Diquark-antidiquark with open charm in QCD sum rules

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New scalar charmed mesons

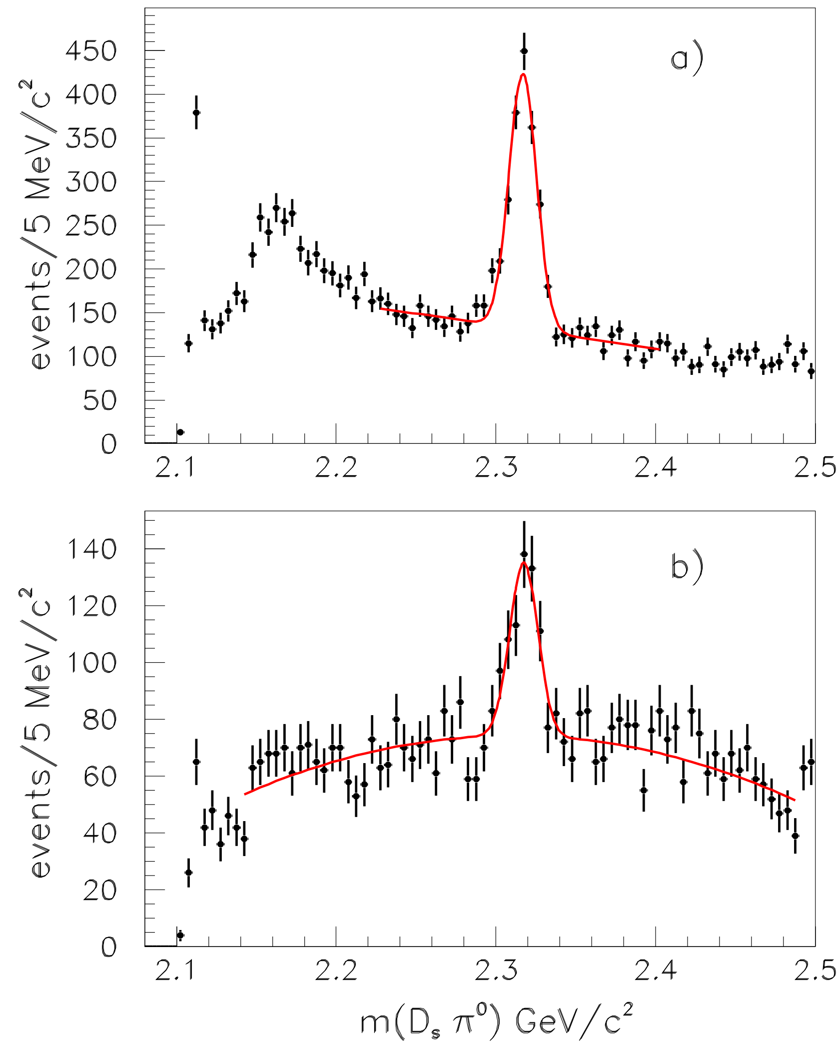
BABAR @ SLAC: (PRL90 (2003) 242001)

very narrow ($\Gamma < 5\,\mathrm{MeV}$)
meson $\rightarrow D_s^+ \pi^0$
$Q = 1,\ C = 1,\ S = 1 \Rightarrow$

minimum quark content: $c\bar{s}$

$D_{sJ}^+(2317),\ J^P = 0^+$

confirmed by CLEO, Belle, FOCUS

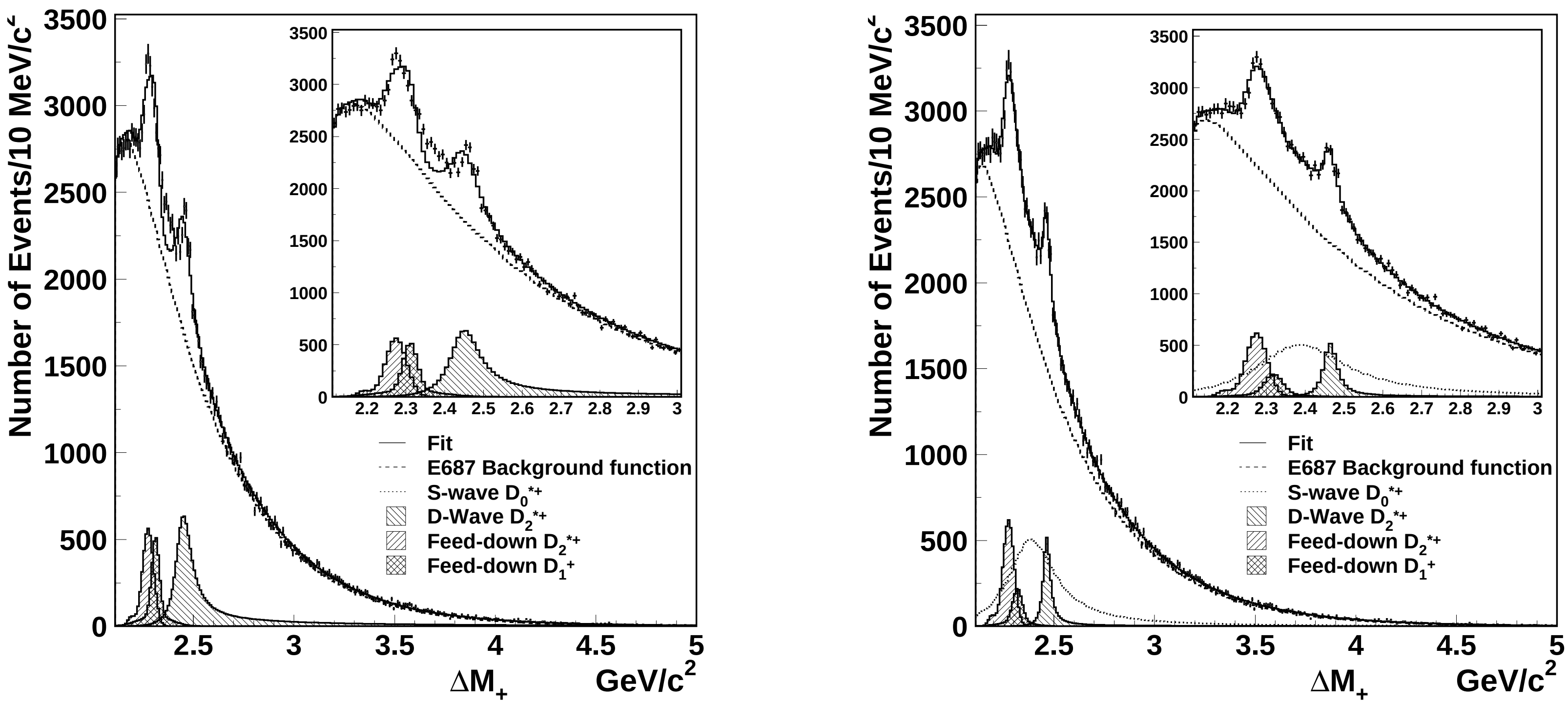


FOCUS @ Fermilab (PLB586 (2004) 11):

Evidence for broad scalar states ($\Gamma \sim 250$ MeV)

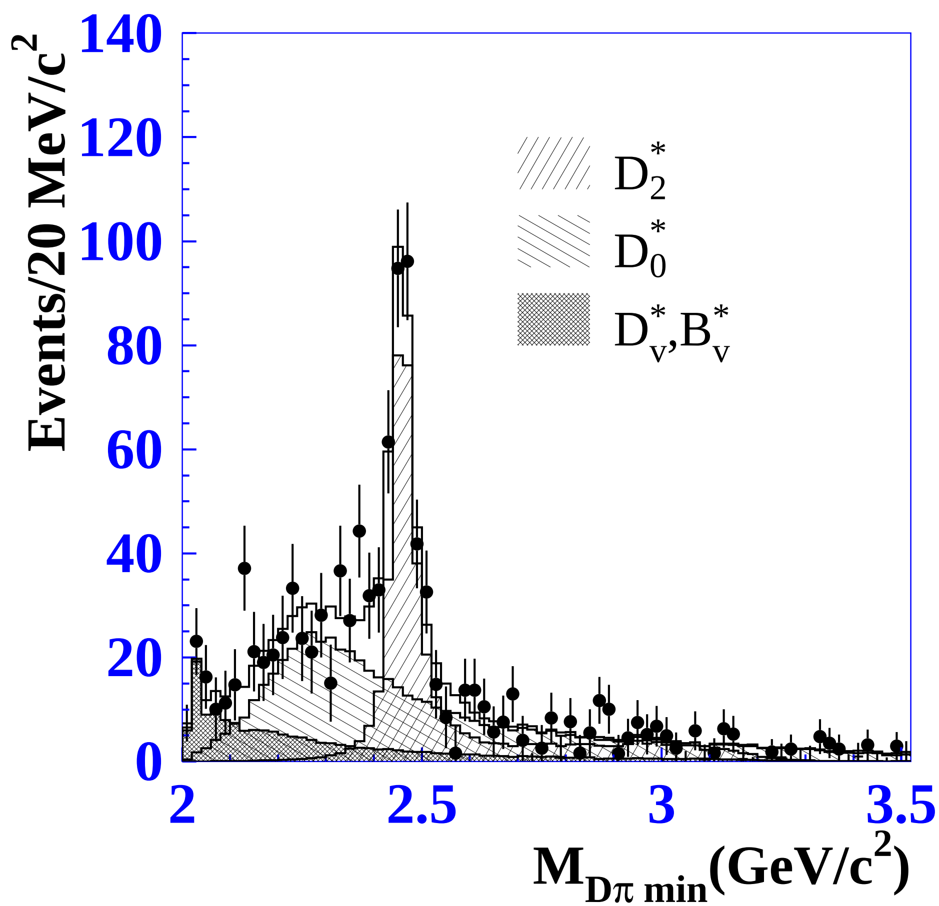
$D_0^{*0}(2407) \to D^+\pi^-$

$D_0^{*+}(2403) \to D^0\pi^+$

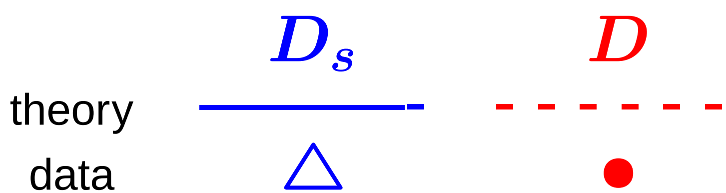


Belle @ KEK (PRD69 (2004) 112002):

Observation of a broad scalar state: $D_0^{*0}(2308) \to D^+\pi^-$
$\Gamma \sim 270$ MeV

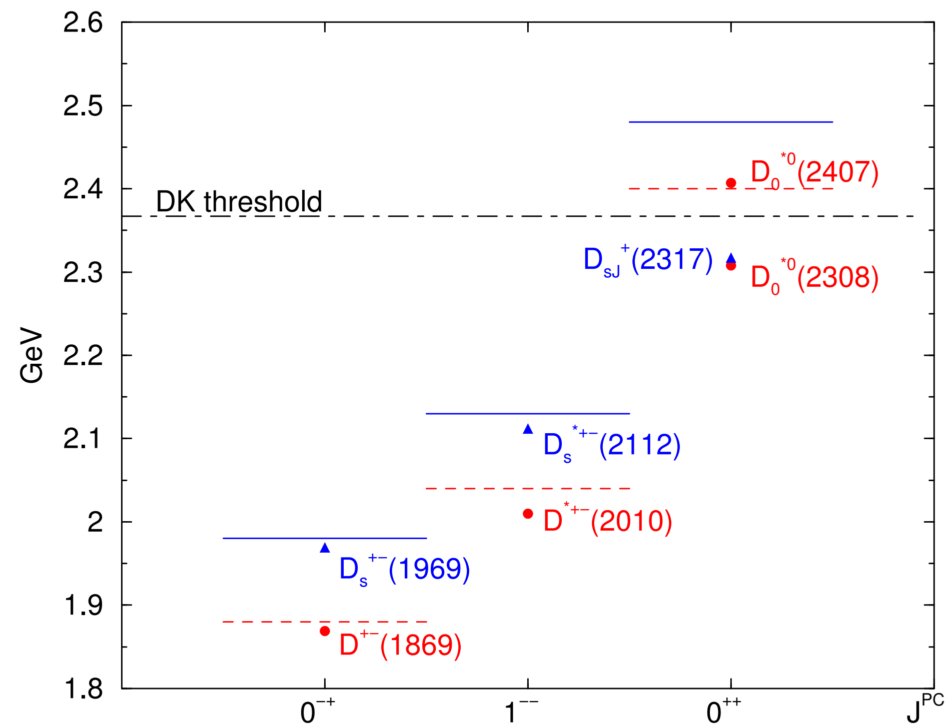


Meson D spectroscopy

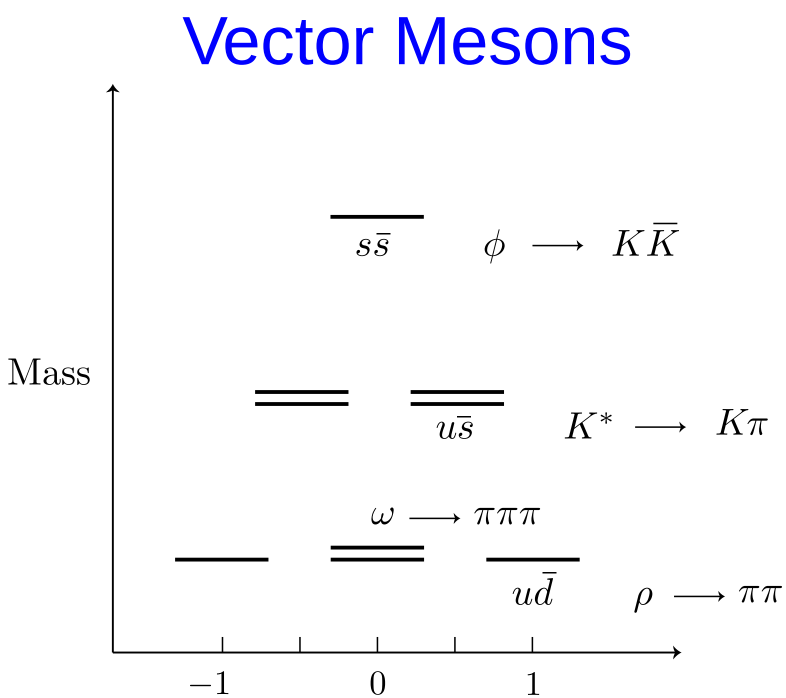


theory: potencial model

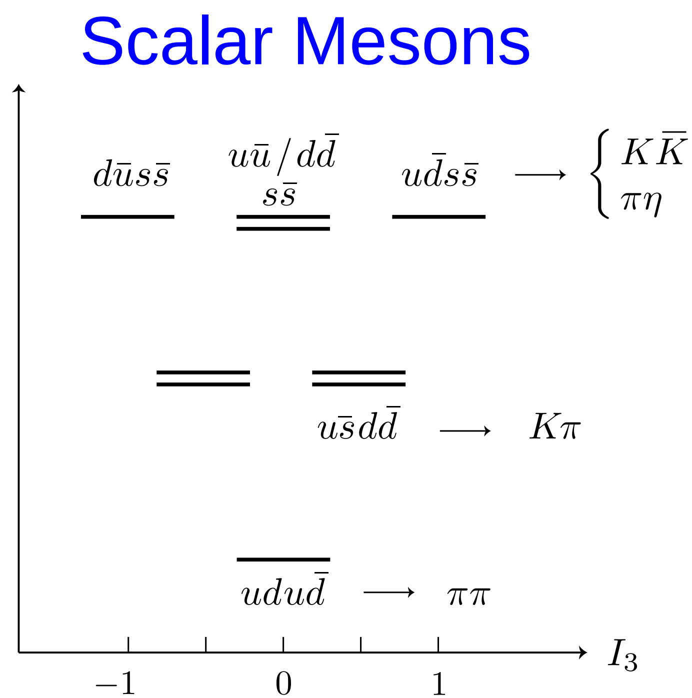
Godfrey & Isgur, PRD32 (1985)



Light Sector



1(a)



1(b)

ϕ(1020)
K^*(890)
ρ(770),ω(780)

f_0(980), a_0(980)
κ(800)
σ(480)

κ(800), σ(480) $\Rightarrow$ E791 Coll. $D \to \kappa\pi$, $D \to \sigma\pi$

E791 Coll. P.R.L. **86** (2001) 765, 770; P.R.L. **89** (2002) 121801

$\mathbf{D_{sJ}^{+}(2317)}$ $\begin{cases} \text{pure } c\bar{s} \text{ state} \\ c\bar{q}q\bar{s} \text{ four-quark state} \\ \text{two-meson molecular state} \\ \text{mixing: two-meson and four-quark states} \end{cases}$

QCD Sum Rules $\begin{cases} D_{sJ}^{+}(2317), \quad D_0^{*0}(2308) \text{ [Belle]} \\ \\ \text{as four-quark states} \\ \text{diquark antidiquark structure} \end{cases}$

$$\Pi(q) = i \int d^4x \, \langle 0|\mathrm{T}[j_S(x) j_S^{\dagger}(0)]|0\rangle e^{iq.x}$$

$$j_S \begin{cases} j_0 = \epsilon_{abc}\epsilon_{dec}(d_a^T C\gamma_5 c_b)(\bar{u}_d \gamma_5 C \bar{d}_e^T) \\ \\ j_s = \frac{\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(u_a^T C\gamma_5 c_b)(\bar{u}_d \gamma_5 C \bar{s}_e^T) + u \leftrightarrow d] \\ j_{ss} = \epsilon_{abc}\epsilon_{dec}(s_a^T C\gamma_5 c_b)(\bar{u}_d \gamma_5 C \bar{s}_e^T) \end{cases}$$

QCD Sum Rule

Fundamental Assumption: Principle of Duality

Theoretical side	Phenomenological side
↓	↓
quark level quark and gluon degrees of freedom	hadron level hadron parameters (masses, couplings, form-factors,...)
↓	↓
Wilson OPE	dispersion relation

To improve the matching $\Rightarrow$ Borel transform

Phenomenological side

$$\Pi^{phen} = \langle 0|j_S|S\rangle \frac{1}{m_S^2 - q^2} \langle S|j_S|0\rangle + \text{continuum}$$

$$\langle 0|j_S|S\rangle = \sqrt{2} f_S m_S^4$$

Theoretical Side

$$\Pi^{OPE}(q^2) = \int_{m_c^2}^{\infty} ds\, \frac{\rho(s)}{s - q^2}, \quad \rho(s) = \frac{1}{\pi}\text{Im}[\Pi^{OPE}]$$

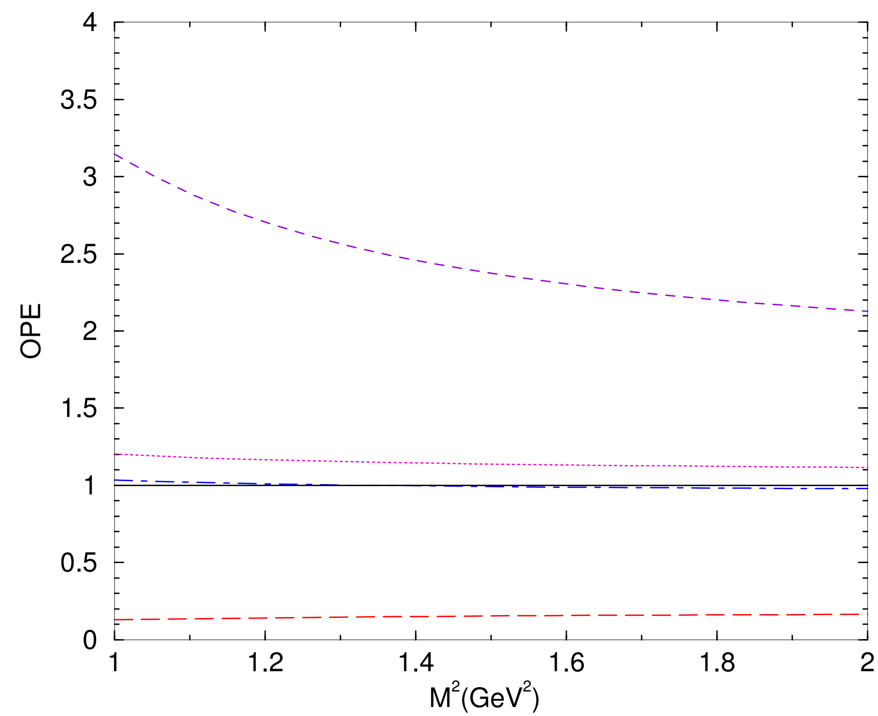
condensates up to dimension 6
- quark condensate
- gluon condensate
- mixed condensate
- four-quark condensate

up to order m_s with m_c finite

Sum Rule

$$2 f_S^2 m_S^8 \, e^{-m_S^2/M^2} = \int_{m_c^2}^{s_0} ds \, e^{-s/M^2} \, \rho_S(s)$$

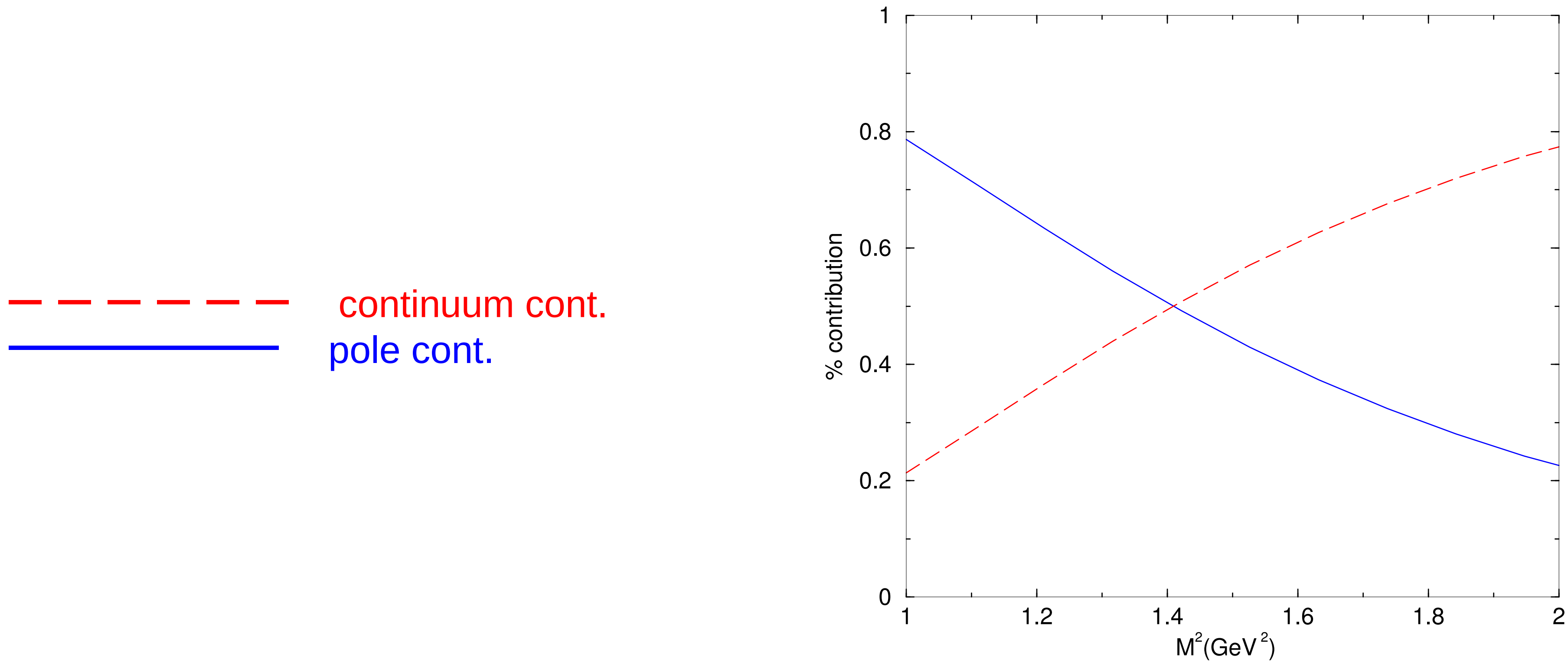
$$m_s = (0.13 \pm 0.02) \ \text{GeV}$$
$$m_c = (1.3 \pm 0.2) \ \text{GeV}$$
$$\langle \bar{q} q \rangle = -(0.23)^3 \ \text{GeV}^3$$
$$\langle \bar{s} s \rangle = 0.8 \langle \bar{q} q \rangle$$
$$\langle \bar{q} g \sigma . G q \rangle = 0.8 \langle \bar{q} q \rangle$$
$$\langle g^2 G^2 \rangle = 0.5 \ \text{GeV}^4$$
$$\sqrt{s_0} = (2.7 \pm 0.1) \ \text{GeV}$$



perturbative
+ quark condensate
+ gluon condensate
+ four-quark condensate
total

Continuum Contribution

OPE side = pole + continuum contribution



Masses

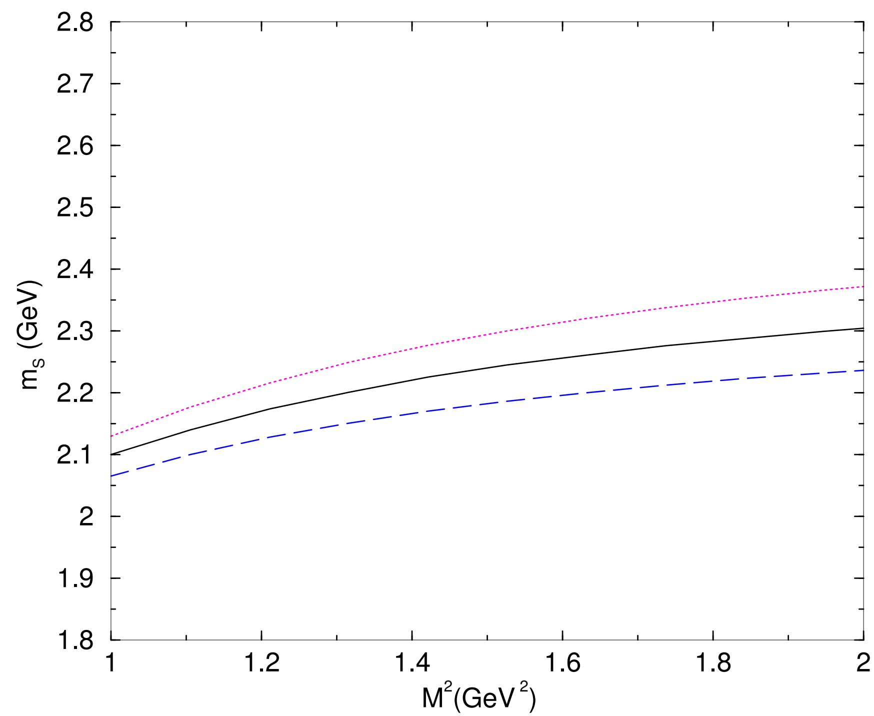
$$m_S^2 = \frac{\int_{m_c^2}^{s_0} ds\, e^{-s/M^2}\; s\rho_S(s)}{\int_{m_c^2}^{s_0} ds\, e^{-s/M^2}\; \rho_S(s)}$$

$j_S = j_0$

- - - - - - $\sqrt{s_0} = 2.6$ GeV

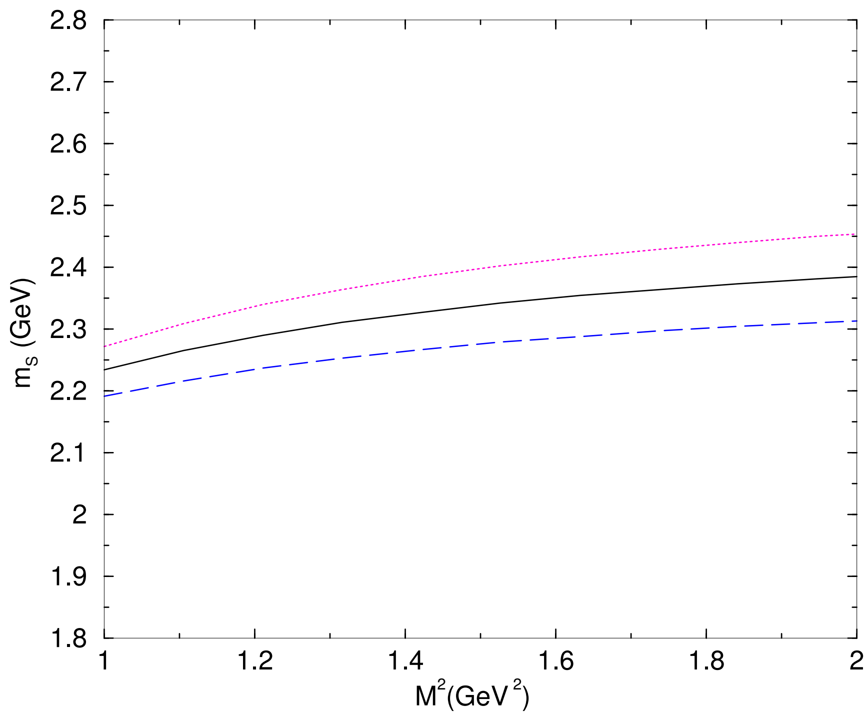
——— $\sqrt{s_0} = 2.7$ GeV

· · · · · · · · · $\sqrt{s_0} = 2.8$ GeV

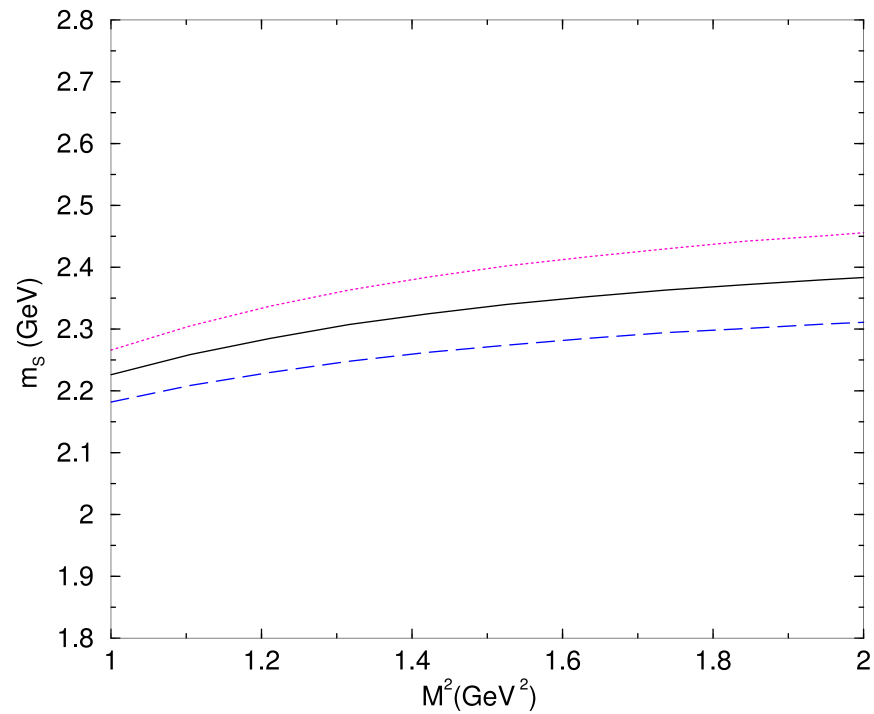


$m_{0s} = (2.22 \pm 0.20)$ GeV

$$j_S = j_s$$



$$j_S = j_{ss}$$



$$m_{1s} = (2.32 \pm 0.20) \text{ GeV}$$

$$m_{2s} = (2.31 \pm 0.20) \text{ GeV}$$

resonance	$D_0^{(0s)}$	$D_0^{(1s)}$	$D_0^{(2s)}$
mass (GeV)	2.22 ± 0.20	2.32 ± 0.20	2.31 ± 0.20

to be seen — $D_{sJ}^{+}(2317)$ — $D_0^{*0}(2308)$

Width

$D_{sJ}^{+}(2317) \to D_s^+\pi^0 \Rightarrow \Gamma < 5$ MeV

(Belle) $D_0^{*0}(2308) \to D^+\pi^- \Rightarrow \Gamma \sim 270$ MeV

$$\Pi^{phen}(M^2) = 2 f_S^2 m_S^8 \int_{(m_\pi+m_D)^2}^{s_0} ds\, e^{-s/M^2} \rho_{BW}(s)$$

$$\rho_{BW}(s) = \frac{1}{\pi}\frac{\Gamma(s) m_S}{(s-m_S^2)^2+m_S^2\Gamma(s)^2}, \quad \Gamma(s) = \Gamma_0 \sqrt{\frac{\lambda(s,m_D^2,m_\pi^2)}{\lambda(m_S,m_D^2,m_\pi^2)}}\frac{m_S^2}{s}$$

$$\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$$

$$\frac{\int_{(m_\pi+m_D)^2}^{s_0} ds\, e^{-s/M^2} s\rho_{BW}(s)}{\int_{(m_\pi+m_D)^2}^{s_0} ds\, e^{-s/M^2} \rho_{BW}(s)} = \frac{\int_{m_c^2}^{s_0} ds\, e^{-s/M^2} s\rho_S(s)}{\int_{m_c^2}^{s_0} ds\, e^{-s/M^2} \rho_S(s)} .$$

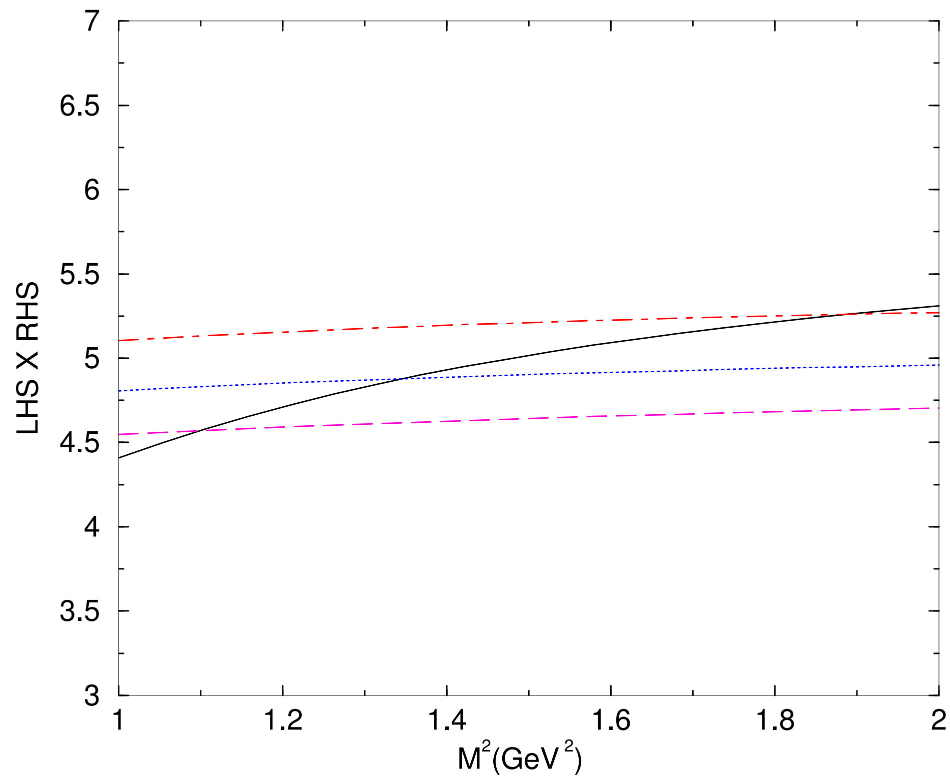
mass is a parameter

- - - - - - $m_S = 2.2$ GeV

· · · · · · · · · $m_S = 2.3$ GeV

— · — · $m_S = 2.4$ GeV

——— RHS

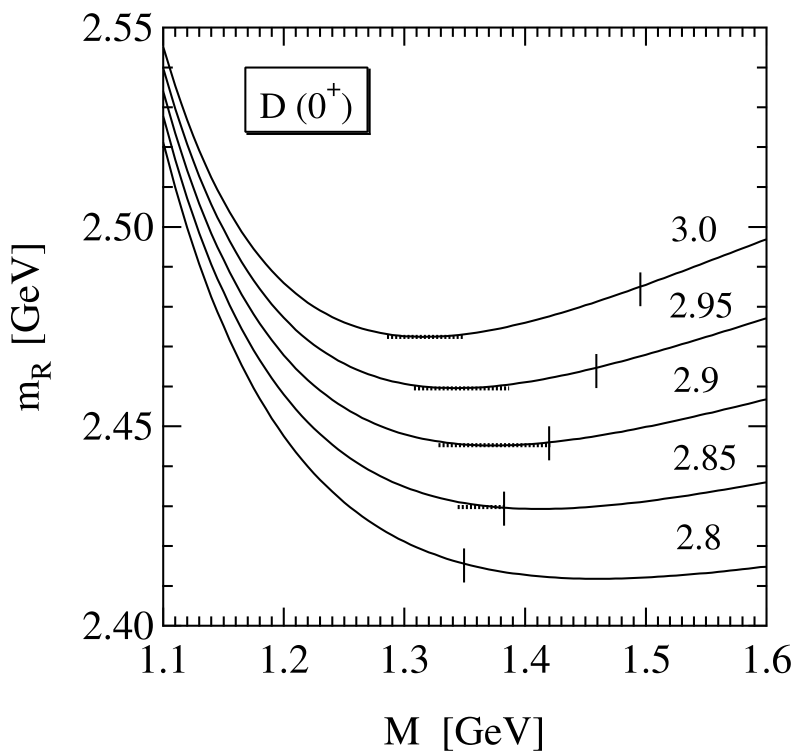


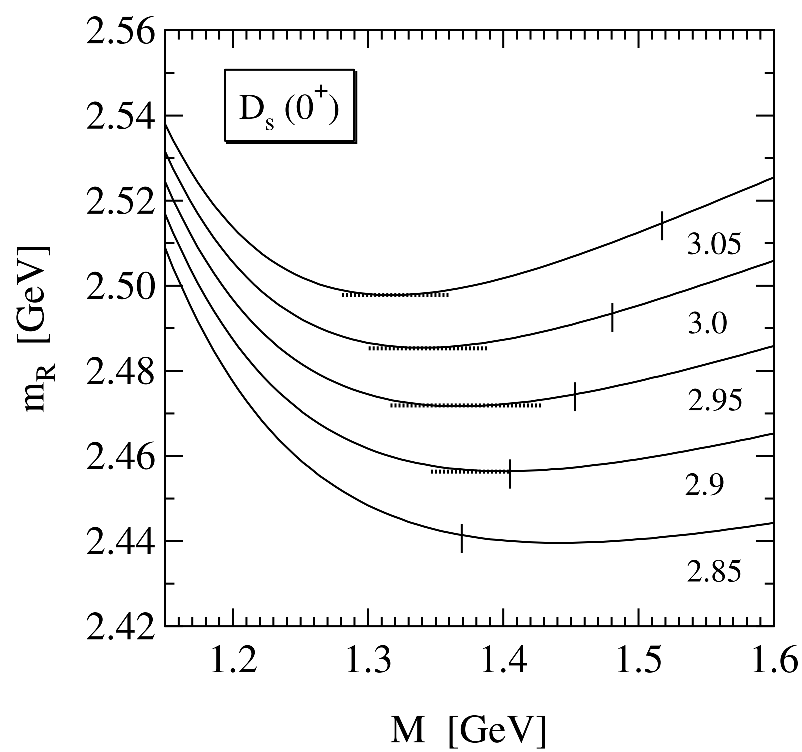
m_S **compatible with 2.3 GeV**

Two-quark states

Hayashigaki & Terasaki (hep-ph/0411285)

resonance	$c\bar{q}$	$c\bar{s}$
mass (GeV)	$\mathbf{2.45 \pm 0.03}$	$\mathbf{2.48 \pm 0.03}$
mass^{exp} (GeV)	**2.308** (Belle), **2.405** (FOCUS)	**2.317**





pseudoscalar and vector mesons compatible with experiment

Light Scalars

Decay width (diquark-antidiquark states) $\left\{ \begin{array}{l} \sigma \to \pi^+\pi^- \\ \kappa \to K^+\pi^- \\ f_0 \to K^+K^- \\ f_0 \to \pi^+\pi^- \end{array} \right.$

$$T_{\mu\nu}(p,p',q) = \int d^4x\, d^4y\, e^{i.p'.x}\, e^{iq.y} \langle 0|T\{j_{5\mu}^{P_1}(x) j_{5\nu}^{P_2}(y) j_S^\dagger(0)\}$$

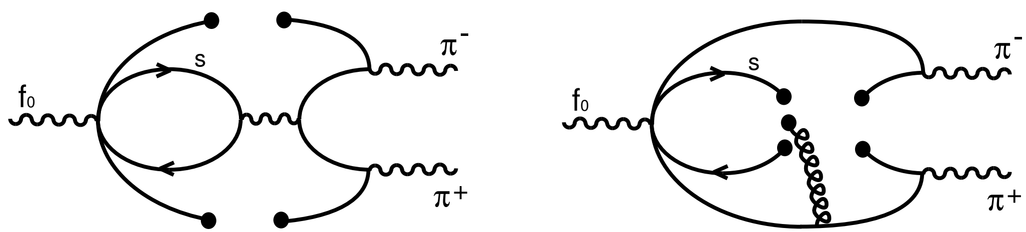
$$T_{\mu\nu}^{phen} = \frac{\sqrt{2} F_{P_1} F_{P_2} m_S^4 f_S}{(m_S^2 - p^2)(m_{P_1}^2 - p'^2)(m_{P_2}^2 - q^2)}\, g_{SP_1P_2}\, p'_\mu q_\nu + \cdots$$

$$\Gamma(S \to P_1 P_2) = \frac{1}{16\pi m_S^3} (g_{SP_1P_2})^2 \sqrt{\lambda(m_S^2, m_{P_1}^2, m_{P_2}^2)}$$

vertex	$\sigma\pi^+\pi^-$	$\kappa K^+\pi^-$	$f_0 K^+ K^-$	$f_0\pi^+\pi^-$
g (GeV) g^{exp} (GeV)	3.1 ± 0.5 2.6 ± 0.2	3.6 ± 0.3 4.5 ± 0.4	1.6 ± 0.1	0.47 ± 0.05 1.6 ± 0.8

PLB 608 (2005) 69

$f_0 \rightarrow \pi^+\pi^-$ mediated by one gluon exchange



(a) (b)

needs α_s corr.

QCD sum rule calculation:

$\Gamma_{D^+_{sJ}(2317)\rightarrow D^+_s\pi^0} \propto (<\bar{u}u> - <\bar{d}d>)^2 \Rightarrow$ very small

preliminary calculation: $g_{D_{sJ}D_s\pi} \sim 0.06$ GeV $\Rightarrow \Gamma \sim 8$ KeV

isovector state: $\Gamma \sim 260$ MeV

Conclusions

We have evaluated the masses of the four-quark states: $(cd)(\bar{u}\bar{d})$, $(cu)(\bar{d}\bar{s})$ and $(cs)(\bar{u}\bar{s})$

resonance	$D_0^{(0s)}$	$D_0^{(1s)}$	$D_0^{(2s)}$
mass (GeV)	2.22 ± 0.20	2.32 ± 0.20	2.31 ± 0.20

The masses of BABAR, $D_{sJ}^{+}(2317)$, and Belle, $D_0^{*0}(2308)$, resonances can be reproduced by the four-quark states $D_0^{(1s)}$ and $D_0^{(2s)}$, although the OPE convergence is not good

The observation of a new scalar charmed meson, with mass ~ 2.2 GeV, would confirm the existence of four-quark states

We interprete the FOCUS, $D_0^{*(0+)}(2405)$, resonance as a normal two-quark $(c\bar{q})$ state