the background obtained from the sidebands. The open histogram is the result of a fit while the dashed one shows the fit function in the case when the narrow resonance amplitude is set to zero. b)The background-subtracted $D\pi$ mass distribution. The points with error bars correspond to the signal box events, hatched histograms show different contributions, the open histogram shows the coherent sum of all contributions.

Parameters	I $D_2^*,\ D_0^*$	II $D_2^*,\ D_0^*, D_v^*$	III $D_2^*,\ D_0^*, D_v^*,\ B_v^*$	IV $D_2^*,\ D_0^*, D_v^*,\ B_v^*$, ph.sp($a_3$)
$Br_{D_2^*}(10^{-4})$	3.21 ± 0.24	3.26± 0.26	3.38 ± 0.31	3.47 ± 0.37
$Br_{D_0^*}(10^{-4})$	6.09 ± 0.42	4.96 ± 0.47	6.12 ± 0.57	8.35 ± 0.94
$\phi_{D_0^*}$	-2.01 ± 0.10	-2.35 ± 0.11	-2.37 ± 0.11	-2.31 ± 0.14
$Br_{D_v^*}(10^{-4})$	–	1.46 ± 0.23	2.21 ± 0.27	2.23 ± 0.32
$\phi_{D_v^*}$	–	0.03 ± 0.15	-0.25 ± 0.15	-0.33 ± 0.19
$Br_{B_v^*}(10^{-4})$	–	–	0.67 ± 0.04	0.72 ± 0.04
$\phi_{B_v^*}$	–	–	-0.27 ± 0.28	-0.39 ± 0.24
$M_{D_2^{*0}}(MeV/c^2)$	2454.6 ± 2.1	2458.9 ± 2.1	2461.6 ± 2.1	2462.7 ± 2.2
$\Gamma_{D_2^{*0}}(MeV)$	43.8 ± 4.0	44.2 ± 4.1	45.6 ± 4.4	46.1 ± 4.5
$M_{D_0^{*0}}(MeV/c^2)$	2268 ± 18	2280 ± 19	2308 ± 17	2326 ± 19
$\Gamma_{D_0^{*0}}(MeV)$	324 ± 26	281 ± 23	276 ± 21	333 ± 37
$a_3 \times 10^5$	–	–	–	0.38 ± 0.65
ϕ_3	–	–	–	−0.10 ± 0.93
N_{sig}	1058 ± 47	1007 ± 44	1056 ± 46	1068 ± 47
$-2\ln\mathcal{L}/\mathcal{L}_{\prime}$	115	26	0	-7
χ^2/N	253.9/129	185.2/127	166.5/125	158.5/123

TABLE I: Fit results for different models. The model used to obtain the results includes amplitudes for $D_2^*,\ D_0^*, D_v^*,\ B_v^*$ intermediate resonances. Adding the constant term (ph.sp(a_3)) does not significantly improve the likelihood.

• DK mass distribution :

CLEO Collaboration, P.R.L. **72**, 1974 (1994).

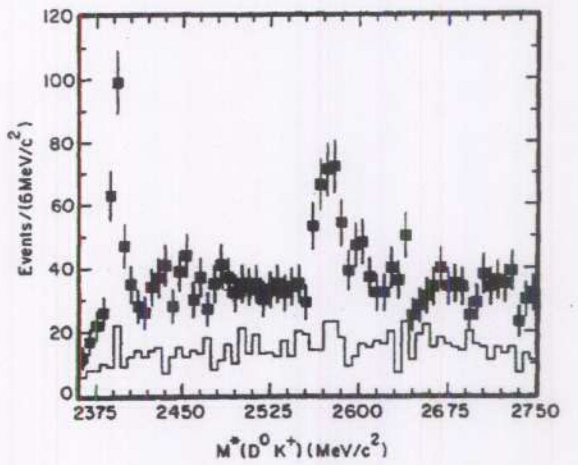


FIG. 1. M^*, "corrected" invariant mass, of $(K^-\pi^+[\pi^0])K^+$ combinations. Data points are for $K^-\pi^+[\pi^0]$ combinations in the D^0 signal region; the histogram shows M^* for $(K^-\pi^+[\pi^0])K^+$ combinations where the $K^-\pi^+[\pi^0]$ combinations were chosen in D^0 sidebands.

– Clear peak at ~ 2.57 GeV $(\Rightarrow D^+_{s2})$

– A false peak at ~ 2.4 GeV from $D^*_1(2.54) \to D^*[\pi^0]K$

– A peak around ~ 2.45 GeV from

$D^*_{s0} \to DK$?

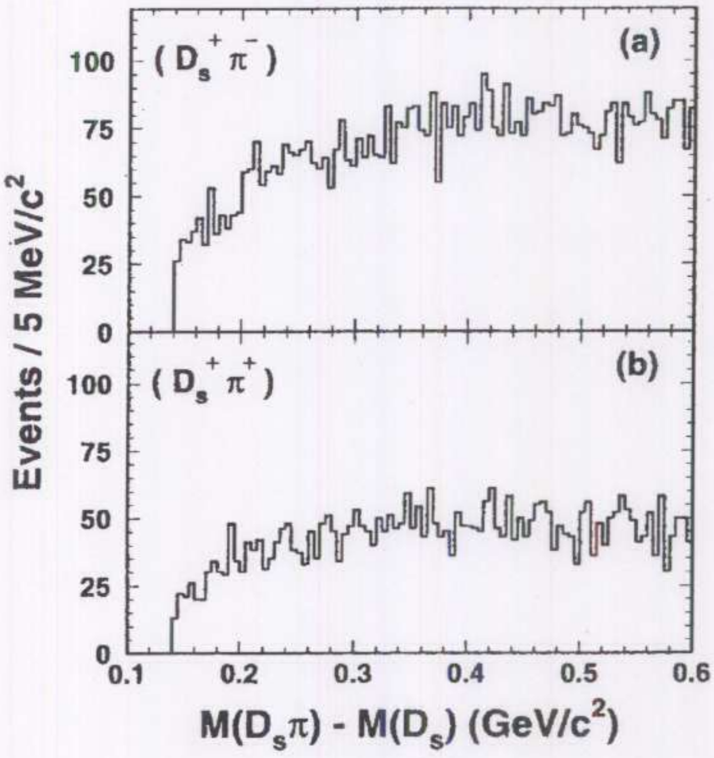
- Production rates of D_{s0} and D_{s1} :
  (Review by J. Wang, hep-ex/0312039)

  - Factorization disfavors the $\{c\bar{q}\}$ but four-quark or molecule models are consistent with experiments.

  - No evidence for a peak in the $D_s^{+}\pi^{\mp}$ (CLEO, hep-ph/0308166)

$$\hat{F}_I^{+}$$

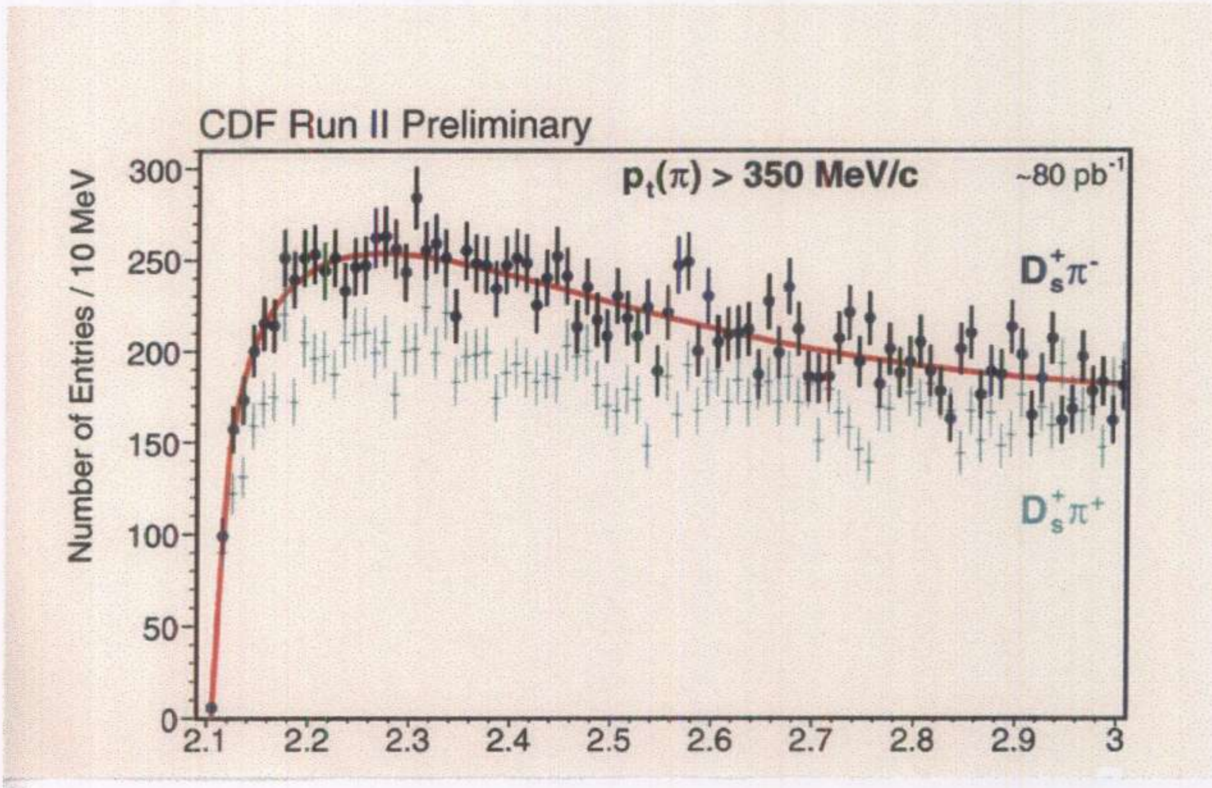
$$\Downarrow$$



- Spectra of the $D_s\pi$:

(Review by F. C. Porter, hep-ex/0312019)

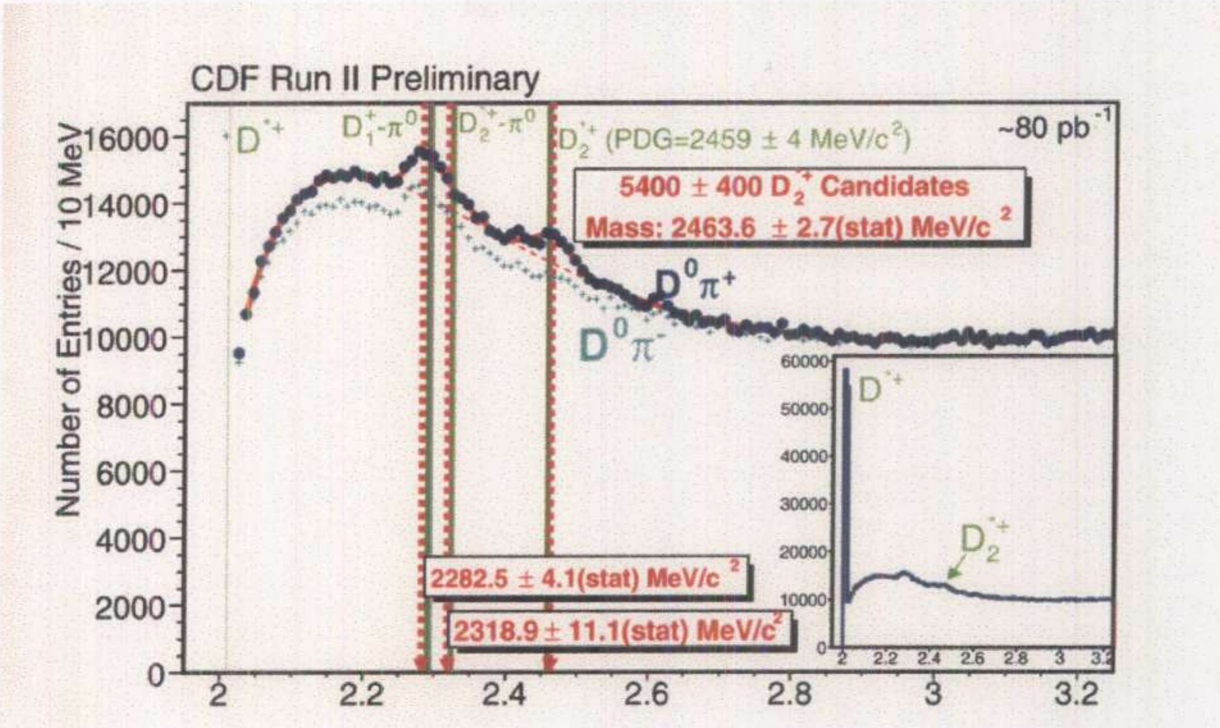
– No evidence for a peak in the $D_s^{\pm}\pi^{\pm}$ (CDF, M. Shapiro)

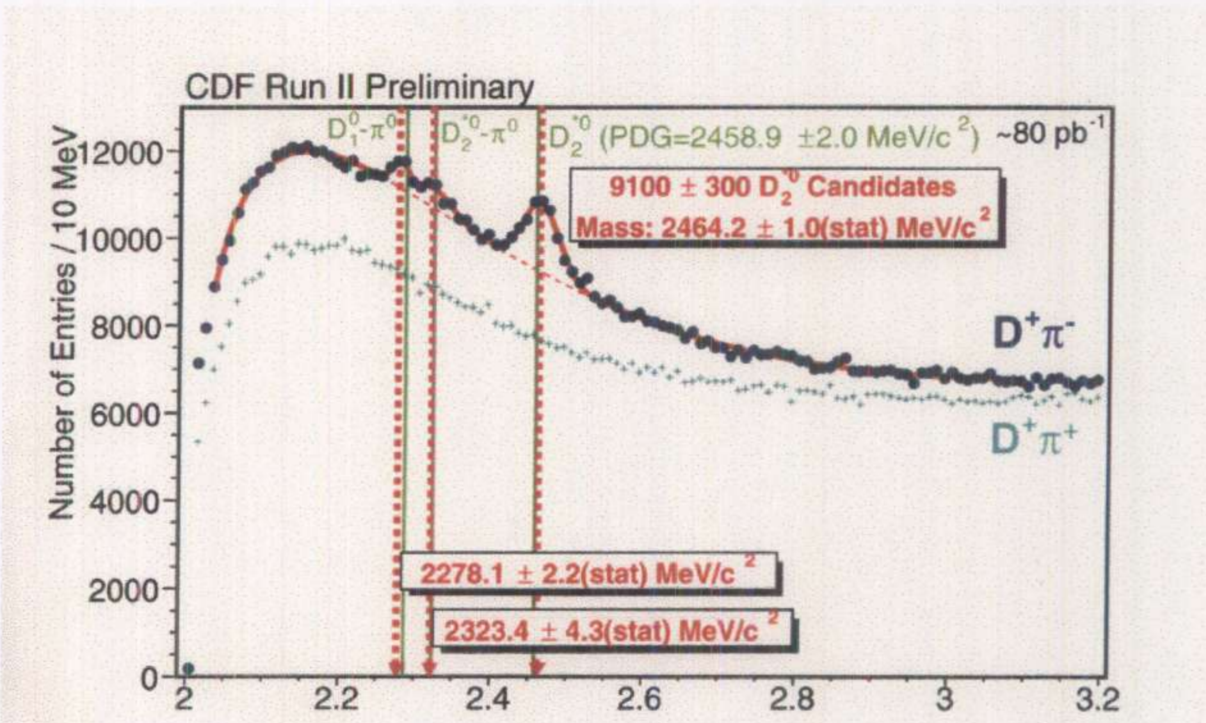


$\Uparrow$

$\hat{F}_I$

- Spectra of the $D\pi$
  (CDF, M. Shapiro)

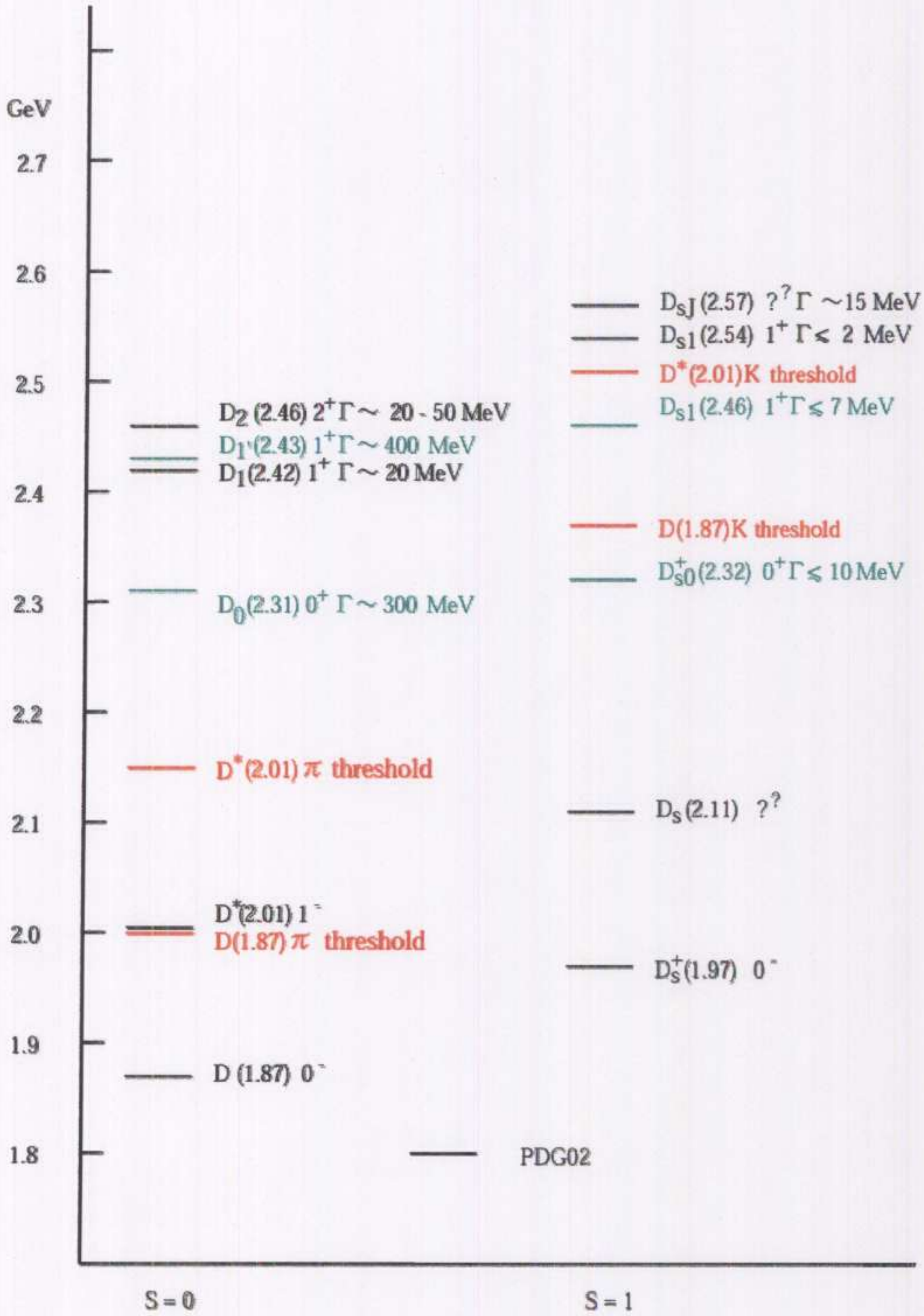




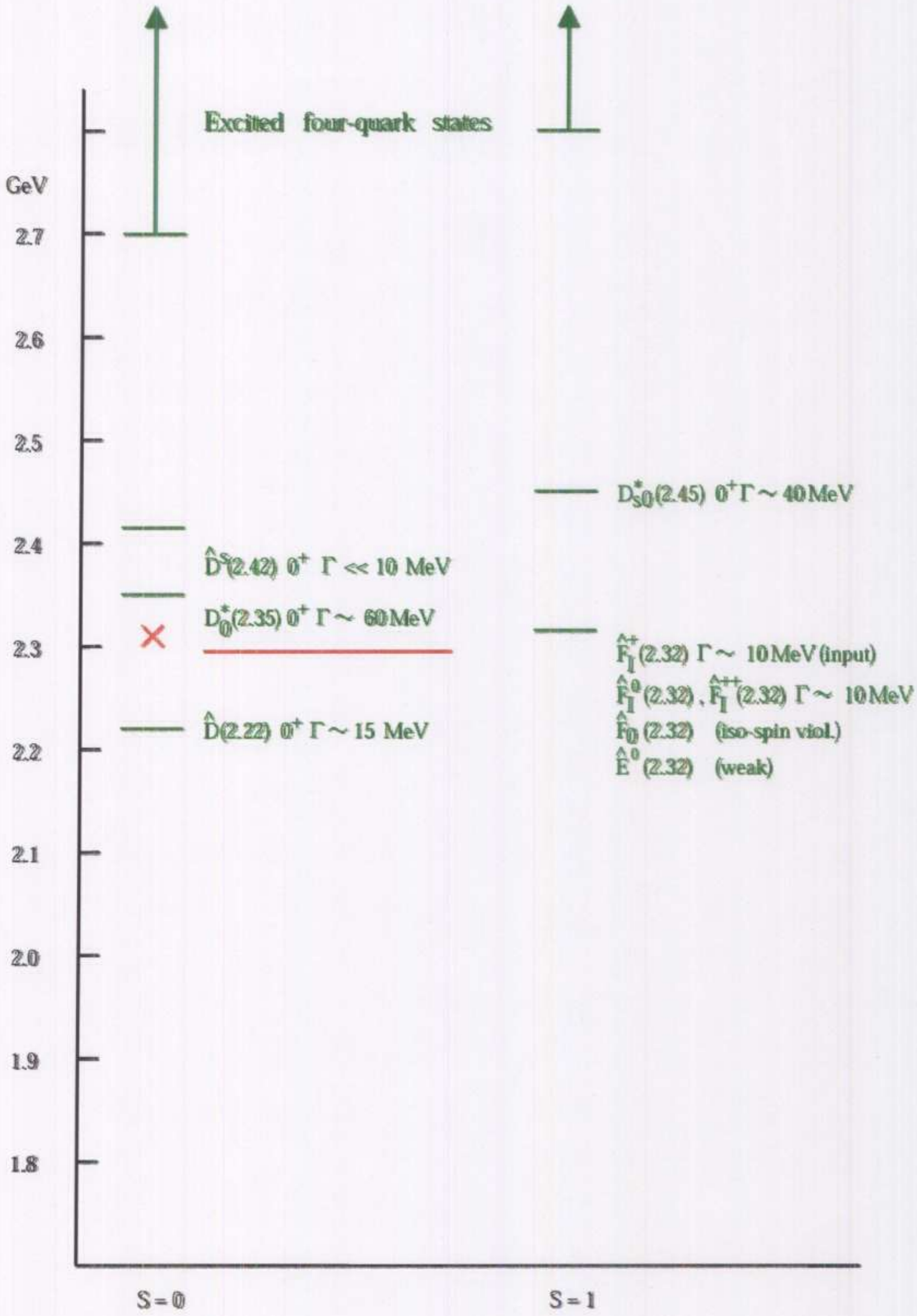
$\Uparrow$ $\Uparrow$

$\hat{D}$ D_0^*

§6. Summary on **PART I**



GeV
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
D2 (2.46) 2+ Γ ~ 20 - 50 MeV
D1'(2.43) 1+ Γ ~ 400 MeV
D1(2.42) 1+ Γ ~ 20 MeV
D0(2.31) 0+ Γ ~ 300 MeV
D*(2.01) π threshold
D*(2.01) 1-
D(1.87) π threshold
D (1.87) 0-
DsJ (2.57) ?? Γ ~15 MeV
Ds1 (2.54) 1+ Γ ≲ 2 MeV
D*(2.01)K threshold
Ds1 (2.46) 1+ Γ ≲ 7 MeV
D(1.87)K threshold
D+s0 (2.32) 0+ Γ ≲ 10 MeV
Ds (2.11) ??
D+s (1.97) 0-
PDG02
S = 0
S = 1


Excited four-quark states
GeV
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
$D_{s0}^*(2.45)\ 0^+\Gamma \sim 40$ MeV
$\hat{D}^s(2.42)\ 0^+\ \Gamma \ll 10$ MeV
$D_0^*(2.35)\ 0^+\ \Gamma \sim 60$ MeV
$\hat{F}_I^+(2.32)\ \Gamma \sim 10$ MeV (input)
$\hat{F}_I^0(2.32)$, $\hat{F}_I^{++}(2.32)\ \Gamma \sim 10$ MeV
$\hat{F}_0(2.32)$ (iso-spin viol.)
$\hat{E}^0(2.32)$ (weak)
$\hat{D}(2.22)\ 0^+\ \Gamma \sim 15$ MeV
S = 0
S = 1

- Charmed meson spectroscopy

J^P	0^-	1^-	0^+	1^+	$1'^+$	2^+
$\{c\bar{n}\}$ $\{c\bar{s}\}$	D D_s	D^* D_s^*	D_0^* D_{s0}^*	D_1^* D_{s1}^*	$D_1'^*$ $D_{s1}'^*$	D_2^* D_{s2}^*
$[cn][\bar{u}\bar{d}]$ $[cn][\bar{s}\bar{n}]$ $[cs][\bar{u}\bar{d}]$ $[cn][\bar{u}\bar{d}]$			$\hat{D}$ $\hat{F}_I,\ \hat{F}_0$ $\hat{E}^0$ $\hat{D}^s$			

- Unexpectedly small mass of $D_{s0}^+(2.32)$:
  $\{m_{D_{s0}}\}_{\text{obs}} < \{m_{D_{s0}^*}\}_{\text{pot}},\ \{m_{D_{s0}^*}\}_{\text{quench}}$
- Very small mass difference:
  $$\Delta m_s \gg \{m_{D_{s0}(2.32)}\}_{\text{obs}} - \{m_{D_0}(2.31)\}_{\text{obs}} \sim 10 \text{ MeV},$$
  $$\Downarrow$$
- Scalar mesons of different strucure ?
  - $D_0^*(2.35) \oplus \hat{D}(2.22)$
    in the broad bump around ~ 2.31 GeV:
  - $D_{s0}^*(2.45)$
    in the DK invariant mass distribution as the strange counterpart of $D_0^*(2.35)$

- No evidence for a peak has been observed

in the $\left\{ \begin{array}{l} D_s^{+}\pi^{\pm} \text{ (CLEO)} \\ \quad \text{and} \\ D_s^{\pm}\pi^{\pm} \text{ (CDF)} \end{array} \right\}$ mass distributions

$\Downarrow$

$\{c\bar{s}\}$ or four-quark (or molecule) ?

  - Production mechanism
    Factorization disfavors the $\{c\bar{s}\}$.

  - Broad $\widehat{F}_I$?
    (Why broad ? — crossing matrices)

  - Experiments with higher statistics and resolution

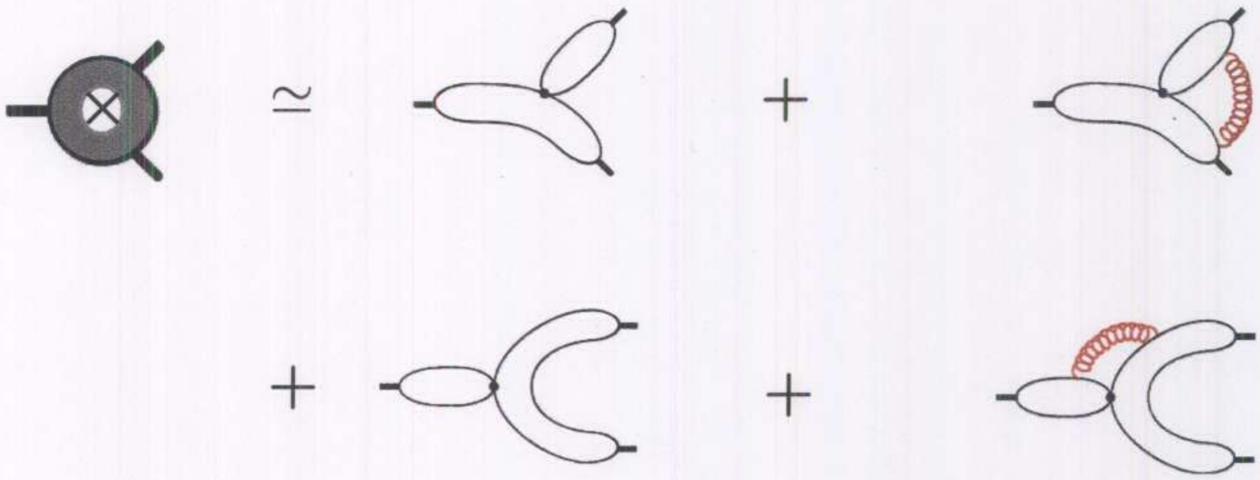
More theoretical and experimental studies will be needed.

PART II: Role of four-quark mesons in hadronic weak decays

§7. Introduction to **Part II**

— A hybrid perspective

$$M_{\text{tot}} \quad \simeq \quad M_{\text{FA}} \quad + \quad M_{\text{NF}}$$



$$\Uparrow \qquad \Uparrow \qquad \Uparrow$$

$$H_w \quad \longrightarrow \quad H_w^{\text{BSW}} \quad + \quad \tilde{H}_w$$

Factorization

Hard pion tech. in the IMF

• : weak vertex with hard gluon corrections

: soft gluon(s)

: weak interaction

Effective Hamiltonian ($Charm$ decays):

$$H_w \simeq \frac{G_F}{\sqrt{2}}\{c_1 Q_1^{(s'c)} + c_2 Q_2^{(s'c)} + \cdots\} + h.c.$$

$$Q_1^{(s'c)} =: (\bar{u}d')_L(\bar{s}'c)_L :$$

$$Q_2^{(s'c)} =: (\bar{s}'d')_L(\bar{u}c)_L :$$

$$(\bar{q}q)_L = \bar{q}\gamma_\mu(1-\gamma_5)q$$

$\downarrow$ Fierz identity (Bauer, Stech & Wirbel)

$$H_w^{\text{BSW}} \simeq \frac{G_F}{\sqrt{2}}\{a_1 Q_1^{(s'c)} + a_2 Q_2^{(s'c)} + \cdots\} + h.c.$$

$$a_1 = c_1 + \frac{c_2}{N_c} \gg a_2 = c_2 + \frac{c_1}{N_c}$$

$+$

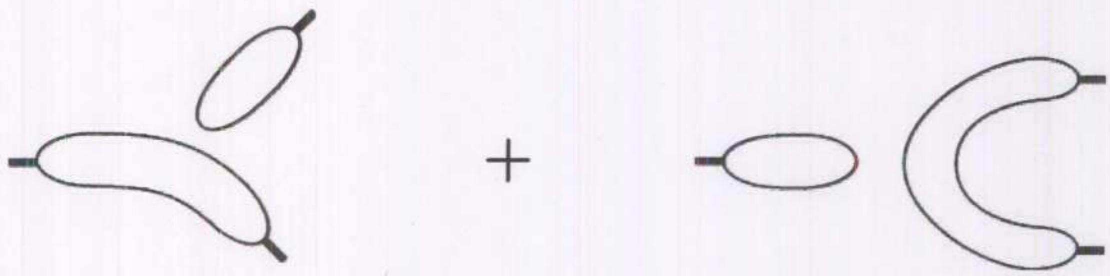
$$\tilde{H}_w \simeq \frac{G_F}{\sqrt{2}}\{c_2 \tilde{Q}_1^{(s'c)} + c_1 \tilde{Q}_2^{(s'c)} + \cdots\} + h.c.$$

$$\tilde{Q}_1^{(s'c)} = 2\sum_a : (\bar{u}t^a d')_L(\bar{s}'t^a c)_L :$$

$$\tilde{Q}_2^{(s'c)} = 2\sum_a : (\bar{s}'t^a d')_L(\bar{u}t^a c)_L :$$

§8. Factorization

$M_{\mathsf{FA}} \sim$ weak factor with hard corrections $\times$ $\Big\{$



helicity suppression $\Big\}$

Factorizable amplitudes (charm decays) :

- Factorization: (Bauer, Stech & Wirbel)
  - Two-body decays ($D \to PP'$):

$$
\begin{aligned}
&M_{\mathsf{FA}}(D^+ \to \bar{K}^0\pi^+) \\
&= \frac{G_F}{\sqrt{2}} V_{cs} V_{ud} \Big\{ a_1 \langle \pi^+ | (\bar{u}d)_L | 0 \rangle \langle \bar{K}^0 | (\bar{s}c)_L | D^+ \rangle \\
&\qquad + a_2 \langle \bar{K}^0 | (\bar{s}d)_L | 0 \rangle \langle \pi^+ | (\bar{u}c)_L | D^+ \rangle \Big\}
\end{aligned}
$$

Matrix elements of currents:

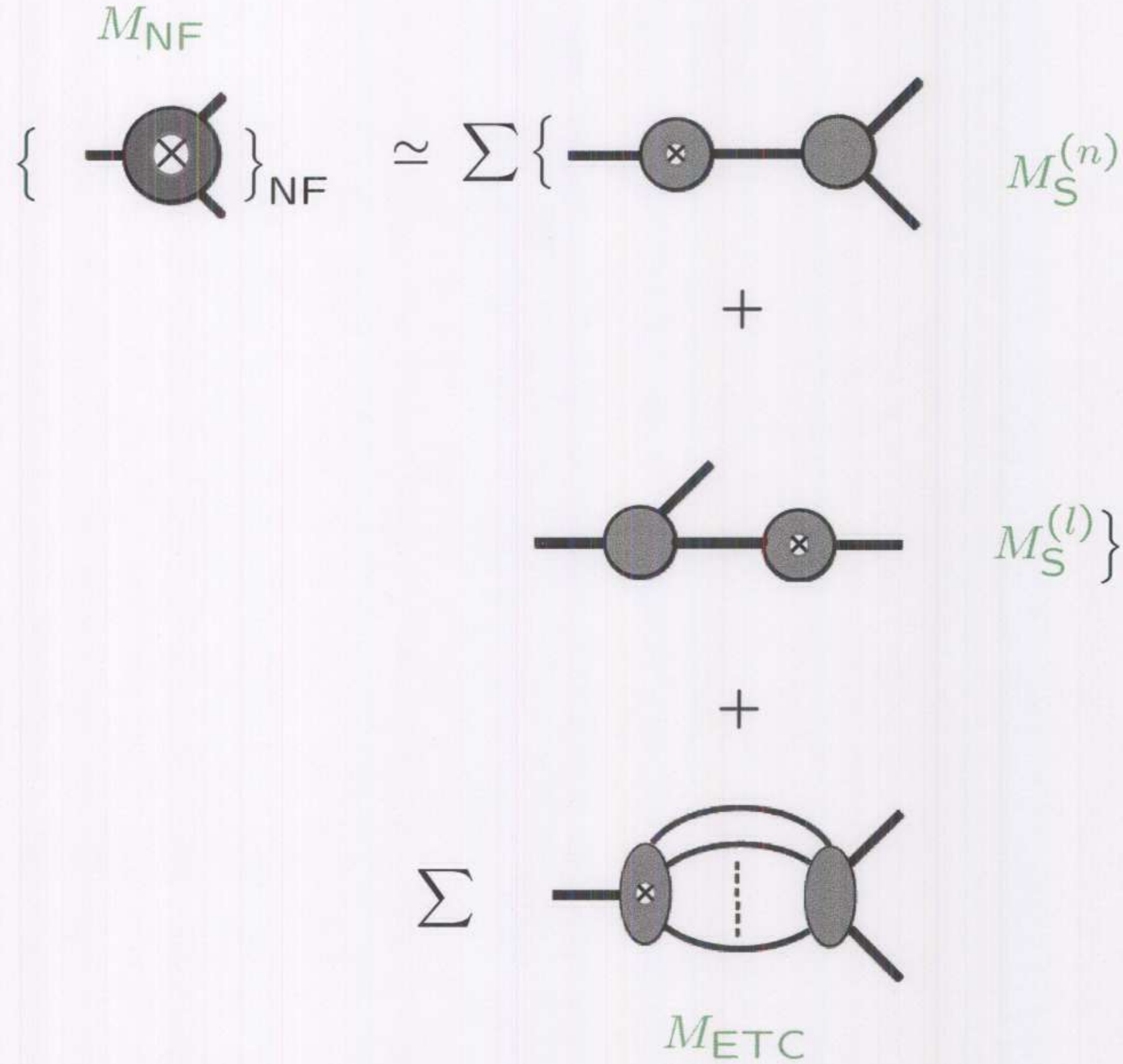
$$
\begin{aligned}
&\langle \pi(q) | A_\mu | 0 \rangle = -i f_\pi q_\mu \\
&\langle P'(p') | V_\mu | P(p) \rangle \\
&\qquad = (p + p')_\mu f_+^{(P'P)}(q^2) + q_\mu f_-^{(P'P)}(q^2)
\end{aligned}
$$

where $q = p - p'$.

Factorized amplitudes for two-body decays of charm mesons.

Decay	A_{FA}
$D^+ \to \bar{K}^0\pi^+$	$i\frac{G_F}{\sqrt{2}}V_{cs}V_{ud}a_1 f_\pi(m_D^2 - m_K^2)f_+^{(\bar{K}D)}(m_\pi^2) \left[1 + \left(\frac{a_2}{a_1}\right)\left(\frac{f_K}{f_\pi}\right)\left(\frac{m_D^2 - m_\pi^2}{m_D^2 - m_K^2}\right)\frac{f_+^{(\pi D)}(m_K^2)}{f_+^{(\bar{K}D)}(m_\pi^2)}\right]$
$D^0 \to \bar{K}^0\pi^0$	$-i\frac{G_F}{2}V_{cs}V_{ud}a_2 f_K(m_D^2 - m_\pi^2)f_+^{(\pi D)}(m_K^2)$
$D^0 \to K^-\pi^+$	$i\frac{G_F}{\sqrt{2}}V_{cs}V_{ud}a_1 f_\pi(m_B^2 - m_D^2)f_+^{(\bar{K}D)}(m_\pi^2)$
$D_s^+ \to K^+\bar{K}^0$	$-i\frac{G_F}{\sqrt{2}}V_{cs}V_{ud}a_2 f_K(m_{D_s}^2 - m_K^2)f_+^{(KD_s)}(m_K^2)$
$D^0 \to \pi^+\pi^-$	$-i\frac{G_F}{\sqrt{2}}V_{cs}V_{us}a_1 f_\pi(m_D^2 - m_\pi^2)f_+^{(\pi D)}(m_\pi^2)$
$D^0 \to \pi^0\pi^0$	0
$D^+ \to \pi^+\pi^0$	$-i\frac{G_F}{2}V_{cs}V_{us}a_1 f_\pi(m_D^2 - m_\pi^2)f_+^{(\pi D)}(m_\pi^2)$
$D^0 \to K^0\bar{K}^0$	0
$D^0 \to K^+K^-$	$-i\frac{G_F}{2}V_{cs}V_{us}a_1 f_K(m_D^2 - m_K^2)f_+^{(\bar{K}D)}(m_K^2)$
$D^+ \to K^+\bar{K}^0$	$-i\frac{G_F}{2}V_{cs}V_{us}a_1 f_K(m_D^2 - m_K^2)f_+^{(\bar{K}D)}(m_K^2)$
$D_s^+ \to \pi^+K^0$	$-i\frac{G_F}{\sqrt{2}}V_{cs}V_{us}a_1 f_\pi(m_{D_s}^2 - m_K^2)f_+^{(KD_s)}(m_\pi^2)$
$D_s^+ \to \pi^0K^+$	$-i\frac{G_F}{2}V_{cs}V_{us}a_2 f_\pi(m_{D_s}^2 - m_K^2)f_+^{(KD_s)}(m_\pi^2)$

§9. Nonfactorizable amplitudes



V. S. Mathur and L. K. Pandit, in *Advances in Particle Physics*, edited by R. L. Cool and R. E, Marshak (Interscience Publishers, 1968), vol.2, p. 383.

- Important players in the non-factorizable amplitudes for two body decays of charm mesons

	ETC term	Surface term			
	$(f_\pi \sim f_K)$	$[qq][\overline{q}\overline{q}]$	$(qq)(\overline{q}\overline{q})$	G.B.	Hyb
$D^+ \to \pi^+ \bar{K}^0$	$\sim (*) \cdot e^{i\delta_{3/2}}$	~ 0	$E^*_{\pi\bar{K}}$	$-$	$-$
$D^0 \to \pi^+ K^-$	$\sim e^{i\delta_{1/2}}$	$\widehat{\kappa}^*$	$E^*_{\pi\bar{K}}, C^*_{\bar{K}}$	$-$	κ_H
$D^0 \to \pi^0 \bar{K}^0$	$\sim \sqrt{\frac{1}{2}} e^{i\delta_{1/2}}$	$\widehat{\delta}^{s*}$	C^{s*}_π	$-$	κ_H
$D_s^+ \to K^+ \bar{K}^0$	$-e^{i\delta_1}$	$\widehat{\delta}^{s*}$	C^{s*}_π	$-$	δ_H
$D^0 \to K^0 \bar{K}^0$	~ 0	$-$	$-$	S^*	σ_H, σ^s_H
$D^0 \to K^+ K^-$	$\sim -e^{i\delta_0}$	$\widehat{\sigma}^{s*}, \widehat{\delta}^{s*}$	C^{s*}, C^{s*}_π	S^*	σ^s_H
$D^+ \to K^+ \bar{K}^0$	$\sim -e^{i\delta_1}$	$\widehat{\delta}^{s*}$	C^{s*}_π	$-$	δ_H
$D^+ \to \pi^+ \pi^0$	$-$	$-$	$E^*_{\pi\pi}$	$-$	$-$
$D^0 \to \pi^+ \pi^-$	$e^{i\delta_0}$	$\widehat{\sigma}^*$	$E^*_{\pi\pi}, C^*$	S^*	σ_H
$D^0 \to \pi^0 \pi^0$	$\sqrt{\frac{1}{2}} e^{i\delta_0(\pi\pi)}$	$\widehat{\sigma}^*$	$E^*_{\pi\pi}, C^*$	S^*	σ_H
$D_s^+ \to \pi^+ K^0$	$\sim e^{i\delta_{1/2}}$	$\widehat{\kappa}^*$	$E^*_{\pi K}, C^*_K$	$-$	κ_H
$D_s^+ \to \pi^0 K^+$	$\sim \sqrt{\frac{1}{2}} e^{i\delta_{1/2}}$	$\widehat{\kappa}^*$	$E^*_{\pi K}, C^*_K$	$-$	κ_H

$(*) = (1 - \frac{f_\pi}{f_K})$

§10. A possible solution

Taking the following values of parameters involved,

- Wilson coefficients:
  $a_1 = 0.825, \qquad a_2 = -0.159$
  $(a_1^{\mathrm{BSW}} = 1.09, \quad a_2^{\mathrm{BSW}} = -0.09)$

- Form factors:
  $F^{(\bar{K}D)}(0) = 0.74 \pm 0.03,$ (PDG96)
  $\left|\frac{F^{(\pi D)}(0)}{F^{(\bar{K}D)}(0)}\right| = 1.00 \pm 0.13,$ (E687)
  $= 0.99 \pm 0.08.$ (CLEO)

- Asymptotic matrix element:
  $\langle \pi^+ | \tilde{H}_w | D_s^+ \rangle = 0.05501 \times 1.166 \times 10^{-5}\ (\mathrm{GeV}^2)$
  $k_a^* = 0.0771,\ k_s^* = -0.0217,\ f_g = 0.0387,$
  $k_H = -0.0144,\ Z = 1.56$

- Phases:
  - Relative phase between factorized and non-factorizable amplitudes;
    $\delta = -19.9^\circ$
  - Strong phases;
    $\delta_0(\pi\pi) = \delta_0(K\bar{K}) = 57.0^\circ,\ \delta_1(K\bar{K}) = 58.7^\circ,$
    $\delta_{1/2}(\pi K) = 84.4^\circ,\ \delta_{3/2}(\pi K) = -26.7^\circ$

- Masses and widths of non-$(q\bar{q})$ mesons:
  $m_{\hat{\sigma}^*} = 1.514\,\mathrm{GeV}, \quad m_{E^*_{\pi\pi}} = 2.164\,\mathrm{GeV},$
  $m_{\sigma_H} = 2.012\,\mathrm{GeV};$
  $\Delta m_s = 0.12\,\mathrm{GeV}, \quad \Delta m_c = 1.3\,\mathrm{GeV}:$

  $\Gamma_{[][]} = 0.198\,\mathrm{GeV}, \quad \Gamma_{()()} = 0.256\,\mathrm{GeV},$
  $\Gamma_H = 0.0456\,\mathrm{GeV}$

- Glue-rich scalar meson – S^*:
  $m_{S^*} = 1.71\ \mathrm{GeV}, \qquad \Gamma_{S^*} = 0.125\ \mathrm{GeV}$

Branching ratios (%) for $D \to PP$ decays (PDG'03)

Decays	(1)	(2)	(3)	(4)	(5)	$\mathcal{B}_{\text{exp}}$(PDG'03)
$D^+ \to \bar{K}^0\pi^+$	3.27	1.06	1.06	2.72	2.72	2.71 ± 0.20
$D^0 \to K^-\pi^+$	2.41	8.41	8.41	3.37	3.83	3.83 ± 0.09
$D^0 \to \bar{K}^0\pi^0$	0.00	3.85	3.85	2.21	2.31	2.30 ± 0.22
$D_s^+ \to \bar{K}^0 K^+$	0.20	5.82	5.82	1.70	3.50	3.6 ± 1.1
$D^0 \to \pi^-\pi^+$	0.15	0.63	0.42	0.21	0.14	0.143 ± 0.007
$D^0 \to \pi^0\pi^0$	0.00	0.19	0.11	0.07	0.09	0.084 ± 0.022
$D^+ \to \pi^0\pi^+$	0.12	0.12	0.12	0.23	0.23	0.25 ± 0.07
$D^0 \to K^-K^+$	0.19	0.48	0.72	0.45	0.42	0.412 ± 0.014
$D^0 \to \bar{K}^0 K^0$	0.00	0.00	0.03	0.03	0.04	0.071 ± 0.019
$D^+ \to \bar{K}^0 K^+$	0.47	1.19	1.19	0.70	0.52	0.57 ± 0.06
$D_s^+ \to \pi^+ K^0$	0.17	0.24	0.24	0.09	0.05	< 0.8
$D_s^+ \to \pi^0 K^+$	0.00	0.07	0.07	0.05	0.06	—

(1) M_{FA}

(2) $M_{\text{FA}} \oplus M_{\text{ETC}}$

(3) $M_{\text{FA}} \oplus M_{\text{ETC}} \oplus M_{\text{S}}^{(S^*)}$

(4) $M_{\text{FA}} \oplus M_{\text{ETC}} \oplus M_{\text{S}}^{(S^*)} \oplus M_{\text{S}}^{\{qq\bar{q}\bar{q}\}}$

(5) $M_{\text{FA}} \oplus M_{\text{ETC}} \oplus M_{\text{S}}^{(S^*)} \oplus M_{\text{S}}^{\{qq\bar{q}\bar{q}\}} \oplus M_{\text{S}}^{\{q\bar{q}g\}}$

§11. Summary on the **Part II**

Hadronic two-body decays of charm mesons assuming that their amplitude is given by a sum of factorizable and non-factorizable ones.

- Color suppression and helicity suppression in the factorized amplitudes.
- Large contribution of multi-hadron intermediate states to decays into non-exotic final states
- Important role of four-quark mesons
  - Masses of four-quark mesons are somewhat higher than the ones predicted by Jaffe.
  - Important role of σ^{s*} in $D^0 \to K^+K^-$ in a possible solution to the long standing puzzle

$$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-)} \sim 3$$

- Hybrid scalar mesons can play a role in annihilation decays ($m_{\pi_H} \sim 2.01$ GeV and $\Gamma_{\pi_H} \sim 50$ MeV).

"Hadronic weak interactions are intimately related to hadron spectroscopy."

It is awaited that existence of four-quark mesons is confirmed.

- Acknowledgements
  - Onogi-*san* for informations of the BABAR experiment and discussions
  - Kunihiro-*san* for discussions and encouragements
  - Members of the high energy physics group, YITP and Kyushu University for discussions
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